Self-Healing Control to improve reliability for the Smart Grid Distribution System

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Abstract

A Smart Grid is a modernised future electric power network that uses various modern technologies, intelligence and approaches in order to provide sustainable, reliable and secure renewable and distributed energy resources. In the contrary, the emergence of time-variant and non-deterministic renewable and distributed energy resources are continuously causing new challenges to the Smart Grid across the world. Optimal control and efficient operation of renewable & distributed energy resources are one of the greatest challenges that are spontaneously leading the Smart Grid to an unstable state from its steady-state. Frequent and large instability results brown-out of the grid equipment which leads plant failure as well as power outage of the grid. Thus, the overall reliability of the power system reduces. Consequently, this thesis focuses on the factors that affect the reliability of the Smart Grid particularly its Distribution System. It has been identified through a literature research that voltage instability is one of the main reasons to brown-out of grid equipment and caused power outage hence reduced reliability of the grid. It has also been identified through research that voltage instability is the direct result of supply-demand unbalance. For example, Photovoltaic solar panel is historically at maximum power generation mode while demand of the system is below the average magnitudes. This results in surplus power to supply to the grid network and causes overvoltage. In addition to Photovoltaic, recently emerged Hybrid Electric Vehicle and small-scale Electric Energy Storage charge and discharge across the consumer terminals. These introduce additional supply-demand unbalances hence voltage instability due to State-of-Charge and Depth-of-Discharge of such distributed energy resources. Consequently, the control and operation of Smart Grid Distribution System are becoming critical day by day. This thesis, therefore, developed a Self-Healing Control Algorithm to improve reliability of a proposed Smart Grid Distribution System. Self-Healing Control is developed as a form of intelligent control technique by integrating modern robust control theory (i.e.: state-variable approach) together with various computer-based artificial intelligence approaches (i.e.: Genetic Algorithm and Bayesian Probability). The Self-Healing Control was implemented to a secondary distribution system in order to improve reliability for mitigating impact of integration of renewable and distributed energy resources focusing voltage instability due to supply-demand unbalance. Two experiments were carried out and results were presented by implementing Self-Healing Control Algorithm in chapter-5. It was also showed in chapter-5 that supply-demand balance was achieved while node voltages remain steady. The experiments and results were simulated and critically analysed in MATLAB Simulink and evaluated by identifying the contribution to knowledge for Ph.D.

Acknowledgement

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List of acronyms

AMI=Advanced metering Infrastructure

AMR= Automated Meter Reading

AC=Alternating Current

CT = Current transformer

DNO= Distribution Network Operator

DSO = Distribution System Operator

DER= Distributed Energy Resources

DC = Direct Current

EES= Electric Energy Storage

HAN= Home Area Network

HEV = Hybrid Electric Vehicle

IDC = Intelligent Digital Controller

NAN=Neighbourhood Area Network

PT= Potential transformer

PV= Photovoltaic

PMU= Phasor Measurement Unit

PLC= Power Line Carrier

RER= Renewable Energy Resources

R&DER= Renewable and Distributed Energy Resources

RTU=Remote Terminal Unit

SG= Smart Grid

SGDS= Smart Grid Distribution System

SCADA= Supervisory Control and Data Acquisition

SM= Smart Meter

SHC= Self-Healing Control

SHCA = Self-Healing Control Algorithm

SST=Solid State Transformer

TSO=Transmission System Operator

VRER= Variable Renewable Energy Resources

WAN=Wide Area Network

UART = Universal Asynchronous Receiver and Transmitter

List of symbols

ƛ = failure rate

µ = survival rate

U_i = Annual unavailability or ouatge time at the load point i

N_i = Number of customers at the load point interrupted by the i th interruption event

T = a random variable representing the failure time

F(t) = the probability that component will fail by time t

R = total number of customers and sustained outage rate at load point

R(t) = Reliability function represents the probability that the component will survive at time t

Z1=Z2=Low-voltage impedance

Zf= Fault impedance

I_f = Fault current

V_o= Voltage response across the load

P = Real power

Q = Reactive power

x(t) = state-variable

u(t) = control variable

y(t) = output variable

Chapter 1: Introduction

The Smart Grid Distribution System (SGDS) is a modernised electric power distribution system that uses intelligent control techniques, Information and Communication Technology (ICT) on sources, loads and distributed power network (DPN) in order to enhance optimal control, efficient operation and intelligent demand response for sustainable future electricity. The renewable and distributed energy resources (R&DER) integration within the existing electric distribution system is the key features of SGDS which have been leading the distribution system to a microgrid system. Small-scale roof mounted Photovoltaic (PV) solar panel is one of the most promising renewable energy resources and various forms of Electric Energy Storage (EES) and Hybrid Electric Vehicle (HEV) are the emerging distributed energy resources that have been continuously integrating into the SGDS. The impact of wide-scale R&DER integration is noticeable such as supply-demand unbalance that causes voltage fluctuation in the system.

Additionally, the smart meter (SM), the smart sensor (SS) and intelligent electronic devices (IED) have been installed throughout the DPN by the distribution system operation (DSO). The SM provides real-time and historic energy consumptions that facilitate DSO to consider real-time pricing (RTP) to the customers. The SS measures real-time voltage, currents, frequency, phase angles and cable temperature that enhance monitoring, control and protection of the SGDS. The IED such as Internet-of-Things (IoT), wireless sensor network (WSN) devices, power line carrier (PLC) communication modem enables real-time communication across the DPN, sources, loads that enable intelligent demand response and efficient operation of the SGDS.

However, the heterogeneous SGDS infrastructure offers many challenges like sustainability, reliability and security of electricity to DSO to implement aforementioned technologies within the existing electric distribution system. The switching surges due to time-variant PV solar power generation, State-of-Charge and Depth-of-Discharge of EES and HEV is presumably one of the key challenges to retain uninterruptable power supply in a SGDS.

The voltage instability was identified as one of the key factors that lead the equipment failure as well as the plant failure or permanent power outage in the proposed SGDS network. It was showed by several case studies and experiments that the proposed SHC technique enhances the reliability by ensuring optimal control and efficient operation while providing voltage stability for the proposed SGDS. The context, aim and objectives of the research are presented in the following sections.

1.1: Context

Electric power distribution system is critical sub-power network responsible for delivering power from the substation to the customer's meters in a unidirectional power flow mode with little or no consumer participation. Most of the distribution circuits are radial and come up with many different configurations, standards, lengths that results complex distributed infrastructure, voltage drops along the line, power losses and interrupted real and reactive power flows. Additionally, there are an unlimited number of substation and distribution system configurations currently available in order to maintain high side and low-side switching, voltage standards, voltage profiles, protective devices coordination and metering in the distribution system. As a result, electric distribution system is traditionally known as one of the most heterogeneous sub-system in the entire power system.

Moreover, the loads in a radial feeder are inherently unbalanced due to the large number of unlike linear, non-linear, single-phase and three-phase loads. Additional unbalance is introduced by non-equilateral conductor spacing of the three-phase overhead line segments. The unpredicted and spontaneous variations in real and reactive power demands inject voltage instability in the radial feeder that also causes critical dynamics and unbalance. Furthermore, over the last few decades, (since the 1960's) several advances have been made in load-flow computation for transmission systems [1]. Its application to distribution system has had limited success due to the radial structure of the distribution system topology, the low X/R ratio and the dynamic condition of load in a distribution system. It was found that such analysis displays poor convergence characteristics for radial systems [2].

Additionally, deregulations in electric distribution system lead to additional organizational complexities. It has resulted in a major cost cutting at many utilities [3] in equipment, crew numbers, operation and maintenance could mean major reduction in reliability. Statutory and non-statutory regulations require additional safeguards materials that increase installation costs consequently energy tariff.

Furthermore, electricity is consumed at the same time it is generated. Hence, the correct amount of electricity must always be supplied to meet the varying peak, off-peak and critical demands. This means, power systems should ensure an adequate supply of electric energy while satisfying load requirements as economical as possible with a reasonable level of security and reliability under any circumstances [4]. To maintain continuity, the system is designed to deliver this energy both reliably and economically. However, the requirements of reliability and economy are largely opposed.

On the other hand, the worldwide power generation is historically dominated by non-renewable fossil fuels (e.g.: coal, natural gas, diesel, petrol) resulting in an increase in CO_2 emissions. In particular, thermal power plants burns coal and produce vast amount of Greenhouse Gases (GHG) causing global warming [5]. Furthermore, non-renewable traditional fossil fuel energy resources have reached their limit on the earth. Rapidly increasing demand of electric energy brought a new challenge for global power industries. Nuclear power plants have emerged to overcome this continuously growing demand. However, the nuclear incident in Japan in March 2011 was catastrophic [6]. This reduced confidence about nuclear power plant across the world dramatically. Recent advancement in renewable energy resources is promising. However, renewable energy resources cannot meet the strict requirements (e.g.: dynamic demand, voltage and frequency stability) of electric system due to their non-deterministic characteristics and resource availability [7].

In addition to the generation system, a highly-meshed and high voltage long transmission line causes load unbalancing, transmission losses, poor visibility and complex monitoring of wide-area grid networks and its assets. High-maintenance costs of wide-area transmission network and grid devices including inadequate energy storage facilities demand spinning reserves for a secure and uninterrupted power supply; are the key indicators for high-energy tariffs. Transmission System Operators (TSO) is spending huge capitals behind load balancing mechanism in every year. Transmission losses in UK's National Grid for 2014-2015 are given in table-1.1.

Table 1.1-Losses from the UK transmission system in 2014-2015 [8]

Period – 01 April 2014 to 31 March 2015		
Transmission system	Loss (TWh)	Loss (%)
England and Wales	4.60	1.65
South Scotland	0.42	1.17
North Scotland	0.67	8.04
Total Network Losses	5.68	1.84

This general structure has worked well for about a century, but is breaking down due to a number of pressures. Probably the most important of these is distributed generation, whereby small sources of energy (especially PV solar panels) are being installed in a wide distribution over the entire network. Other examples include small wind turbines and then, on an intermediate scale, small hydro-electricity stations, tidal and wave power sources and industry-specific thermal power stations, possibly using waste heat. Another technological change which is transforming the network is the growing interest in small-scale energy storage (e.g.: EES and HEV). The major component of this is expected to be batteries in electric vehicles, which have the additional complication that their location, state of charge, depth of discharge and willingness to be an energy source are all rather unpredictable [9]. However, if it is also expected that fixed and more predictable battery energy systems might become popular, in addition to older ideas such as flywheels and compressed air storage. Beyond these changes, there is the additional potential transformation to DC distribution within the home, implying the possibility of DC distribution over wide areas.

Above these technological considerations are significant influences of politics and economics. The pressure on governments to reduce carbon dioxide emissions means that the significance of large thermal power stations will necessarily be greatly reduced. In terms of economics, customers will want the cheapest deal possible for their energy supplies and this means that they are likely to be attracted to intelligent metering, which can seek out cheaper sources of electrical energy for less critical loads which are able to accept disruptions of supply or usage only at low-cost times (historically this has been the night time, but this may be reversed if PV solar panels, HEV and EES become a dominant source of electricity).

Consequently, the concept of an integrated Smart Grid Distribution System integrated with Smart Sensor, Smart Meter, Advanced Metering Infrastructure and Intelligent Electronic Devices is being proposed. The SGDS is expected to differ from the conventional electric distribution system in a number of ways. In SGDS, Renewable and Distributed Energy Resources (R&DER) will be the dominating energy sources, Self-Healing Control will be the key control and automation technique for optimal control, efficient operation and intelligent demand response; real-time pricing and customer participation will be the key cost-effective energy management schemes, active distribution network management will be the key advantage to the DNO and DSO, ICT will be the key technology for real-time DPN monitoring including many more advanced and customer-oriented facilities. Table 1.2 shows more features of a typical Smart Grid focusing SGDS comparing with a conventional power grid focusing electric distribution system.

Table 1.2: A Comparison between conventional and Smart Grid Distribution System including reliability issues [10-20]

Grid transformation		
Compared Points	**Existing Grid**	**Smart Grid**
Structure	Electromechanical	Electronic
Generation	Centralised	Distributed
Transmission and Distribution	Hierarchical	Distributed
Communication	One-way	Two-way
Sensor and actuator	Few	Everywhere (throughout)
Control	Limited	Distributed self-healing or market based
Supervision/Monitoring	Remote or centralised	Intelligent real time
Management	Centralised	Decentralised or market based
Status	Blind (invisible	Visible devices (real time

	devices)	update)
Fault management	Manual check and test	Self-healing
Recovery	Manual restoring	Self-healing
Outage management	Failures and blackouts	Adaptive and islanding
Market	Few customer choices	Many customer choices
Reliability improvement in SGDS:		
Compared point	**Existing grid**	**SGDS**
Reduce fault	Rely on historical data	Real-time data, AMI, Smart sensors
Reconfiguration	Interconnected laterals and feeders in 11kV or upstream networks	Interconnections are not mandatory, DER provides flexibility in network reconfiguration
Identifying fault location	Calculation based on symmetrical components, fault impedance/resistance	Bounded uncertainty provide resilience to the system and enhance response times
Switching and protection equipment	Conventional	Intelligent, linear and non-linear programming-based, advanced robust controlled
Communication	Based on Telecommunication	Power line carrier, Hybrid AMI, and Internet of Things (IoT) will provide greater reliability in communication

1.2 Aim

The aim of this thesis is to develop a Self-Healing Control Algorithm in order to enhance the reliability of a proposed Smart Grid Distribution System.

1.3 Objectives

The following key objectives that were proposed for this research project are to:

1. Carry out literature survey to establish the state of the art of the reliability in an existing electric distribution system

2. Outline the factors that affect the reliability by identifying shortcomings of measures currently taken to improve reliability and the published work that proposes to improve the reliability in future.

3. Propose a Smart Grid Distribution System by modifying an existing electric distribution system that includes Photovoltaic solar panel as a renewable energy resource, Electric Energy Storage and Hybrid Electric Vehicle as distributed energy resources

4. Investigate the key impact of modification to the Smart Grid distribution focusing the reliability

5. Develop a Self-Healing Control Algorithm by means of state-variable approach, Bayesian inference and Genetic Optimisation Algorithm to mitigate supply-demand unbalances as well as voltage instability focusing the reliability.

6. Evaluate the feasibility of the Self-Healing Control Algorithm for enhancing the reliability to the proposed Smart Grid Distribution System

1.4 Contribution

This thesis is aimed to implement optimal control and efficient operation for SGDS by means of an SHCA in order to enhance the reliability. The supply-demand unbalance is identified as one of the key factors that cause reverse power flow, plant failure, and transient voltage instability to the SGDS. Consequently, a centralised SHCA is implemented to optimise the operation of R&DER as well controlled loads and an enhanced supply-demand balance is found for the SGDS. Although, the supply-demand for wider-area power system is being already in place, however, such investigation for SGDS is quite new in the power industry. A constant flux machine (i.e.: a distribution transformer) instead of a constant voltage source (i.e.: a generator) is considered as the main power source. Historically, the electric distribution system has been treating as a sink. The emergence of R&DER is making it possible to treat distribution system both as a consumer as well as prosumer. Therefore, supply-demand balance due to inhibiting reverse power flow as well plant failure is considered and contributed to the knowledge of this thesis. Eventually, the following contributions are outlined in this thesis:

- A centralised SHCA
- Optimal control and efficient operation for achieving supply-demand balance, inhibiting reverse power flow, and plant failure or power outage
- Optimise the R&DER integration and consider the annual load growth for its future integration

Chapter 2: Literature review

2.1 Introduction

The research was carried out a comprehensive investigation on structure, reliability indicators, voltage controllers and surge protectors in an existing electric distribution system in order to outline the technological development required to transform current system into a Smart Grid Distribution System. The investigation outcomes have lead to a resarch hypothesis by identifying gaps in control and protection required for the SGDS and opened a new horizon for the research contribution. Thus the literature has focused the following key points:

i. Fundamental structure of a typical elecric distribution system
ii. State of art of the reliability in an elecric distribution system
iii. Factors affecting the reliability in an elecric distribution system
iv. Measures taken to improve reliability in an electric distribution system
v. Related published work and research argument
vi. Research hypothesis and conclusion

2.2 Electric distribution system

Historically, the art of electric distribution system is formulated of one or more distribution substations that are fed by secondary transmission or sub-transmission system and are consisting of multiple feeders as shown in figure 2.1. Majority (with a rare exception) of the feeders are radial and are characterised by having only one path for power to flow from the distribution substation to each customer meter (i.e.: to loads) [21]. There are various configurations such as single-mainline, branched-mainline, express feeder, very-branched mainline available for radial feeder based on real and reactive power demand, load centres and geographical location for example radial feeder structure for urban, rural, island, hill and mountain area are different from each other. Voltage control, controlled power flows, fault current protection and low cost are among the greatest advantages of a radial feeder. One-way power flow, voltage fluctuation at the far end, outage in entire network due to fault in a small part of the feeder, short feeder length, heavily loaded of far end are the main disadvantages of a typical radial feeder.

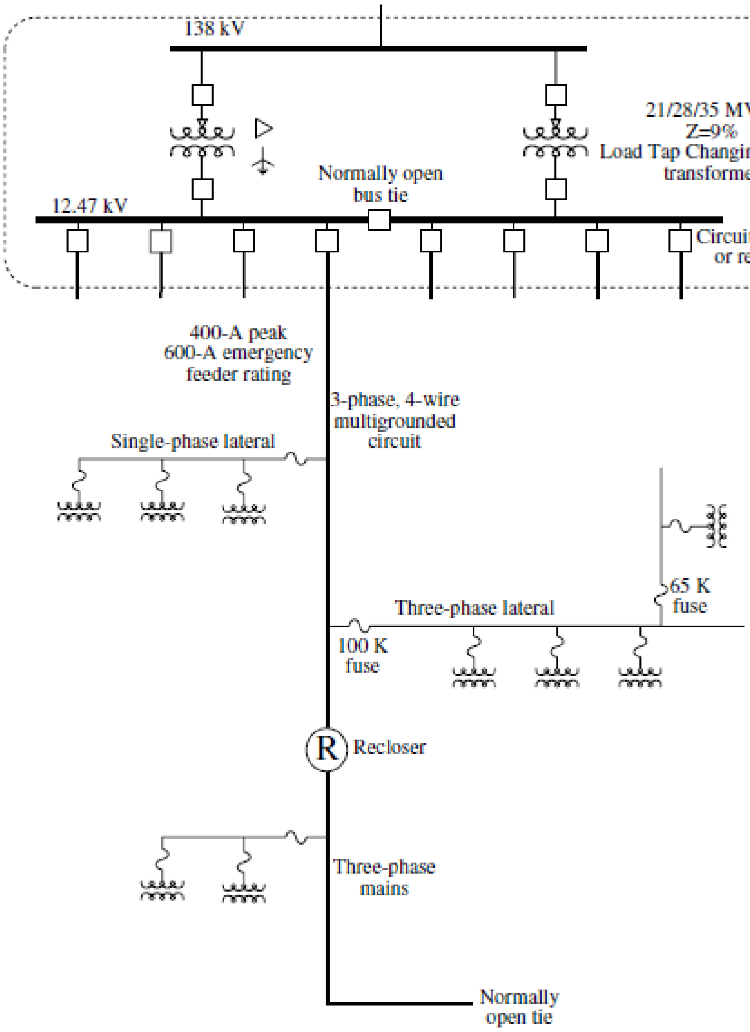


Figure 2.1: Radial feeder of a typical electric distribution system [22]

Substation is generally equipped with high-tension, low-tension switchgear. In addition to this, typical components required to design radial distribution circuits are three-phase primary “main” radial feeder, three-phase, two-phase (sometimes called “V” phase) and single-phase laterals, step-type voltage regulators, automatic voltage regulators (AVR), Auto-tap (on/off) changing transformers (OLTC), series/shunt capacitor (SC) regulators, distribution transformers (DT), secondary service mains, surge protecting devices (SPD), induction-type overcurrent relay, T-link and K-link fuses, reclosing switches, sectionalising switches and various linear and non-linear three-phase and single-phase loads [23]. Figure 2.2 shows some common equipment used for designing a typical radial feeder in existing electric distribution system. Different equipment function different purposes such as fuse, relay, recloser are for protection, capacitor banks, voltage regulator are for voltage regulation.

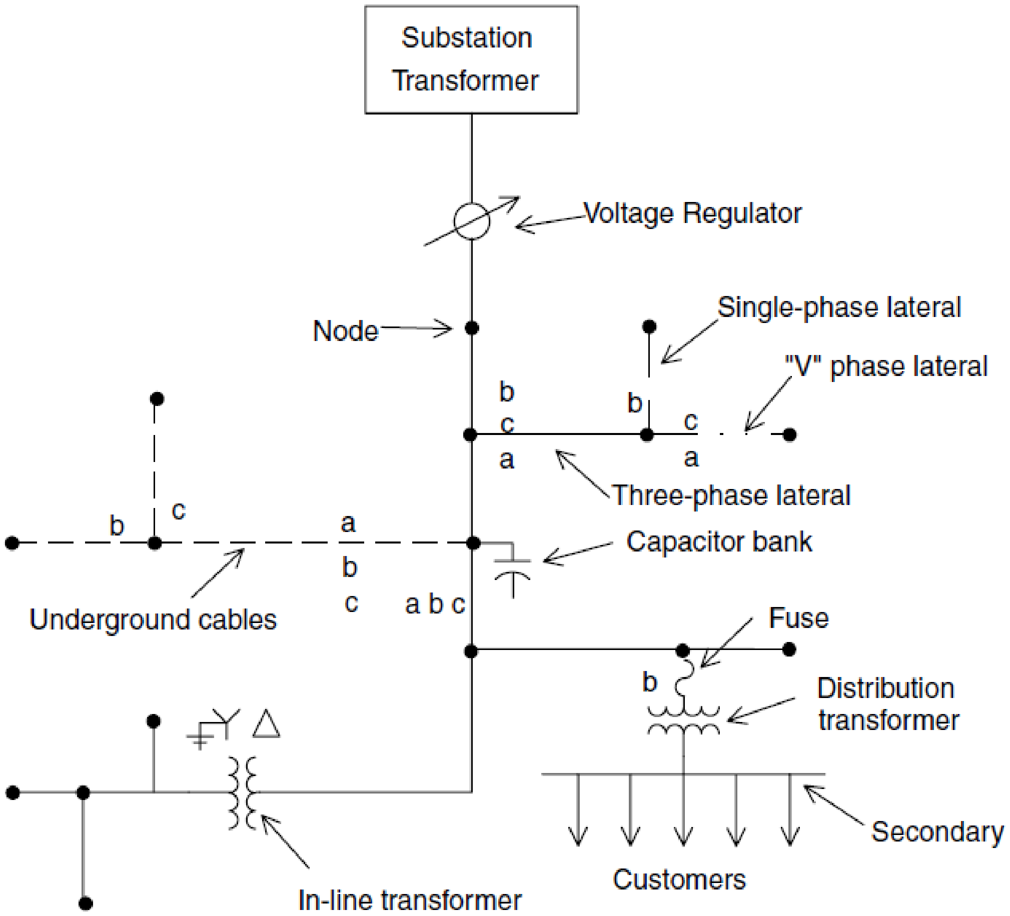


Figure 2.2: Typical distribution substation with one of multiple radial feeders [24]

The conventional radial feeder in electric distribution system forms primary distribution and secondary distribution system. Standard voltage level at primary distribution system is typically 11kV and secondary distribution system is 400V in the Europe respectively [25], as shown in figure 2.3. Most primary electric distribution systems run along the high street in the city and are three-phase multi-grounded radial circuits. The radial feeders of primary distribution system interconnect through normally open tie switch at a convenient location for satisfying demand in different location during disturbances. The radial feeder contains auto-reclosing switch, sectionalising switch, relay, current transformer and potential transformer in order to response with faults experience on the lines. The surge arrester and relays use to protect lines form the overvoltage and undervoltage. The automatic voltage regulator, off-load tap-changing transformer and capacitor banks installed along the radial feeder to regulate voltage at each node

Primary distribution system	Secondary Distribution System

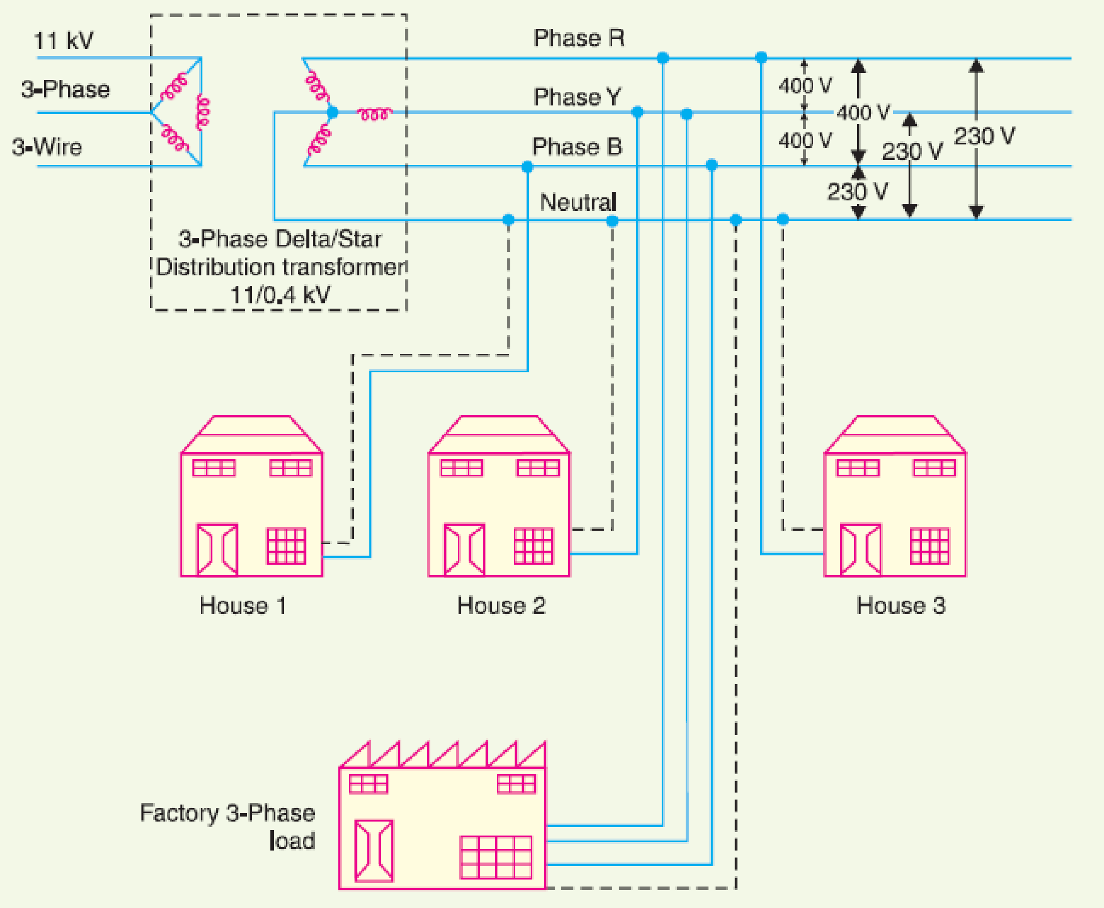


Figure 2.3: Primary and secondary distribution system voltage level [26]

In the secondary electric distribution system, distribution transformer taps with primary feeder through fuses as shown in figure 2.1. Distribution transformer steps down the voltage level to 400V. The secondary electric distribution mostly supplies power to the domestic consumers, small and medium commercial and industrial consumers. The line to line voltage in secondary is 400V while line-neutral voltage is 230V. The domestic consumers feed by 230V service mains and small and medium commercial and industrial consumers are connected with 400V service mains [27]. Hence, the secondary electric distribution system consists of single phase and three phase loads. As a result of mix-mode load distribution, the electric distribution system is inherently unbalanced. Small scale disturbances affect its neighbouring circuits and cause flickering, voltage dip, voltage fluctuation. However, control and protection operation is based on the primary electric distribution system where device-to-device coordination (selectivity) uses to protect lines and devices from the faults and disturbances.

2.3 Methods use for reliability analysis

2.3.1 Concept of reliability

The reliability for electric power distribution system can be defined as the probability of a distribution component or distribution network performing its function adequately, for the period of time intended, under the operating conditions intended [28]. This means, not only the probability of failure but also its magnitude, duration and frequency are important. It should be noted that reliability, stability and security measures for electric distribution system are different from each other. Stability and security are time-varying attributes which can be judged by studying the performance of distribution system under particular set of conditions. Reliability, on the other hand, is a function of time-average performance of the distribution system. It can only be judged by consideration of the system's behaviour over an appreciable of time.

Since, the reliability is characterised by a function of the time-average performance of a distribution network. Therefore, it is possible to define the probability [29] of failure of a given system or component as a function of time as:

$$P(T \leq t) = F(t) \quad \text{at } t \geq 0 \qquad [2.1]$$

Where, T is a random variable representing the failure time

F(t) is the probability that component will fail by duration of time t

Thus, F(t) is the failure distribution function, which is also known as unreliability. Since the probability of survival and failure of a component is complementary function. Therefore, the reliability of the component or system can be express as a function of time as

$$R(t) = 1- F(t) \qquad [2.2]$$

Where,

R(t) = Reliability function represents the probability that the component will survive at time t

If the time-to-failure random variable T has a density function f(t), the reliability can rearrange as

$$R(t) = 1 - \int_0^t f(t)dt$$

By simplifying, R(t) can be given as:

$$R(t) = \int_t^{\infty} f(t)dt \qquad [2.3]$$

Since the relationship between reliability and time-to-failure is exponential, as a result, reliability can be written as

$$R(t) = e^{-\int_0^t \lambda(t)dt} \qquad [2.4]$$

Equation (2.4) is known as the general reliability function. Hence, the hazard function of a component can be formulated as the numbers of failure per unit time and can be describe by the bathtub curve [26] shown in Figure 2.4.

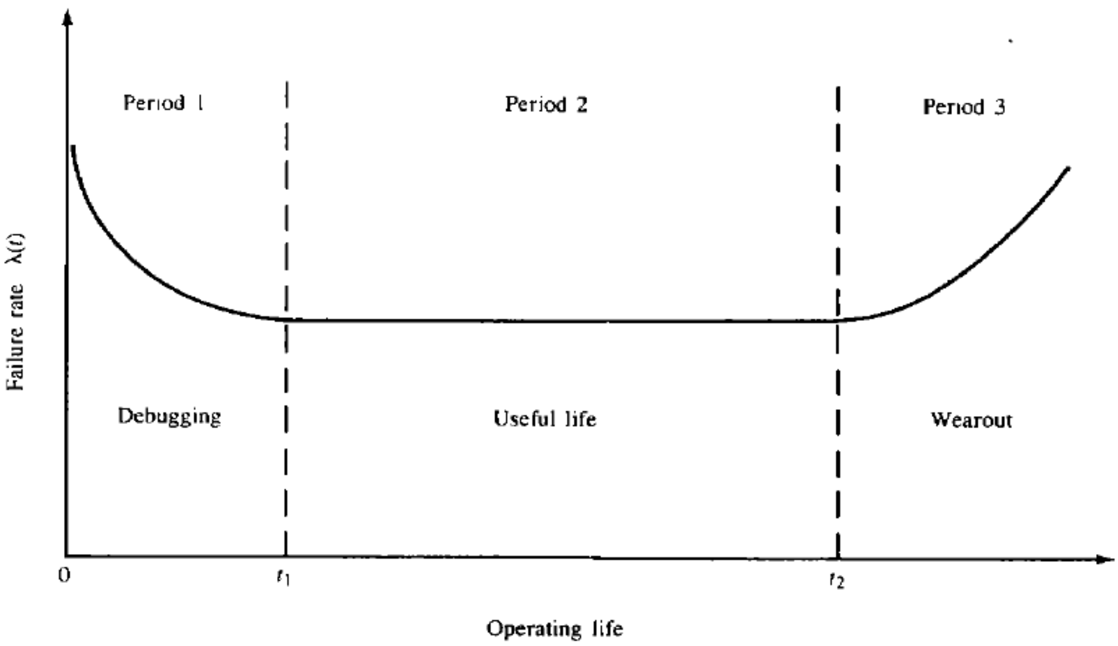


Figure 2.4: The Bathtub Hazard Function [30]

The first period t_1, represents the infant mortality period, which is the period of decreasing failure rate. This initial period is also known as debugging period, break-in period, burn-in period or early life period. In general, failures occur due to design or manufacturing errors. The second part is known as the useful life period or normal operating period. The failure rates of this period are constant. Failures occur randomly and unpredictably in this period. The third period is known as the wear-out period. The hazard rate increases as the component or equipment deteriorates because of aging. If the time t_2 could be predicted, reliability due component failure can dramatically be improved.

If, ƛ = Failure rate and

μ = Repair (healing) rate

The probability that the power is available at time t can be exposed as:

$$P(t) = \frac{\mu}{ƛ+\mu} + \frac{ƛ e^{-(ƛ+\mu)t}}{ƛ+\mu} \qquad [2.5]$$

Performing boundary conditions, the probability of availability of power in initial and steady state condition of the system can be found as:

At t=0, ƛ and μ remain constant and

P(t) = 1 means the continuous power (i.e.: automatic restoration performs during momentarily interruptions)

At $\infty \leq t < 0$ the steady state of power supply will be,

$$P(t) = \begin{cases} -\dfrac{\mu}{ƛ+\mu} & at \quad t < 0 \; (availability\ of\ the\ power) \\ \dfrac{ƛ}{\mu+ƛ} & at \quad \underline{t \leq \infty} \; (Unavailability\ of\ the\ power) \end{cases} \qquad [2.6]$$

It is important to note that the failure rate is based on the interruption frequency experienced by the customer. Thus, the probability of steady state condition of availability of electric energy can be found once ƛ and μ are determined. Thus, probability of series, parallel and series-parallel distribution feeder and component can be determined from equation [2.6]. These equations used in statistical analysis reliability analysis. Traditional electric distribution system collected data from voltage profile recorder, outage management data, sensor data, distribution management system and customer complain. Thus benchmark for reliability analysis was introduced for reliability analysis to evaluate performance of electric distribution component and system. The following section briefly explained three key benchmark used for reliability analysis.

2.3.2 Benchmarks use for reliability analysis

Utilities most commonly use two indices, System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) to benchmark reliability.

SAIFI is defined as [31-32]:

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customer\ served}$$

Mathematically,

$$SAIFI = \frac{\sum_{i\varepsilon R} ƛi\ .\ Ni}{\sum_{i\varepsilon R} \mathrm{N}i}\ frequency\ per\ year \qquad [2.7]$$

Where,

$ƛ_i$ = failure rate

N_i = Number of customers at the load point interrupted by the i th interruption event

R = total number of customers and sustained outage rate at load point

SAIFI indicates how often the average customer experiences a sustained interruption over a period of time. Figure 2.5 shows SAIFI for different voltage level in one distribution system collected from one utility in southern U.S. It is shown that low-voltage networks/feeders have comparatively lower number of inteeruption in a year.

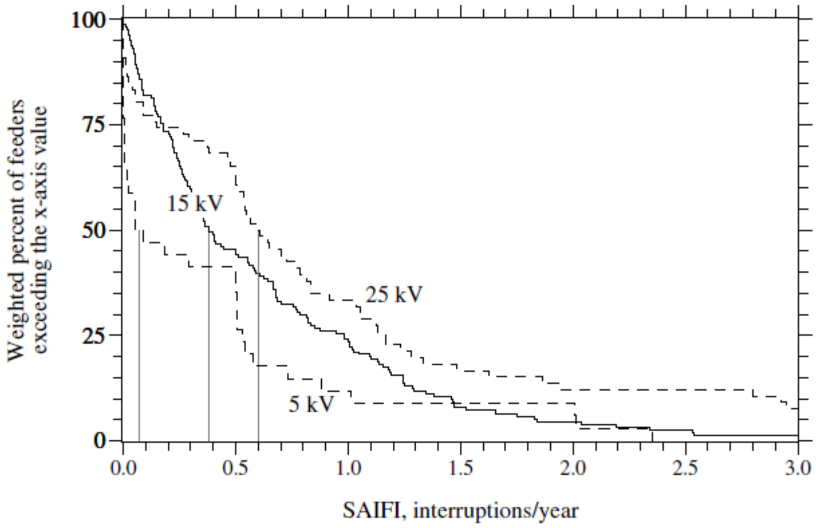


Figure 2.5: SAIFI and MAIFI for different voltage levels recorded for one utility in southern U.S [33]

SAIDI is defined as [34-35]:

$$SAIDI = \frac{Sum\ of\ customer\ interruptions\ durtions}{Total\ number\ of\ customers}$$

Mathematically,

$$SAIDI = \frac{\sum_{i\varepsilon R} Ui\ .Ni}{\sum_{i\varepsilon R} Ni} \frac{hours}{year} \qquad [2.8]$$

Where,

U_i = Annual unavailability or ouatge time at the load point i

N_i = Number of customers at the load point interrupted by the i th interruption event

The SAIDI in distribution reliability index indicates the total duration of outage for the customer during a period of time when there is a sustained service interruption leading to power loss. SAIDI measures in hours per year (h/yr).

MAIFI:

MAIFI stands for momentary average interruption frequency index. It is defined as an event of interrution of a circuit interrupter that results a zero votage for momentarily to the system. MAIFI event in electric distribution is a common events due to transient phenomena such as active operation of reclosing switch, cricuit interrupters and fault clearance [37]. Some MAIFI events are endanger for DPN assests for example MAIFI during arc flash, transient overvotlage, flickering, impulsive transient and so on. It is shown that MAIFI event in low voltage radial feeder found comparatively less that high voltage radial feeder as shown in figure 2.5 in the previous page.

2.4: Factors that affect the reliability

There are many technical and non-technical factors that affect electric power distribution system. However, characteristics of these factors vary in conventional and Smart Grid Distribution System. Most common technical factors that affect reliability for both systems are:

- Power outage
- Design and setting of protective devices and
- Variations in load density and demand fluctuations

2.4.1 Power outage

2.4.1.1 Outage in electric distribution system

Power outage outlines the state of a distribution component or system while it is not available as intended caused by small and large disturbances or permanent failure directly associated with that component or system [38]. Power outage is found as the key factors that affect reliability in distribution system as shown in figure 2.6 where about 70% of businesses were affected due to power outage. To calculate the cost of reliability, cost of an outage must be determined. Statistical model uses to determine the reliability cost for the conventional distribution system. However, actual costs of power outage may never been obtained as consumer appliances failure usually discovered after the outage or disturbance occur and never been considered by DSO in reliability benchmark.

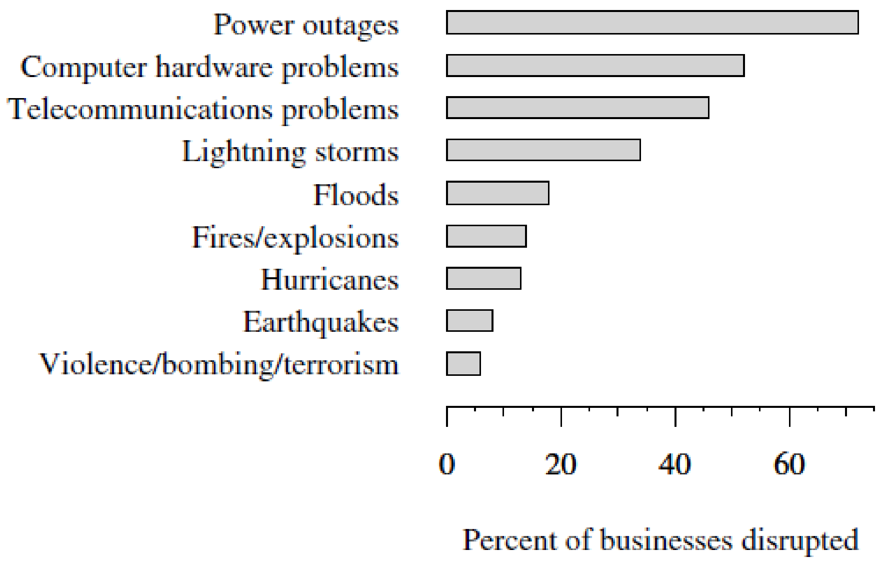


Figure 2.6: Percentages of business disrupted for several factors [39]

If an outage lasts for less than 1 minute (typically 30 s or less) is defined as a momentary interruption [40]. Historically, about 70% of faults in distribution systems are momentary interruptions [41] that result under voltage across the distribution feeder. On the other hand, most modern electronic devices are sensitive in voltage fluctuations. Hence, such momentary interruptions can be a hazard to ubiquitous electronic controlled equipment in customer workplace and households. Additionally, momentary interruption is responsible for power quality and voltage sags. Power quality is another significant aspect of reliability. Delivery of quality power is a paramount concern to untold critical and large industrial loads. Increasing use of electronic hardware is inaugurating more loads that acknowledge to distribution system power quality indicators.

This problem is intensified by the non-linear nature of distributed loads. For example, a voltage flickering can cause electronic industrial equipment to trip off and leading to costly manufacture losses. Another example such as a customer switching on high-wattage motor or arc welders can create voltage dips as well as impact overall power quality in the nearby feeders. Momentary interruption sometimes leads sustained interruption [42] as shown in figure 2.7 where the entire distribution service area is interrupted due to a momentary fault on one radial feeder.

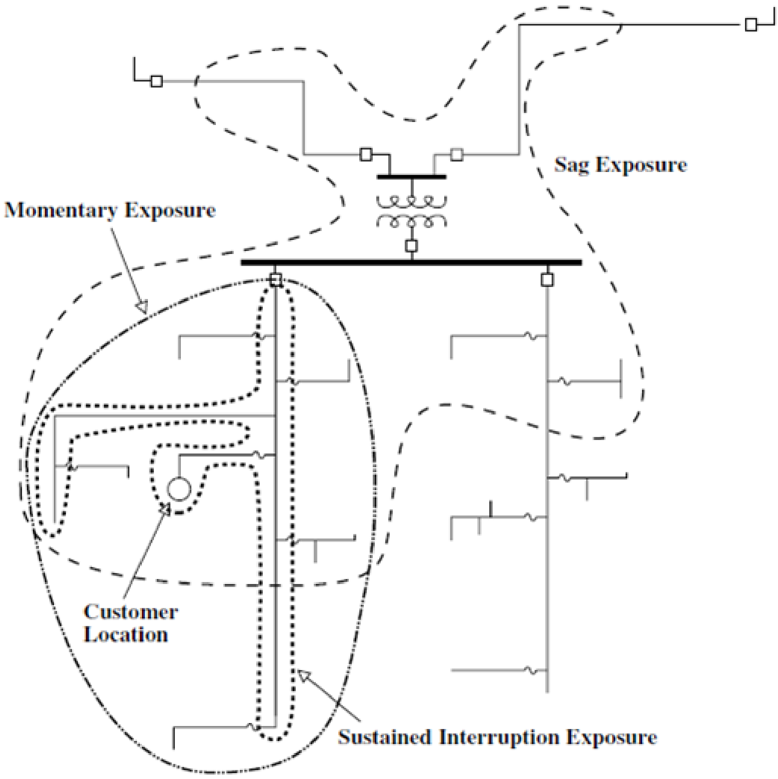


Figure 2.7: Sustained interruption due to momentary interruption [43]

Additionally, if a typical outage that lasts for longer than 1minute to 5 minutes or more is defined as sustained interruption [44]. A sustained interruption originated by permanent faults due to components failure, major event day, adverse weather, storms and so on. Above 60% of the faults in distribution systems is single-line to ground as shown in table 2.1, causes sustained interruption.

Table 2.1: Faults in distribution system and their ratio [45]

Fault	Percentage
Single-line to ground	63%
Phase to phase	11%
Two phase to neutral	2%
Three phase	2%
One phase on the ground	15%
Two phase on the ground	2%
Three phase on the ground	1%

A study on fault analysis can be found that equipment failure to be a primary cause of sustained interruption [46]. Failure rates (frequency) of a distribution component can be invaluable for analysing reliability during a sustained interruption. Table 2.2 shows the reasons of permanent failure causes by conventional distribution components.

Table 2.2: The generic and specific causes for outages [47]

Voltage control equipment failure	Electric and Mechanical	Weather
Voltage regulator	Fuel supply	Lightning
Automatic tap changer	Transformer failure	Storm/Hurricane/Tornado
Capacitor	Generating unit failure	Flood/Heavy rain
Reactor	Switchgear failure	Wind
System operations	Conductor failure	Cold/Ice
Stability	Tower, pole attachment failure	Heat/Hot weather
Under voltage/Over voltage		Miscellaneous
High/Low frequency		Vehicle hits poles
Line overload		Bird/animal/tree contact
Transformer overload		Dig-in
Unbalanced load		Fire/Explosion
Neighbourhood power system		Sabotage/vandalism
Schedule maintenance		
Maintenance error		
Voltage reduction		
Insulation failure		

The significant factors that lead equipment failure are overload and overvoltage of the system. Voltage dip (i.e.: under voltage) [48] is defined as a drop of the voltage magnitude between 10 and 90 percent of nominal voltage during 0.5 cycles up to 1 minute as shown in figure 2.8 (a) and (b). Voltage swell (i.e.: over voltage) [49] is defined as an increase of the voltage magnitude between 10 and 80 percent of nominal voltage during 0.5cycles up to 1 minute.

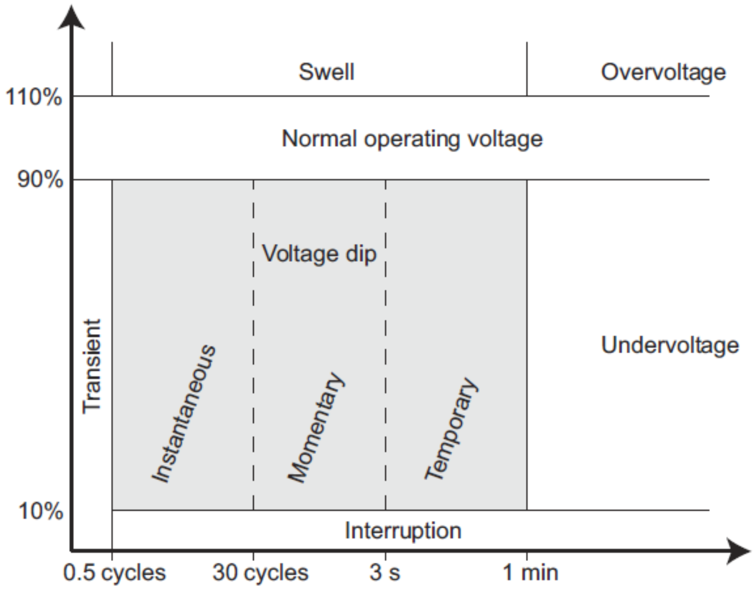


Figure 2.8 (a): Over voltage and under voltage in EDS [50]

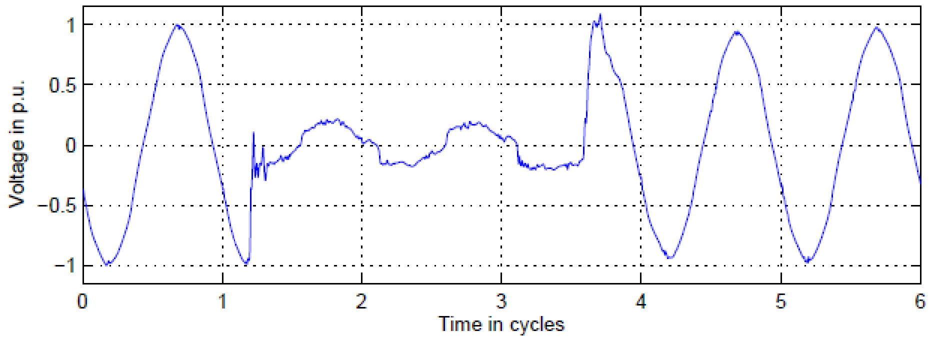


Figure 2.8 (b): Voltage as a function of time [51]

Under voltage is defined as [52] decreases of root-means voltage (rms) voltage between 10 and 90 percent of nominal voltage (I_n) for one-half cycle to one minute. Under voltage conditions generally causes by small and large disturbances of the distribution system. Overload or load fluctuations over utility fuses, circuit breakers and distribution and tap-changing transformers are additional reasons for under voltage. During the peak demand periods the demand for power exceeds the capability of the transformer that also result the voltage drops. These conditions can occur without warning and provide no obvious indications. Not only equipment failure but also their failure rate impact overall reliability in conventional distribution system. Table-2.3 shows components failure rate of one distribution system. However, failure rate varies for rural and urban distribution system due to the geographic locations as s shown in table 2.4.

Table 2.3: Overall component failure rates [53]

Component	Failure rate per Year
Transformer (All types)	0.62%
Transformers 300kVA to 10000kVA	0.59%
Transformers >10000kVA	1.53%
Switchgear bus (insulated)	0.113%
Switchgear bus (bare)	0.192%

Table 2.4: Component failure rates in rural and urban system [54]

Component	Failure Rates per Year	
	Rural (%)	Urban (%)
Transformers	0.027	0.0614
Switches	0.126	0.0775
Fuses	0.45	0.374
Capacitors	1.05	0.58
Reclosers	1.50	1.44
Voltage regulators	2.88	N/A
Conductors	1.22/100 mile	1.98/100 mile

The duration of sustained interruptions varies with the type of component and their behaviour. For example, if a relay controlled circuit breaker trips, or a recloser locks-out due to a sustained interruption can manually restore once fault is cleared. In such these cases, sustained interruption duration can predict. Therefore, reliability indices can be measure statistically. However, if a component failure occurs permanently and it needs to be replaced, the duration of interruption is longer than expected given as table 2.5. For example, a lateral fuse blows up, a circuit breaker, a recloser or a distribution transformer burn out needs to be replaced. Planning maintenance is another major cause of sustained interruption which increases operational costs; hence decreases reliability of the distribution system.

Table-2.5 Component repair time [55]

Component	Repair time (hour)
Circuit breaker	6
Distribution transformer	8
CT/PT	4
Surge arrestor	6
Voltage regulator	6
Shunt capacitor banks	6

Additionally, electromechanical devices, for example, relays, relays controlled circuit breakers, fuses, reclosers including three phase motors and pumps, are designed to be operated at very specific voltage levels. If these devices are allowed to operate at under voltage levels, they will draw higher currents. Increase in currents causes overheats in the mechanical contacts, fuse wires, relay coils as well as winding and coils of the other ancillary equipment damaging the critical insulation protecting them. Operating in undervoltage conditions can drastically reduce the life of the electromechanical equipment and lead to premature failure [56]. Some historical power outages due to voltage instability have been discussed in the next section.

2.4.1.2 Historic power outages due to voltage instability

There are numerous numbers of wide-area power outage have been noted in the early years of this millennium in the so-called modern civilisation where electricity drives the global economy to individual lifestyle. These power outages were caused by a specific disturbance as given in table 2-2 in each case and there were underlying technical reasons for such large disturbance in the wide-region of DPN [57]. The cross-border trades in interconnected power networks in Europe and North America has significantly increased as a result of increased liberalisation of electric power industry in the end of the last century. This means that the interconnected power system is used for purposes for what they were not designed. Interconnections in power systems grew by relatively weak tie-lines so that careful wide-area monitoring was required. The loop flow effect may not be accounted appropriately that impacted power flows in wide-area due to a disturbance in a small area/feeder. This effect was compounded by high-penetration of wind generation, Photovoltaic solar panel generation and other distributed generators. By all means, the traditional power system control and operation was resulted inadequate and slow responses to contingencies. Therefore, several historic power outages [58-64] has been noted in the past decades and briefly discussed in this section.

Athens Blackout in 2004

There were five million people affected by this power outage in southern Greece and Athens. The Hellenic power system was well known to prone to voltage instability for its very long transmission system from the generation to the load centres in Athens. Figure 2-9 shows P-V nose curve that represented consequences of blackouts in Athens during

Olympic Games in 2004. When load was on increase just after midday on a summer heatwave day in July 2004 due to turn-on air-conditioners, a large disturbance was experienced in the system.

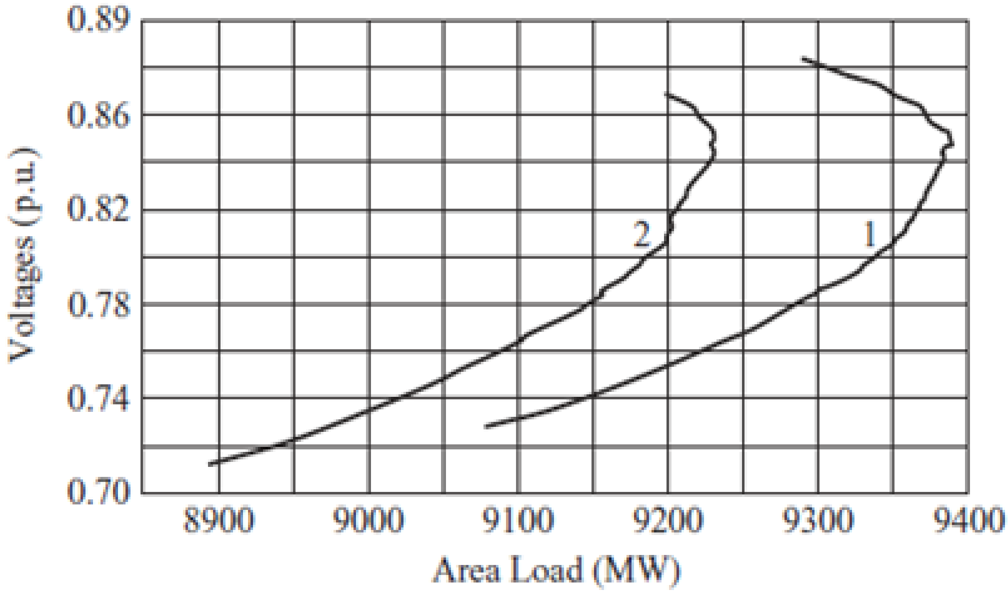


Figure 2-9: PV curves: (1) before Athens blackout; (2) after the second unit tripped.

The autotransformer, capacitor banks were about to install for Olympic Games to compensate voltage from source to sink. But the blackout took pace during the commissioning of voltage compensation equipment in the transmission lines. At first, a generation unit near Athens was tripped-off that brought the system to an emergency state. Load-shedding near Athens was initiate relatively a small-area as indicated by line 1 in figure 2-9 but rapidly expanded when second unit of generator tripped-off as indicated by line 2 in figure 2-9. The system was noted its peak demand as 9390MW and the blackout started when demand reached about 9320MW which is slightly less than peak demand.

US/Canada Blackout in 2003

There were about fifty million people in SS/Canada affected by this widespread blackout in 2003. The disturbance was the direct cause that resulted undetected cascaded tripping of transmission lines. Consequent tripping of lines gradually lowered the voltage along the lines as shown in figure 2-10.

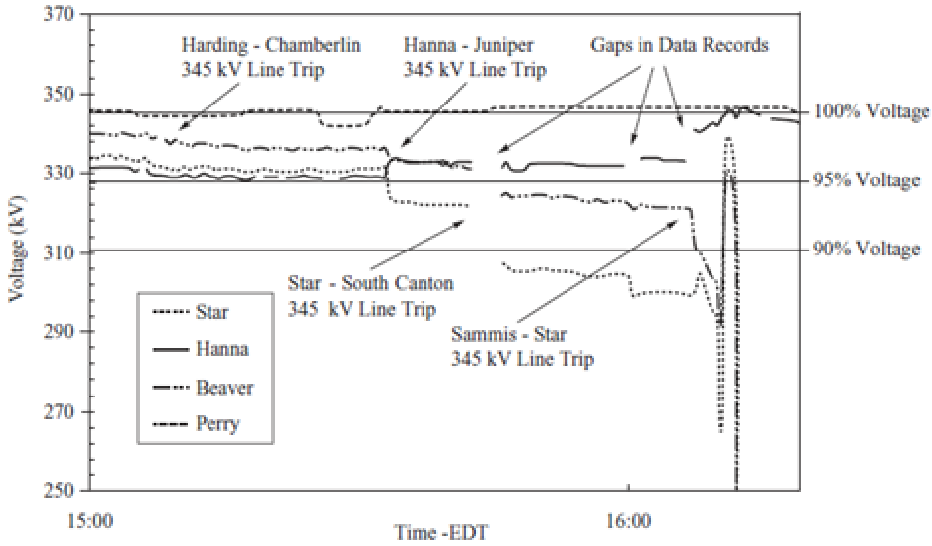


Figure 2-10: Cascaded line trips depressing voltages during US/Canada blackout

It was shown by subsequent analysis that the power outage was inevitable due to an unnecessary tripped by distance protection. Figure 2-11 shows how system dynamics varied from equilibrium to unbalanced during consecutive tripping. The curve indicated that depressed voltages and higher currents caused by prior transmission lines outage caused a reduced magnitude of apparent impedance measured by the relay as shown by cross indicator in the circle in figure 2-11. The relay tripped cascaded lines and generators resulted blackouts of a large part of the Canada and United States.

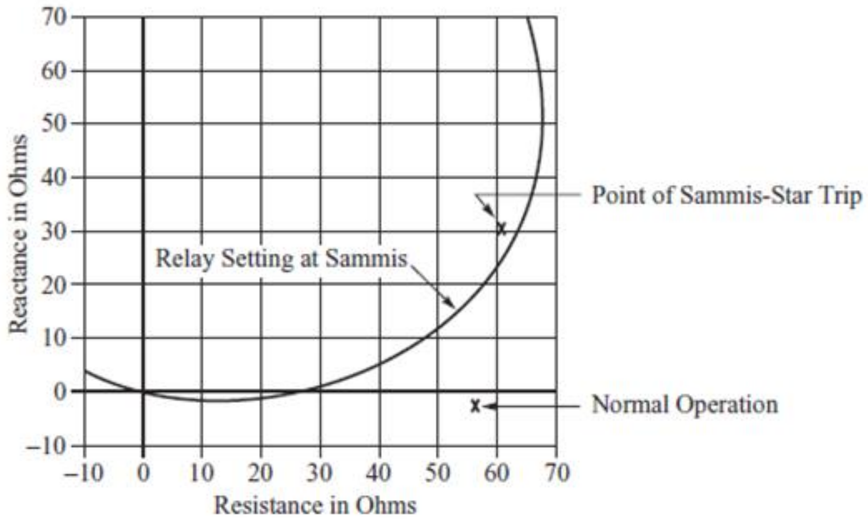


Figure 2-11: Normal operating point and the tripping point of Sammis–Star line during 2001 US/Canada blackout

Scandinavian Blackout in 2003

This blackout occurred in eastern Denmark and southern Sweden where about 2.4 million customers were affected. At first, one 1200MW generator unit tripped due to problem with a feed-water circuit valve. A double bus-bar fault occurred within fifteen minutes at a substation in southern Sweden that caused 1800MW generation unit and four 400kV transmission lines to trip as shown in figure 2-12.

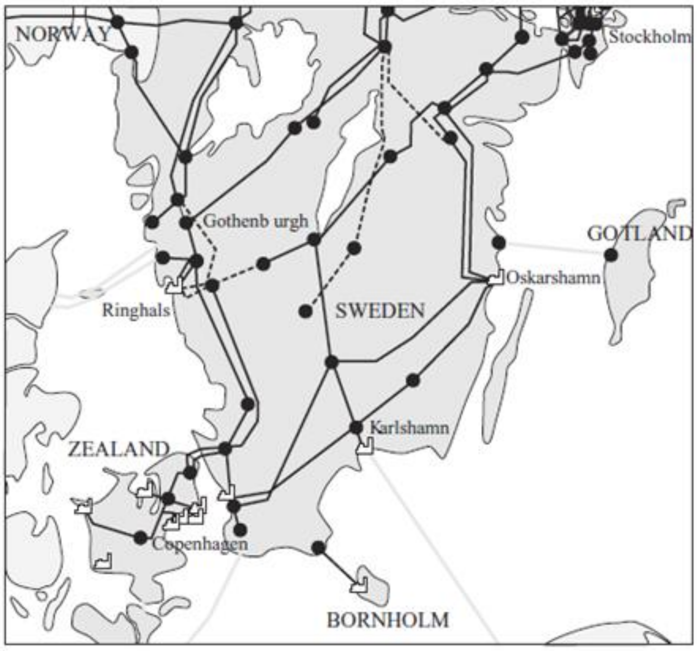


Figure 2-12: The grid 15 s after the substation fault. Tripped transmission lines are shown by dashed lines. Karlshamn Power Station was out of operation.

Such heavy losses of generation and transmission system resulted heavy power flows on the remaining part of the system in the southern Sweden. System and node voltage started to fall consequently that caused no generation and left over in southern Sweden but local power plants in eastern Denmark managed to retain power supply and were able to keep the voltage level equal to the nominal voltage level as shown in figure 2-13.

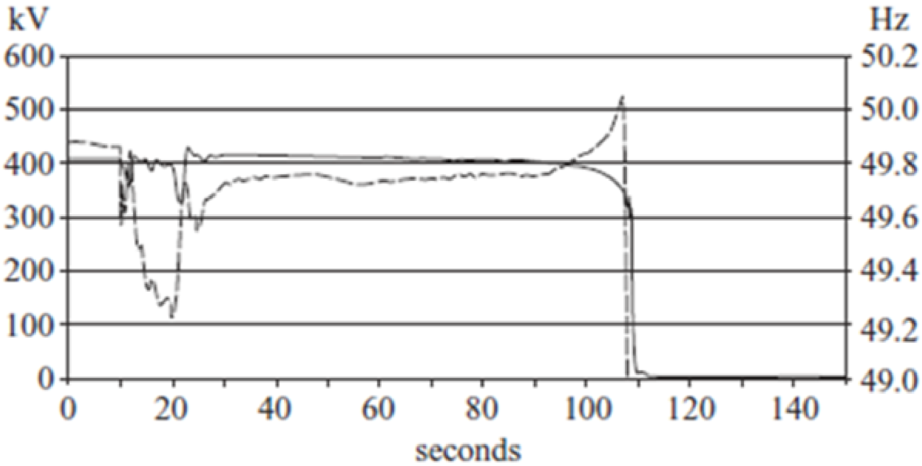


Figure 2-13: Voltage (solid line) and frequency (dashed line) measured at 400 kV connection between Sweden and Denmark.

2.4.2 Design and settings of protective devices

Designing of system voltage, system capacity (i.e.: capacity of feeder and distribution transformer) and control and protection strategy is the safeguard [65] of a distribution system. This is because, an optimum design ensures that the system will be in effect under all required conditions and abstain from utilising for so required. For example, if a feeder can design to use lower voltage for a long distance (e.g.: 0.4kV), the feeder will encounter a small number of outages from line contact with vegetation. Nevertheless, with lower voltage, the thermal line losses will be greater and the system will be thermally less efficient. Furthermore, low-voltage distribution system has potential to improve momentary interruption (SAIFI and MAIFI-Momentary Average Interruption Frequency Indices) as shown in figure 2.14. There are many standard distribution voltage levels like 34.5kV, 23.9kV, 14.4kV, 13.2kV, 11kV and 4.16kV.

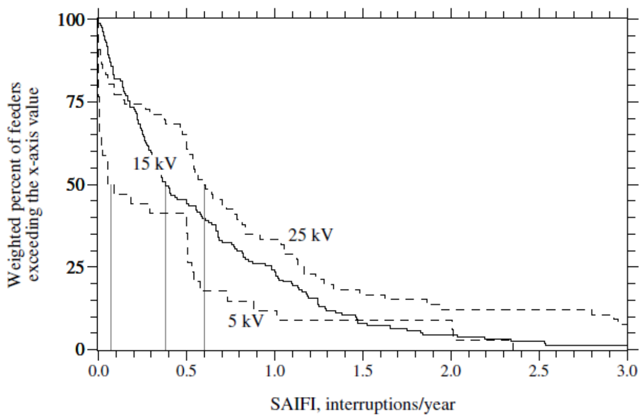


Figure 2.14: SAIFI and MAIFI for different voltage levels recorded for one utility in southern U.S [66]

Sectionalising is most heavily linked to frequency or number of events (SAIFI). A good sectionalising scheme reduces the extents of interruption (minimise outages for at least customer as possible). Switching capability enables a feeder system to transfer load to alternate service routes and thus restore service to customers during outages. This means it has effect on SAIDI. The parameters settings of protection and control devices have to take into account in order for appropriate selectivity (coordination). Incorrect installation and setting of protective devices and their deteriorating performances (e.g.: mechanical components may seize up, contact may become rough or burnt due to frequent operation or tarnished due to atmospheric contamination) may interfere [67] for correct functioning of the system. It is also necessary to test the complete protection scheme (relays, CTs/PTs, and other ancillary services) after a regular interval by covering its all aspects including operational and environmental conditions.

2.4.3 Variations in load density and demand fluctuations

The characteristics of a distribution system change with time due to changes in loads, geographical location and ability to dispatch energy from the substation. Longer circuit lead more interruptions. This is burdensome to avoid in normal radial circuits, even though distribution engineer can somewhat compensate [68] by adding reclosers, sectionalisers, fuses, additional switching points, or automation. Furthermore, adding components means increasing the probability of failure rates. Circuit exposures mostly affect SAIFI than CAIDI. Figure 2.15 shows the effect in SAIFI due to exposure in natural environment.

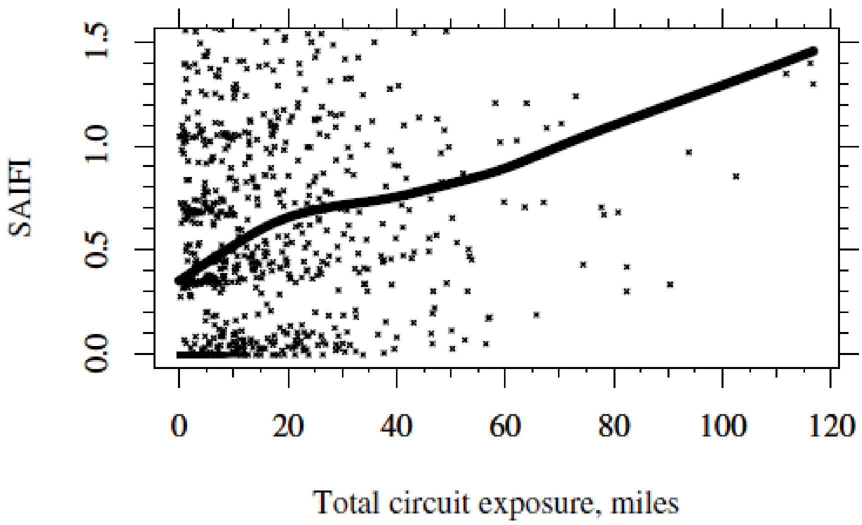


Figure 2.15 Effect of circuit length on SAIFI for one utility in the southwest U.S [69]

Table-2.6 has given a comparison of the reliability of Differnent Distribution Configurations which shows the highest sustain interruptions in radial circuit. However, primary auto-loop circuit experiences the highest momentary interruptions.

Table-2.6: Comparison of the reliability of Differnent Distribution Configurations [70]

	SAIFI Interruptions/Year	CAIDI Minutes/Interruption	MAIFI Momentary Interruptions/Year
Simple radial	0.3-1.3	90	5-10
Primary auto-loop	0.4-0.7	65	10-15
Primary selective	0.1-0.5	180	4-8
Secondary selective	0.1-0.5	180	2-4
Spot network	0.002-0.1	180	0-1
Grid network	0.005-0.02	135	0

2.5 Related work and evaluation

Although planning, maintenance and operation was significant steps taken by utilities to improve reliability. However, most common methods that have been carrying out to improve reliability by DSO are:

- Design and configuration
- Protection
- Voltage control and
- Advanced Distribution Automation

2.5.1 Design and configuration

As part of design and configuration, the primary-loop was assumed to be one of the most significant methods to improve reliability. Figure 2.16 show typical primary-loop connected via a normally open tie switch and two normally closed tie switch and a normally open and a normally closed tie switch respectively [71]. Two normally closed tie switch is used where high reliability is deserved. The feeder still operates radially. The tie switch closes during a fault to restore as many customers as possible from the healthy feeder.

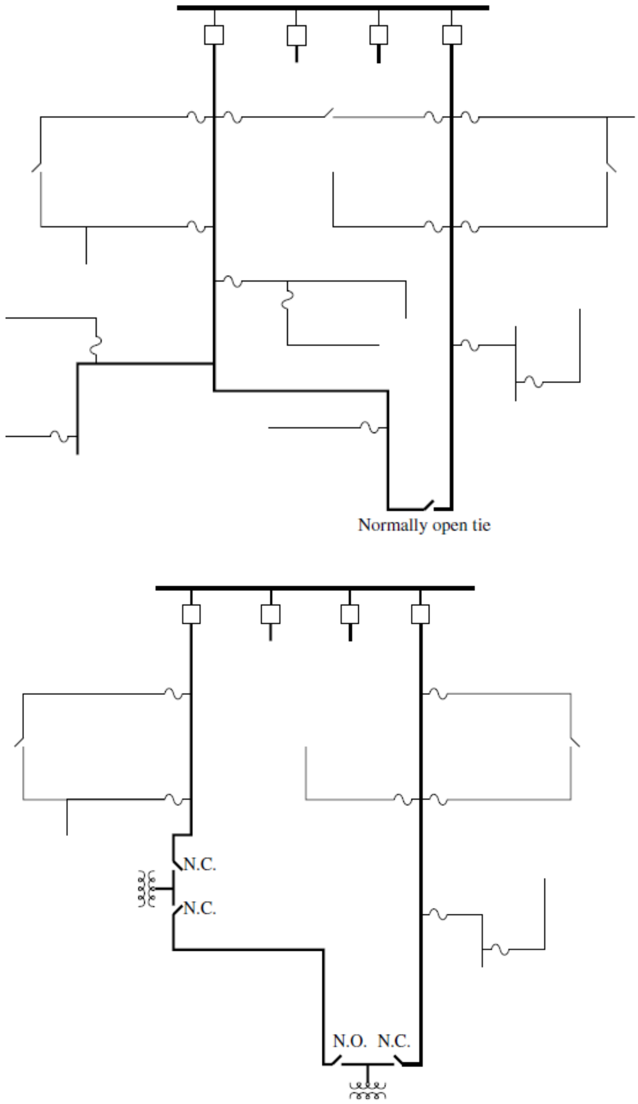


Figure 2.16: Primary loops [72]

However, this is expensive and complicated to implement. For example, in rural area and in some geographical area such as area near river, island, hill, forest, looping of primary feeder is almost impossible. Furthermore, series-parallel or parallel-series component configuration is costly. Load growth can cause additional complexity in identifying fault location and regulating voltage. Fault rates for system component will increase hence overall system reliability reduce.

The secondary service main can be looped, known as secondary banking shows in figure 2.17 (a), (b), (c) and (d) respectively [73]. However, they were impractical in some cases due their costs, load density and geographical area in some distribution area.

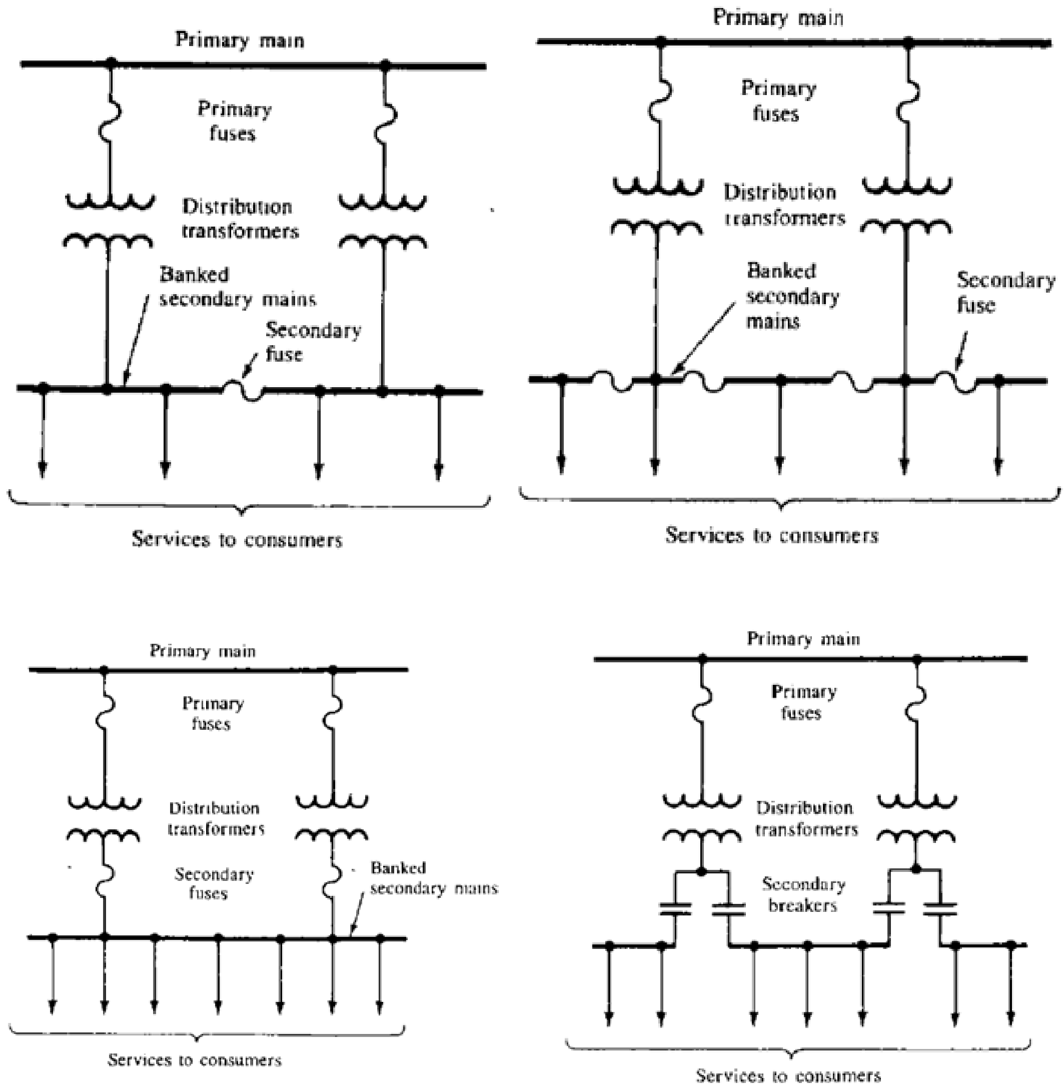


Figure 2.17: Secondary bankings (a), (b), (c) and (d) [74]

Such a secondary banking result [75] complex distribution structure, increase probability of component failure, increase system and component failure, complex fault identification and poor power quality due to presence of non-linear loads and power swing.

2.5.2 Protection

On the other hand, the main objectives of distribution system protection are to minimise the duration of a fault and to minimise the number of consumers affected by the fault. Relay controlled circuit breakers, fuses and reclosers are used in distribution protection system. Historically, coordination schemes are used to interrupt faults and restore system as much as possible. However, the philosophy of distribution protection differs from transmission and industrial protection. Distribution protection uses fuses where transmission system doesn't have any fuses in high-tension lines. As a result, this irrelevant dependency can create miscoordination. For example, it is impossible to coordinate two fuses in series with high fault currents [76]. Because the high current can melt and open both fuse in approximately the same time. Therefore, close to the substation, fuse coordination is non-existent.

Furthermore, the detection of high-impedance faults on electric distribution systems has been one of the most difficult and persistent problems. These faults result from the contact of an energised conductor with surfaces or objects or when an energised overhead conductor breaks and falls to the ground that limit the current to levels below the detection thresholds of conventional protection devices. Such faults create serious public hazards. Because of the random and intermittent nature of low current faults, it is still impossible [77] to detect all high-impedance faults.

In addition, capacitor banks pose special coordination issues with regulators. There are several other situations where coordination is not possible. Some low-level faults are very difficult — some would say impossible — to detect [78]. A conductor in contact with the ground may draw very little current. The “high-impedance” fault of most concern (because of danger to the public) is an energized, downed wire.

Moreover, distribution feeder uses reclosing switch which has been using to clear faults. However, switching of reactive loads, for example, transformers and capacitors, create transients in the kilohertz range. Electromechanical switching device interacts with the distributed inductance and capacitance in the AC distribution and loads to create Electric Fast Transients (EFTs) [79]. Transients are also triggered from capacitor switching, from line energization and from faults. Surge arresters work well against short-duration over-voltages from lightning and switching transients. But arresters have trouble conducting temporary power-frequency over-voltages; they absorb considerable energy trying to clamp the overvoltage and can fail. Small arresters often are the first component to fail in equipment.

2.5.3 Voltage control

Genertation and transmission system have been using excitatyion system, engine governor, on-load tap-changing transformer and power elecronics converters to control bus and node voltages across the wide-area power network (WAPN) [80]. However, electric distribution system at first rely on interconnected transmission system for voltage control. Secondly, several equipment uses for volatge regualtor rather than voltage control. Therefore, it is a statuatory regulation to have volatge protection while desinging consumer electronics goods and appliances. This section has discussed voltage control techniques used in electric distribution system.

2.5.3.1 Volt/Var optimisation

In order to improve voltage profiles and minimise losses, a desire limits of voltage control and capacitor switching are considered as effective means [81]. These deffered maintenance and construction costs and eventually improve reliability. Voltage control has to consider demand side management, dispersed generation and unbalanced multi-phase distribution system operation. However, volt/Var largely depedns on propser communication between Distribution System management (DSM) and control equipment such as switching capacitor, substation switchgear and so on. Additionally, voltage-profile optimisation is a prominent technique for radial feeder as shown in figure 2.18.

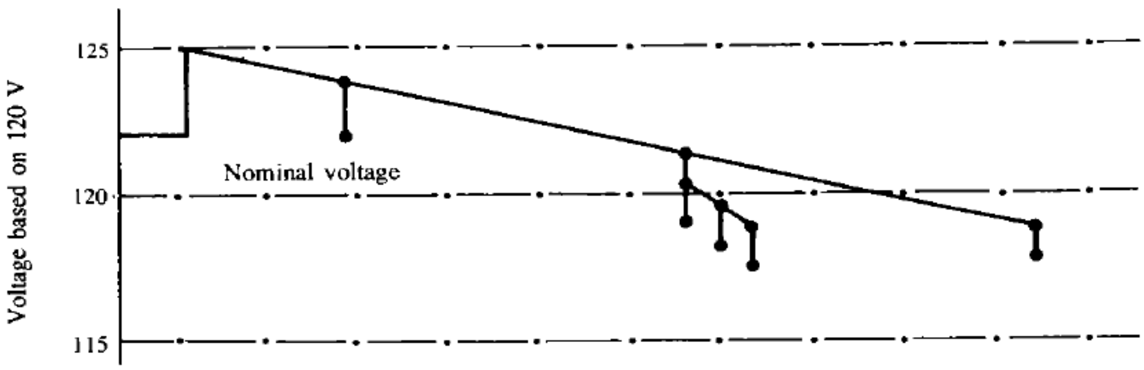


Figure 2.18: Voltage profile of a 120V radial feeder [82]

2.5.3.2 Capacitor bank switching

Main function of capacitor whether connected in series or parallel is to regulate the radial feeder voltage and reactve power flows along the nodes. The series connected capacitor does it by directly offsetting the inductive reactance of the circuit whereas the parallel connected capacitor does it by changing the power factor of the load [83]. Figure 2-19 shows series and parallel configuratio of capacitors in a single line diagram of electric distribution system.

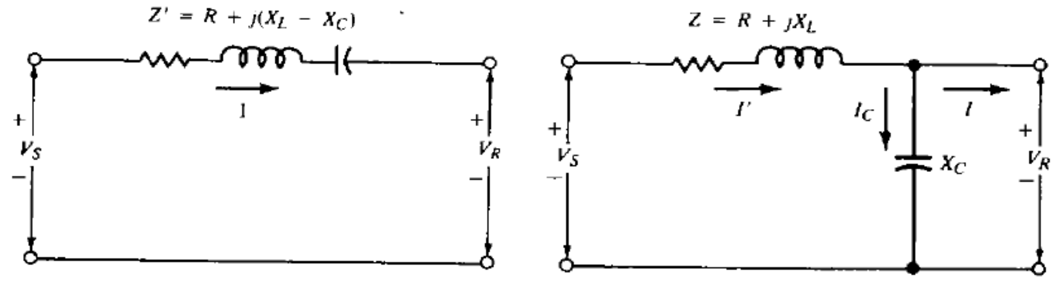


Figure 2-19: Series-parallel connections of capacitor in a radial feeder [84]

Series capacitors have limited used in electric distribution system than a shunt caapcitor. Although series capacitor rises net voltages in the line and has little effect on source current but increases voltage drops along the feeder. Shunt capacitor on the other hand has extensive use in electric distirbtution system. It has similar effect as overexcited synchronous condenser to regulate voltage and reactive power. Parallel connected capacitor modifies inductive load characteristics by drawing leading current that counteracts the lagging component of the inductive load current.

2.5.3.3 Automatic (on-load or off-load) tap-changing transformer (OLTC)

Figure 2-20 shows an OLTC. In an OLTC, a number of secondary tapping privide as shown in the configuration. The effective secondary turns varied [85] as tap position varied, hence output voltage (i.e.: secondary terminal) of the transformer changed as appropritate. Whenever tap change occurs output voltage drops means power supply interrupted. Thus MAIFI occurs. Additionally, secondary terminal of OLTC has fixed number of taps as shown in the figure. Therefore, the output volatge cannot change beyond the limit of numer of tap. This limits the operation in light load and sudden heavy load demand. Also, tap changing event takes time, thus voltage cannot change instantly.

This can introduce SAIDI to stabilise the operation. However, distribution system has little use of OLTC due to frequent MAIFI but it is widely used in transmission system.

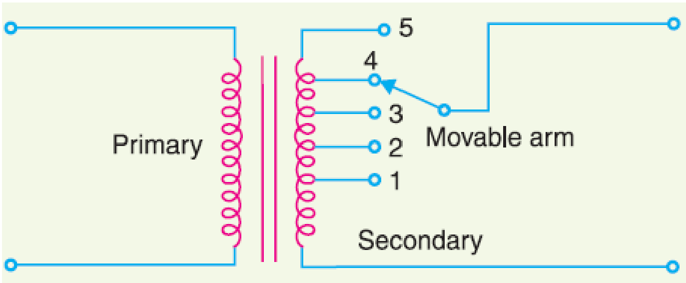


Figure 2-20: Automatic tap-changing transformer [86]

2.5.3.4 Voltage withstand of appliances

Withstand voltage idenfied by the maxium amount of voltage-level that an equipment can tolerate. The capability of components and appliances to withstand voltage surges have tremendous imopact on reliability [87-90]. There are various test such as withstand voltage test, basic insulation level (BIL) test available and carried out during product design for consumer appliances. Moreover, modern consumer electroncs contain built-in withstand voltage tolerance system. However, it is always not economical to design appliances and elecronics goods for a high-voltage withstand due to its cost and failure rates.

2.5.3.5 Advanced Distribution Automation

Research has been carried out on Advanced Distribution Automation (ADA) in improving system reliability over last decades [91-94]. Feeder automation, distribution automation and control functions (DAF), Supervisory Control and Distribution Automation (SCADA) and Advanced Distribution Automation (ADA) have emerged to improve reliability. DSO also use distribution automation for Volatge/Var control as part of planning, monitoring, analysis, reconfiguration and restoration that is a complex process and has time delay that increas SAIFI and MAIFI. Short circuit analysis in feeder automation largely rely depend on overcurrent analysis in transmission system, insufficient (not-existed in some cases) for distribution system. ADA including SCADA and PMU is a promising technology to monitor and control distributed network and components. However, bulk integration of DER integration and their bidirectional power flow cannot handle with ADA. In addition, reliability in existing ADA depends on detection of fault types, fault locations and communication technologies. Manual operations take place to return power supply back to normal which sometimes prolong outages. Moreover, several projects around the world emphasised on installing more line reclosing switches, load break switches, sectionalising switches, capacitor banks and line regulator in order to improve reliability. Addition of more equipment in a diverse DPN could increase failure rates, transient effect and MAIFI which will ultimately reduce reliability in a long term calculation.

2.6: Published work and research argument

SHC for distribution systems with and without Distribution Generation (DG) has previously been analysed in several publications, [95-106].

Theory of Self-Healing Control is proposed for smart distribution system without any evidence and technological innovation [95]. No mathematical evidence is shown in the publication. There is no simulation work presented to support self-healing control functionality in smart distribution system.

Distribution relaying intelligence has been focused for transmission system. The relay is expected to communicate and coordinate to implement an adaptive current differential relaying function [96]. Relays in each zone is assumed as an agent and this is how multi-agent based theory is been implemented to select protection zones. However, this is an improvement of an existing system while transmission system protection philosophy in a proven technology which doesn’t work in distribution system. Additionally, coordination is used for unidirectional power flow while Smart Grid is expected to be a bidirectional power flow system.

An Ant Colony Algorithm is proposed to optimise power in faulty part of the power network. The algorithm is applied on 33 node test system where unidirectional power flow is focused [97]. The interconnected systems are used as distributed generators in order to use reconfiguration and restoration of the fault network. The Self-Healing Control is used to reconfigure interconnected transmission lines to maintain a continuous power flow to the customer premises. However, fault in distribution system will not work for reconfiguration in transmission lines. Distribution system requires its own control strategy while DER is an opportunity to supply power to the local loads during a permanent fault by optimising power absorbed by loads.

A cooperative Multi-Agent System (MAS) control structure is proposed for the implementation of the self-healing operation [98]. The control agents possess the intelligent ability to use communication and negotiation in order to determine the current and predicted states of the system and then set their actuators and switches in a way that will achieve their own objectives as closely as possible while satisfying any constraints. Each distribution feeder is divided into segments (zones) based on the location of protective devices. However, this is a conventional protection system with no innovations.

In this paper, heuristic searching method is used to reconfigure the radial feeder to restore as much service as possible after a permanent fault in a smart distribution network [99]. However, this paper is focused on theory of a restoration method without any strong evidence (e.g.: simulation or mathematical model). How a smart distribution network will operate DERs during a fault is a significant question so far is not addressed in the paper.

In this paper, an alarm management framework is proposed for intelligent alarm processing [100]. Firstly, the alarm for self-healing smart distribution system is categorized. Then a model based intelligent alarm processing method is proposed for effective management alarms and events by multi-level analysis in alarm level, constraints level and systematic level. Finally, example is presented based on a proposed framework. However, this is a statistical model to manage abnormal events of the system. Who and how this alarm is going to manage is not been clarified. If this alarm can be managed by SCADA or RTU, a two way communication including IEDs is required in smart distribution network which has not been focused in the paper.

This is a survey paper on Self-Healing Control for Smart Distribution Grid which emphasise the significance of a new control strategy for future electric energy system [101]. According to this paper, for large-scale, distributed wide area distribution networks, it is needed to establish a synchronization information based on wide-area protection and control theory and technology to coordinate the integration of network components protection, regional optimizing control, preventive and corrective control, emergency recovery control with multi-line of defence of self-healing power grid control system. The key technology of realizing self-healing control of distribution network is based on wide area measurement and information exchange, which is the solution that global and local parts can be decentralized and centralized with coordination of function and speed, for achieving coordination of wide- control and the distribution protection control. However, importance of smart sensor for measurement and two-way communication for monitoring (data exchange) is still a research and development topic.

This paper proposed for deploying a Smart Fault Current Clear (FCC) device and expected that the utility can prevent breakdown of the coordination [102]. The Smart FCC regulates the fault current to the point to make protection devices operate properly and maintain the protection integrity. The Smart FCC controller calculates firing angle and controls fault current under the reference value, therefore protection devices operate as designed. However, high penetration level of grid connected DGs will result in larger fault current level and may destroy the harmony of fitly coordinated protective gears, hence collapse coordination, for example, by blowing the fuse faster than other circuit breakers. This causes nuisance tripping of the critical loads located downstream from the fuse. Technically, huge financial loss or damage to the equipment sensitive to power quality may occur.

According to this paper, quick response to overload contingencies and restore power grid to the normal operation condition is the major requirement of overload control strategies [103]. The power flow redistribution strategy needs to coordinate with backup relays to avoid undesired tripping, which may result in cascading tripping, and even blackouts. Traditional power flow redistribution strategies cannot fully meet the requirement of quickly relieving overload in a safe and efficient way. A Universal Power Flow Controller (UPFC) is proposed to overcome these problems. However, component failure due to overload and overvoltage is not a subject of power flow control. Power flow control can

According to this paper, the existing power flow redistribution methods employ power flow (PF) or optimal power flow (OPF) for calculations [104]. The computation cost for PF and OPF is relatively long when considering the speed requirement of quickly relieving overloads in the self-healing power grid. A UPFC is proposed here like previous paper where, it is repeatedly mentioned that power flow is subject to stability of the system cannot meet the requirements of bidirectional power flow.

This is a survey paper published from IEEE Smart Grid Forum where requirements of Smart Grid are focused [105]. This paper identified Self-Healing Control as the most desirable control strategy for the Smart Grid. According to his paper, Self-Healing Control is an automatic or semi-automatic restoration of grid operation in case of component/grid faults helps power system and infrastructure operators.

The goal of the paper was to find the optimal position of the switches in order to guarantee more continuity of the service [106]. In particular, for each possible fault, an optimization problem was solved and the creation of self-supplied islands was suggested by installing more and more sectionalising switches. However, sectionalise switch has two significant problems. Firstly, it doesn't coordinate with circuit breaker or autorecloser. Secondly, its costs are not worth than their operational outcomes. Additionally, such switches increase the failure rate of the system.

In addition, most of these works addressed 11kV radial interconnected radial feeder with a normally open tie switch. Several works suggest replacing lateral fuses, circuit breaker, and reclosers by intelligent switch/controller or smart reclosers and so on. However, most of the work focused for unidirectional power flow and limited control and protection in feeder level. Lateral, sublateral and distribution transformer levels are ignored. Also, most of this research is either in the preliminary stages or based on traditional energy distribution systems.

Additionally, the most significant issue, on the other hand, in future power system is integration of renewable and distributed generators are not addressed or ignored. The protection and control scheme in operation at the current time has designed for one-way power flow with inadequate communication facilities. Integration of low voltage DER (5V-24V DC) in medium voltage (e.g.: 11kV) system can potentially affect the behaviour of distribution system as well as the entire power system. High power inverter, voltage and frequency synchronous (synchroniser and stabiliser) converter will be required which will result high installation and maintenance costs. The future distribution system eventually has to deal with bidirectional power flow.

Moreover, in current literature, domestic PV doesn't work during a blackout as it is designed [107]. In fact, PV is installed without any intelligence in Smart Meter. PHEV charging and discharging requires intelligence which is not yet invented. A typical PHEV take about 8 hours to charge. It is designing to discharge by coordinating with the main grid. Vehicle-to-Grid (V2G), is expecting HEV to charge in a charging station as well. Like the fuel station, V2G will coordinate with HEV charging station where grid stability can deserve. However, gaps between end user to grid or substation can cause potential stability issue which can instable the entire system. Additionally, some other significant integration issue such as system transient and harmonics has to be addressed appropriately.

2.7 Summary of research

The aformentioned research survey indicated that distribution system control and opertation largely rely on the control and operation of interconnected transmission systems where conventional distribution system is considered as a sink. Any effect in transmission system effects the control and operation of the distribution system even though control and regulating units are installed in the distribution system. Moreover, it can be outlined from the proposed publications that optimisation and artificial intelligence thechniques are required for improving the reliability of the SGDS. However, such advanced technologies are based on digital control using digital signal processing.

It has also been shown through several research work that Smart Meter and Advanced Metering Infrastructure along with Intelligent Electric devices are the key indicators for transforming existing system into a smart system (e.g.: conventional distribution to smart distribution system). However, the limitations of Smart Meter are already well-know as it acts as an automatic meter reader with no monitoring and control operations. Additionally, Advanced Metering Infrastructure is still under research and development stage and been facing challenges in processing signal over the comparatively high-voltage, low-frequency power line.

Eventually, this research summarised the reliability of SGDS by means of a Self-Healing Control Algorithm. The algorithm is able to incorporate with SCADA and DMS in order to ensure the optimal control and efficient operation for a proposed SGDS under various operation conditions. The SHCA is invetigated for various R&DER integration levels connected to radial feeder that is competely a new approach than any prior work for example distributed R&DER on 0.4kV single and three phase lines. It has also been considerd that modern consumer electronic goods such as air conditioners, lifts, escalators, washing machines, fridge-freezers and many more controlled loads are connected through an Intelligent Power Switch (IPS) in order to implement SHCA for the proposed SGDS. The IPS has direct link with SHCA so that an optimal control and efficient operation of such controlled loads can be achieved for the interest of this thesis contribution. The key contribution of SHCA is assumed that it actuates IPS according to the R&DER states of the proposed SGDS. It means a washing machine or central heating can be run while R&DER is available for example EES is fully-charged or PV is at MPPT or fridge-freezers can be switched-off for a pre-defined time until the steady-state is achieved during a large disturbance or supply-demand unbalance. The switching operations of washing machines, fridge-freezer, air-conditioner and other consumer electronics can be performed by an Intelligent Power Switch [108-109]. Although, such switching operations of customer equiment can arise concern about the durability of equipment as well as the customer comfort. However, the SHCA is designed and implemented in such a way that it compromises among equiment safety, customer comfort, R&DER availability and operational states of the main power grid.

However, the existing electric distribution system is already operating at a critical stage. In this circumstances, innovative smart grid technology (ISGT) concept is still a vision. Additionally, complete transformation of exiting infrastructure is almost impossible and economically unviable. Therefore, supply-demand balance should put as a first priority in modifications of existing system to the smart grid distribtution system. Therefore, this thesis propsoed a SGDS by optimally R&DER integrating and presented in the following chapter before move to the SHCA.

Chapter 3: Proposed Smart Grid Distribution System

3.1 Introduction

In a number of countries (e.g.: Germany, Denmark, Australia, Italy and Spain) levels of renewable energy resources including distributed energy resources base electricity have already exceeded the local power grids hosting capacity. This facilitates storing electricity by charging of Electric Energy Storage and emerging Hybrid Electric Vehicle while generation is surplus than demand. This distributed energy resources discharge to satisfy sudden changes of demands, peak demands and provide steady state operation to the Smart Grid distribution System. These also improve reliability by providing schedule maintenance over the day when Photovoltaic solar panels generation is at maximum and distributed energy resources are fully charged. One significant features of such wide-scale integration is to satisfy the annual load growth without installing additional substation transformer or increasing substation transformer capacity. Therefore, modelling most an appropriate and universal Smart Grid Distribution system is crucial in order to investigate its control (i.e.: Self-Healing Control for this thesis) and operation under normal as well disturbance conditions.

As consequences, a conventional electric distribution system as shown in figure 2.1(a) (as mentioned in section 2.2) modified by integrating renewable and distributed energy resources in order to model a proposed Smart Grid Distribution System. IEEE European Union Low-Voltage Test Feeder parameters are used as a benchmark in order to investigate the impacts of modification on the proposed Smart Grid Distribution System. The 4kW photovoltaic solar panels, 5kWh-15kWh electric vehicles and 25 kW electrical energy storages are integrated across the secondary distribution network of the IEEE European Union Low-Voltage Test Feeder. The R&DER ratings for the existing electric distribution system are commercially available and implemented in several Smart Grid Projects across the world [110].

The proposed medium-voltage (11kV) Smart Grid Distribution System consists 12-nodes 11kV primary feeder as shown in figure 3.1. Photovoltaic solar panels, Electric Energy Storages and Hybrid Electric Vehicles are integrated on low-voltage (0.4kV) proposed

Smart Grid Distribution System as shown in figure 3.2. Figure 3.2 also represents an expanded view of subfeeder F10 with R&DER values that integrated at their original location. Identical low-voltage (0.4kV) Smart Grid Distribution Systems are modelled by integrating different amount of Photovoltaic solar panels, Electric Energy Storages and Hybrid Electric Vehicles in each subfeeder of 11kV network for the purpose of their simultaneous operation and further investigation. However, this research considered figure 3.2 as its proposed Smart Grid Distribution System and presented outcomes in the following chapters. Additionally, Photovoltaic solar panels have integrated as renewable energy resources, Electric Energy Storage and Hybrid Electric vehicle have integrated as distributed energy resources in the proposed Smart Grid Distribution System and commonly addressed as Renewable and Distributed Energy Resources (R&DER).

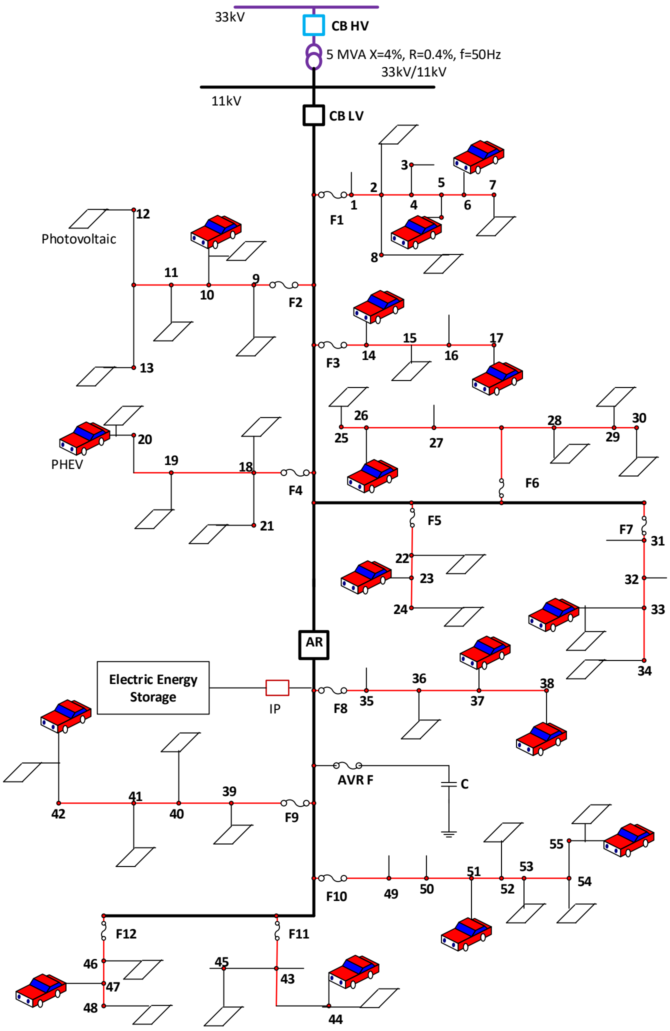


Figure 3.1: Proposed medium-voltage (11kV) Smart Grid Distribution System (11kV primary and 0.4kV secondary)while R&DER are integrated on secondary distribution network

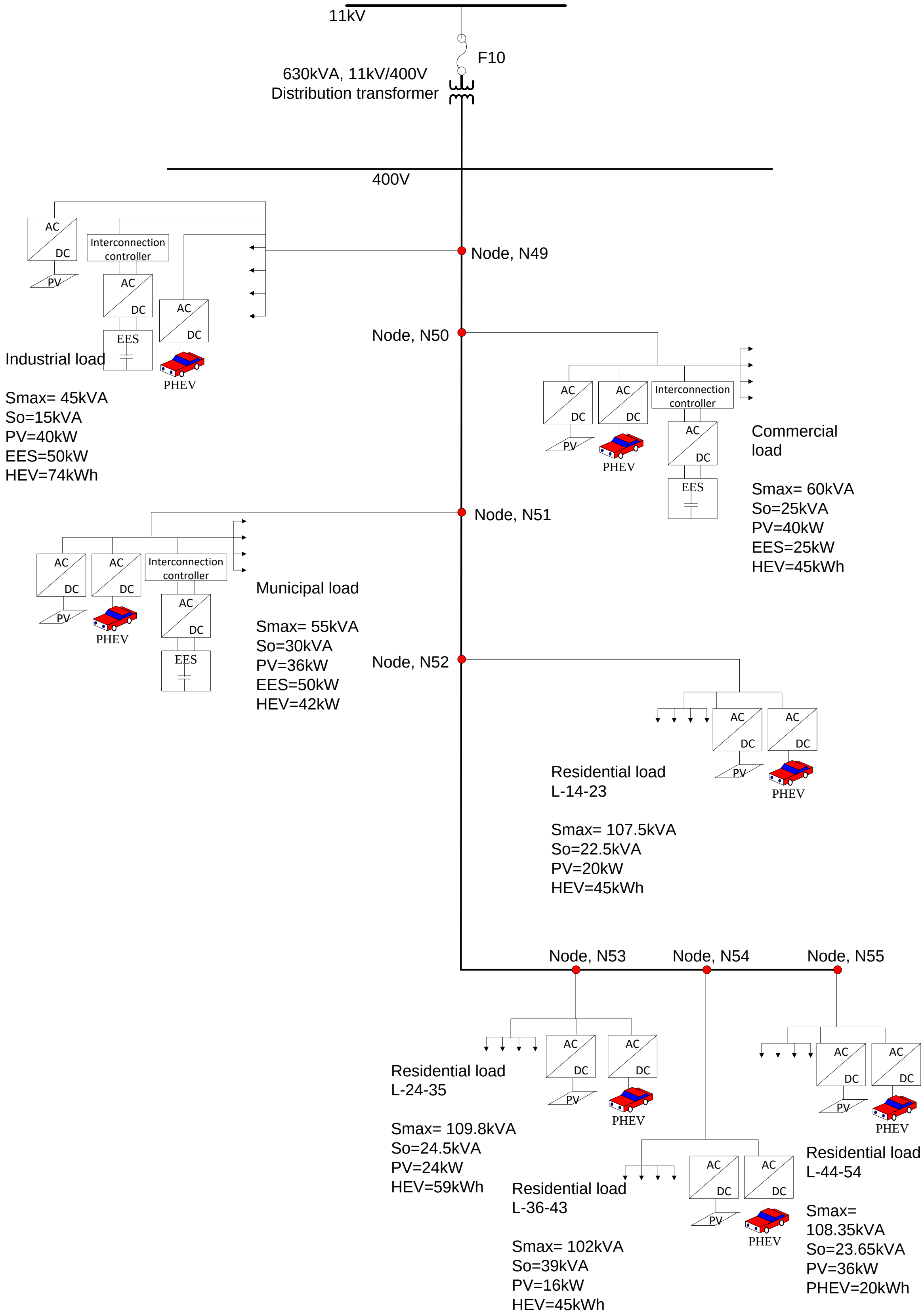


Figure 3.2: Proposed Smart Grid Distribution System with actual location and amount of R&DER (on 0.4kVsecondary distribution system)

Historically, 11kV primary feeder runs along the high street of the city and urban area from where electricity supplies to the customer meter through 11kV/400V distribution transformer. As a result, wide-scale integration of medium-scale R&DER (e.g.: 100kW PV & EES) has become popular in recent days. Therefore, 100kW grid-tied PV and 100kW EES have installed on primary feeder as shown in figure 3.1. It is also assumed that control, protection (e.g.: autorecloser) and regulating (AVR) equipment mostly installed along 11kV feeder. It has shown in figure 3.1 that wide-scale integration of R&DER is fundamentally changing this principle infrastructure. Additionally, R&DER acts as load while charging and acts as sources while discharging. These impacts power flow, stability, protection, control and operation of the system.

Low voltage R&DER on the other hand, has been integrated on 400V secondary feeder such as integration of roof mounted Photovoltaic solar panels and Hybrid Electric Vehicle and community Electric Energy Storage. In principle, control and protection of primary feeder largely protect the secondary equipment. Additionally, consumer equipment has built-in voltage suppressor and protective devices. These devices work well for predefined regulated voltage and current limit. However, wide-scale diverse integration might have been breaking down this limit due to time-variant and non-deterministic behaviour.

Eventually, a single-line diagram for proposed Smart Grid Distribution System is outlined in figure 3.3. The 11kV primary feeder is feeding by a 33kV/11kV, 5MVA substation transformer. It is a radial distribution sub-feeder with a base frequency of 50Hz. A 100kW resistive load is connected on 11kV bus as shown in figure 3.3. The sub-feeder F10 is connected to the medium voltage (MV) system i.e. 11kV/400V through a 630kVA distribution transformer. The distribution transformer steps down voltage from 11 kV to 400V. F10 supplies electricity to 54 consumers that include industrial, commercial, municipal and domestic loads. The R&DER distribution for 54 load points is given in table 3.1 and supply-demand and R&DER is given in table 3.2.

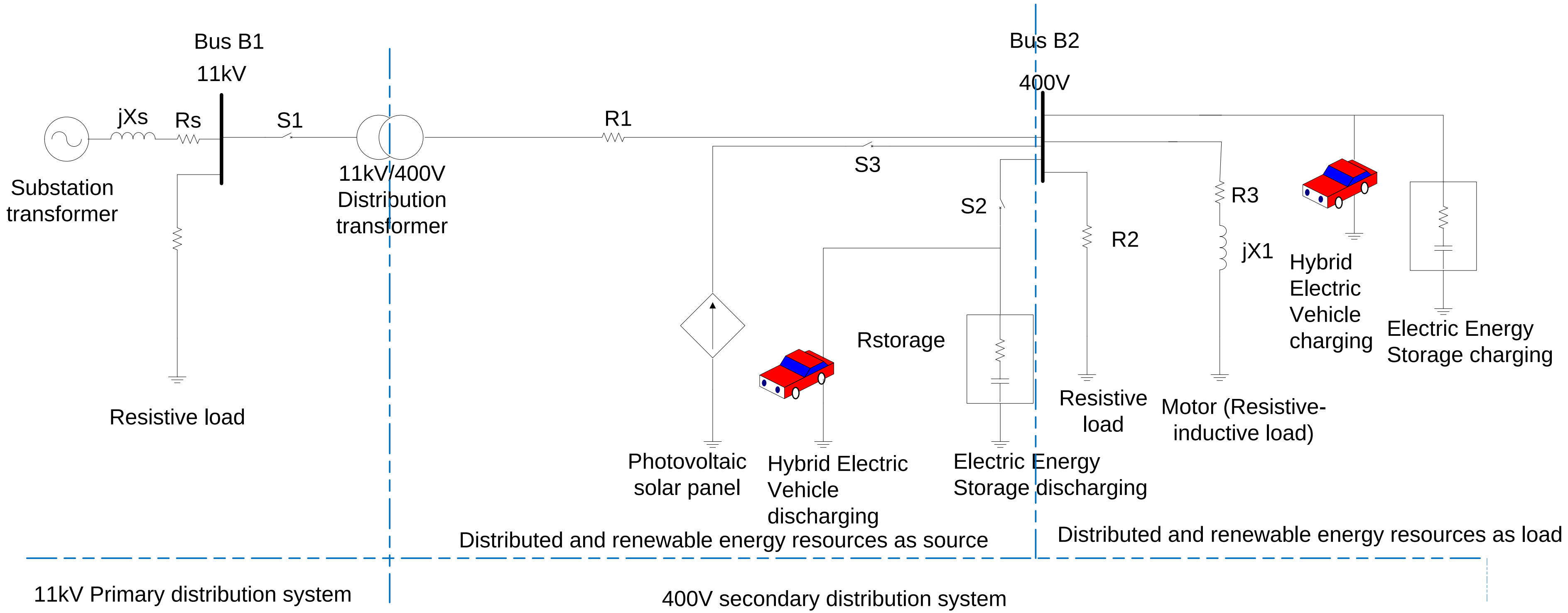


Figure 3.3: single-line diagram of proposed Smart Grid Distribution System

Table 3.1: R&DER distribution in SGDS

Node	Consumer	PV (kW)	EES (kW)	HEV (kWh)
Industrial R&DER distribution N49	1	0	0	12
	2	0	0	10
	3	0	0	10
	4	0	0	15
	5	0	0	12
	6	40	50	15
	Total	**40**	**50**	**74**
Commercial R&DER distribution N50	7	0	0	12
	8	0	0	8
	9	0	0	10
	10	40	50	15
	Total	**40**	**50**	**45**
Municipal R&DER distribution N51	11	0	0	15
	12	0	0	12
	13	36	50	15
	Total	**36**	**50**	**42**
Residential R&DER distribution N52	14	0	0	8
	15	4	0	0
	16	0	0	0
	17	0	0	12
	18	0	0	0
	19	4	0	0
	20	0	0	10
	21	4	0	0
	22	4	0	15
	23	4	0	0
	Total	**20**	**0**	**45**

Node	Consumer	PV (kW)	EES (kW)	HEV (kWh)
Residential R&DER distribution N53	24	4	0	0
	25	0	0	0
	26	0	0	12
	27	4	0	0
	28	0	0	10
	29	4	0	0
	30	4	0	0
	31	0	0	10
	32	4	0	15
	33	0	0	0
	34	4	0	0
	35	0	0	12
	Total	**24**	**0**	**59**
Residential R&DER distribution N54	36	4	0	0
	37	0	0	0
	38	0	0	15
	39	4	0	0
	40	0	0	12
	41	4	0	10
	42	4	0	0
	43	0	0	8
	Total	**16**	**0**	**45**
Residential R&DER distribution N55	44	4	0	0
	45	4	0	0
	46	4	0	0
	47	4	0	8
	48	0	0	0
	49	4	0	0
	50	0	0	12
	51	4	0	0
	52	4	0	0
	53	4	0	0
	54	4	0	0
	Total	**36**	**0**	**20**
	Overall	212	150	330

Table 3.2: Sources, demands and loads used for proposed Smart Grid Distribution System [111]

Customer type	Number of electric meter	Single-phase	Three-phase	Smax (kVA)	Smin (kVA)	PV (kW)	EES (kW)	HEV (kWh)
Industrial load (N49)	4	0	4	45	15	40	50	74
Commercial load (N50)	6	0	6	60	25	40	50	45
Municipal load (N51)	3	1	2	55	30	36	50	42
Residential load, L-14-23 (N52)	10	10	0	107.5	22.5	20	0	45
Residential load, L-24-35 (N53)	12	12	0	109.80	24.6	24	0	59
Residential load, L-36-43 (N54)	8	8	0	102	26	16	0	45
Residential load, L-44-54 (N55)	11	11	0	108.35	23.65	36	0	20
Total	54	42	12	587.65	166.75	212	150	330

Number of meter represents the number of customers. Almost all load node supplies electricity to the lighting and air-conditioning loads. In addition, commercial load node supplies electricity to the commercial fridge-freezers, cookers, blending and grinding machineries, industrial load node supplies electricity to the process control machineries, and residential load nodes supply electricity to the domestic appliances. However, municipal load includes water and gas distribution system, street lighting, school/college, hospitals, irrigation and ancillary services. Thus, Distribution Network Operator supplies power to mixed-mode resistive and resistive-inductive loads. The resistive-inductive loads demand for reactive power that causes voltage instability. Additionally, streetlights turn on only in the day, water and gas distribution operator regulate their supply mostly overnight and irrigational pumps turn on overnight. On the other hand, demands of ancillary services are quite unpredictable. As a result, demand curve for municipal loads frequently vary with respect to time. Therefore, rapid response for real and reactive demand is necessary.

Additionally, there are 7 nodes (54 load points) considered for F10 sub-feeder. The distribution transformer size is 630kVA and is protected by two K-link fuses (slow responses fuse saving scheme). There is no voltage regulator presents on the sub-feeder. The primary feeder contains automatic voltage regulator, shunt capacitor and off-load tap changing transformer (OLTC) in order to response with voltage fluctuations. All Aluminium Alloy Conductor (AAAC) is used for three-phase sub-feeder and copper conductor for service mains. Due to the statutory regulations, 4kW capacity of Photovoltaic solar panels install on the domestic consumer roof. In general, Hybrid Electric Vehicles are rated from 5kWh to 15kWh. Electric Energy Storages for community users (e.g.: to provide local amenities) rated about 25kW. The distribution transformer runs with 30% to 70% load with 80% emergency rated. Although maximum connected load is about 86%. However, connected maximum demand does not occur simultaneously for example some municipal loads (e.g.: schools) close in the evening and early in the morning; two peak sessions.

From the above discussions, it can be seen that total R&DER capacity (692kW) is more than distribution transformer (630kVA or 567kW for average p.f=0.9). This results supply-demand unbalance, transient voltage and current instability, critical infrastructure and harmonics. Thus, the overall equipment efficiency could reduce. Consequently, system overall reliability would potentially be reduced. The following sections demonstrated case studies for energy management and impacts of proposed wide-scale R&DER integration in contrast with conventional electric distribution system focusing reliability indices.

3.2 Impacts on load curves

The real and reactive power demands of different consumers vary in accordance with their activities. The load on a substation is therefore never constant. It varies time to time. Sometimes, these changes are rapid and large. This inherent variability due to supply-demand unbalance of the load demands by the consumers is responsible for most of the complexities (i.e. disturbances) of modern power plant operation. It also leads additional equipment requirements, increase generation cost and highly complex infrastructure design that consequently decrease the reliability. Therefore, investigation of load variability for proposed Smart Grid Distribution System is vital and is discussed in this section.

The load variability is demonstrated in terms of load factor, demand factor and diversity factor from the load curves to measure the load demand both for conventional and proposed model. Loads for conventional electric distribution system are modelled using data from IEEE EU LV test feeder load.csv files. The base load is specified using kW and power factor (p.f) for each load from the load.csv file. Time-series simulation is used for defining lad shapes. Loads for proposed Smart Grid Distribution Systems are modelled using table 3.1 and 3.2 respectively. The linear regression method is used to scale the loads for proposed Smart Grid Distribution System. Linear regression provided the relationship between load variability due to supply-demand unbalance and time in one day (i.e.: 24 hours = 1440 minutes). Application of linear regression method for node N49 is presented here.

Let $y=mx+c$, where m is the slope of the regression and c is the y intercept. Load is plotted on y axis and time is on x axis. The minimum and maximum demand for node N49 is 15kVA and 45kVA respectively. Therefore, the slop for N49 over 24 hours is calculated to 20.83. Thus, the load curve for N49 is plotted over 1440 minutes with 1 minute step-size and shown in figure 3.4. The blue line represents generic demand of substation feeder for node N49. The red line represents demand variations for integration of R&DER at node N49 while PV is in generation, EES and EV are charging. The green line represents demand variations for R&DER at node N49 while PV is in generation and EES and EV are discharging. Similarly, load curves for Node N50-N55 for proposed SGDS is found and presented in figure 3.5 to figure 3.10.

Node 49: Industrial loads

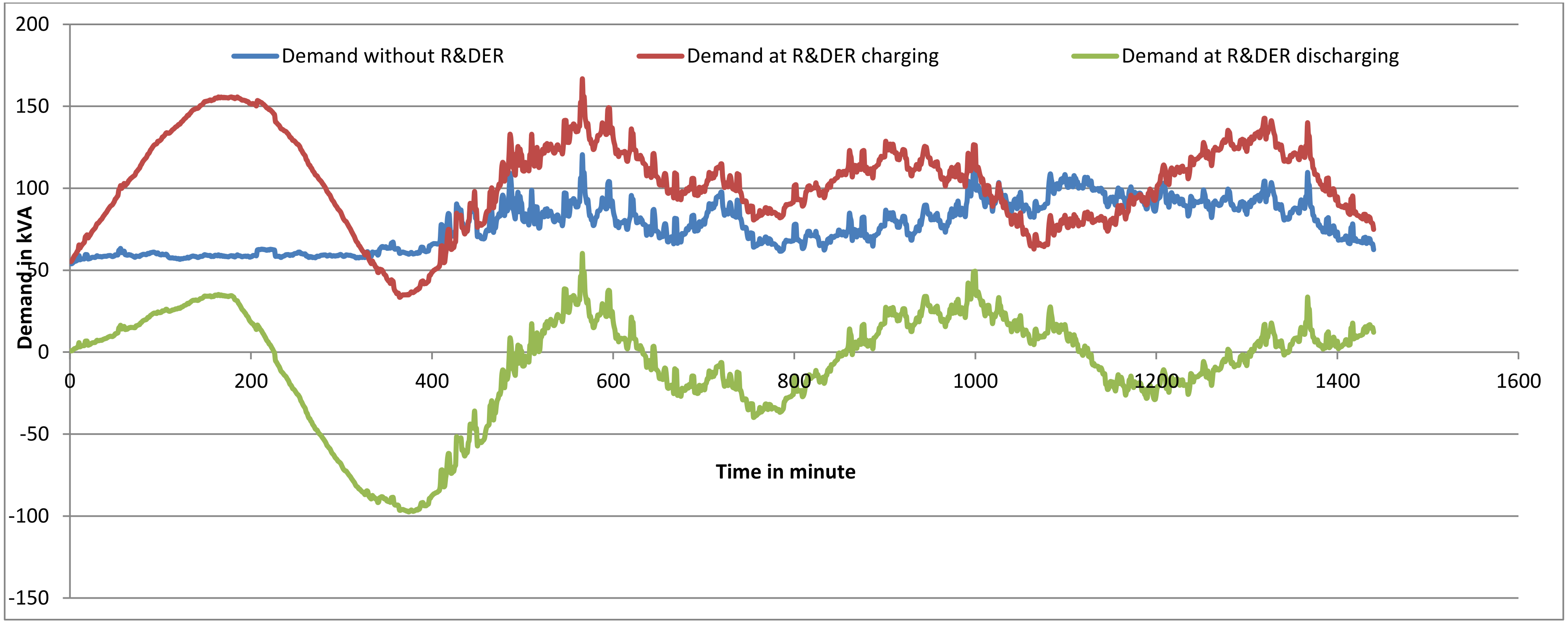


Figure 3.4: Load curve for industrial load node N49

Load variability on N49 is almost steady and predictable due to the reason that it has its own R&DER to response dynamic response. However, rapid changes in demand for example resistive-inductive load (i.e.: motor, electric arc) could potentially results impulsive and oscillatory transient that is discussed in section 3.3.

Node N50: Commercial loads

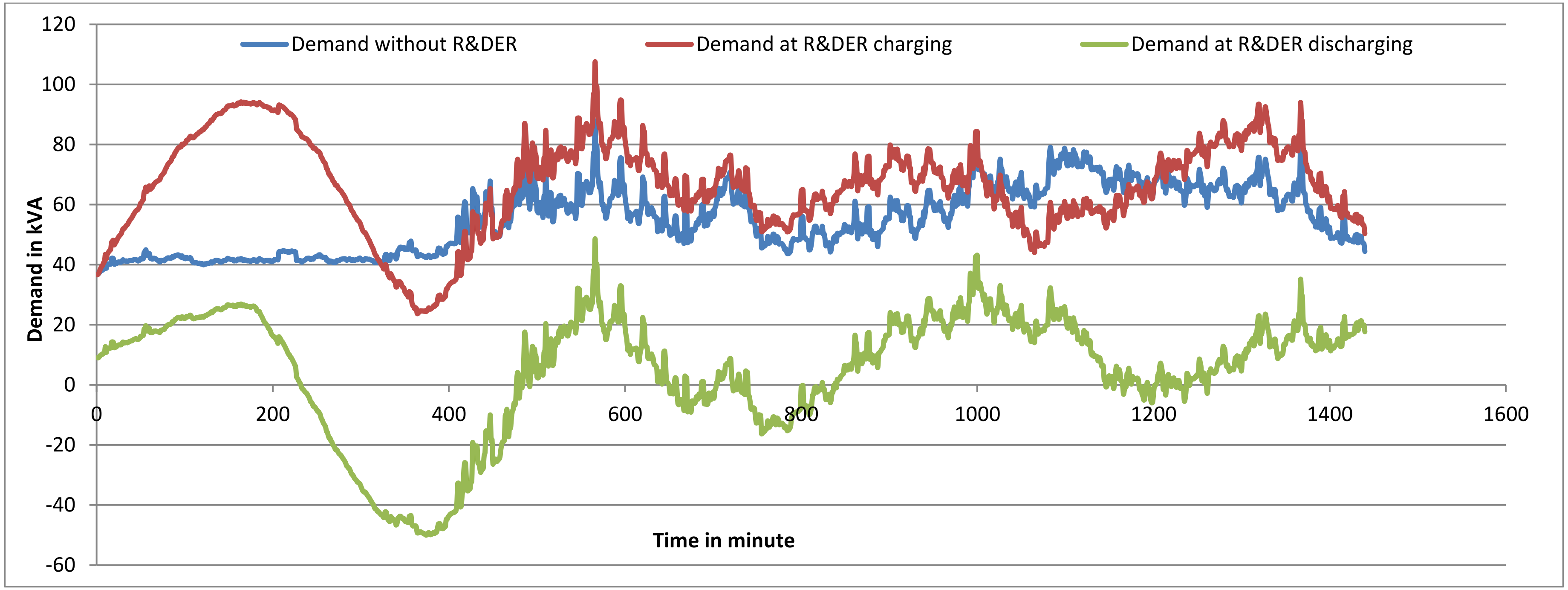


Figure 3.5: Load curve for commercial load node N50

Load variability on N50 results reverse power flow due to R&DER operation. When Photovoltaic solar panels are in full-mode generation and EES and HEV charge, adequate amount of energy remains surplus while in discharge mode, bulk amount of energy tends to flow back to the grid. However, due to the presence of distribution transformer, energy can't flow back to the grid or it results substation reverse power flow relay to trip-off. The reliability decreased.

Node N51: Municipal load

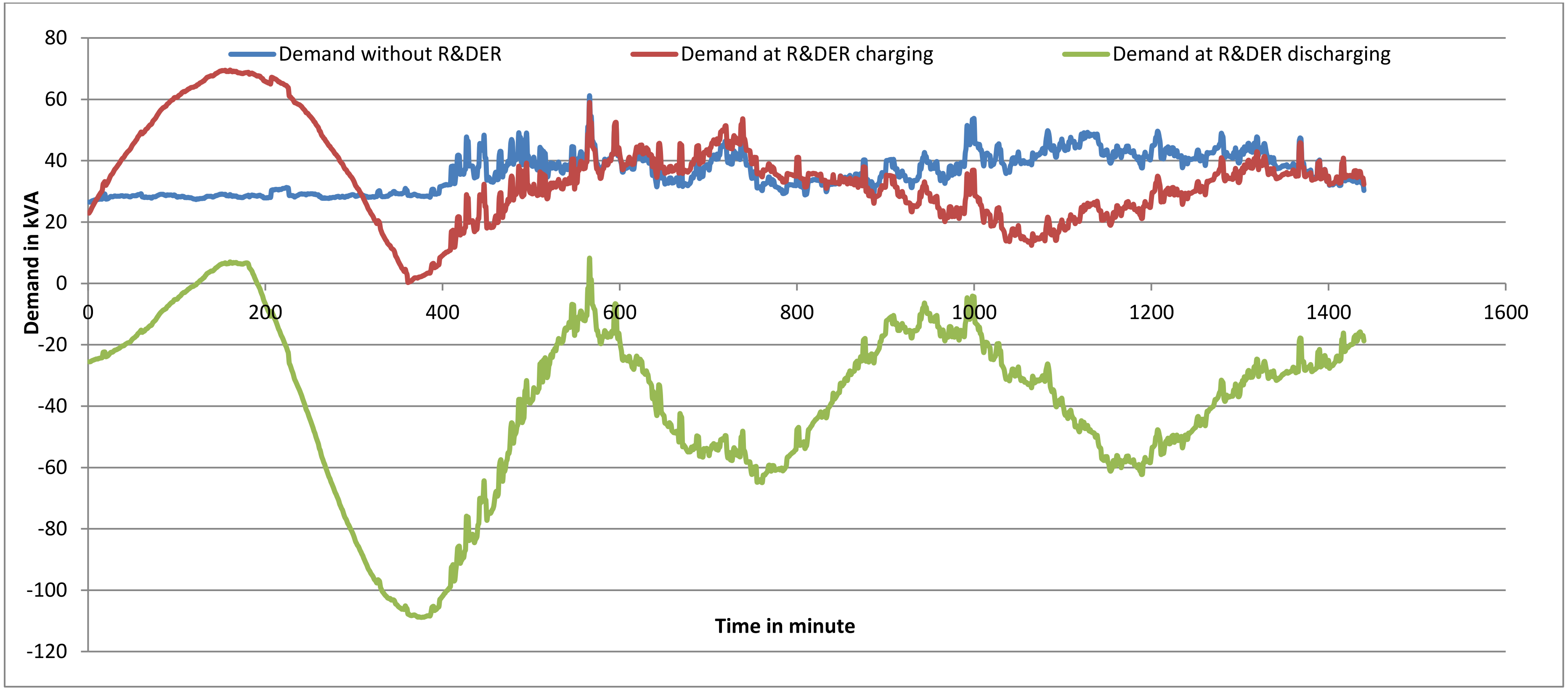


Figure 3.6: Load curve for municipal load node N51

Due to the nature and schedule switchover of the load, historically, municipal load are almost steady. However, emergence of R&DER has been changing this condition to rapid changes in load variability as well as load rejection to reverse power flow as shown in figure 3.6.

Node N52: Domestic loads

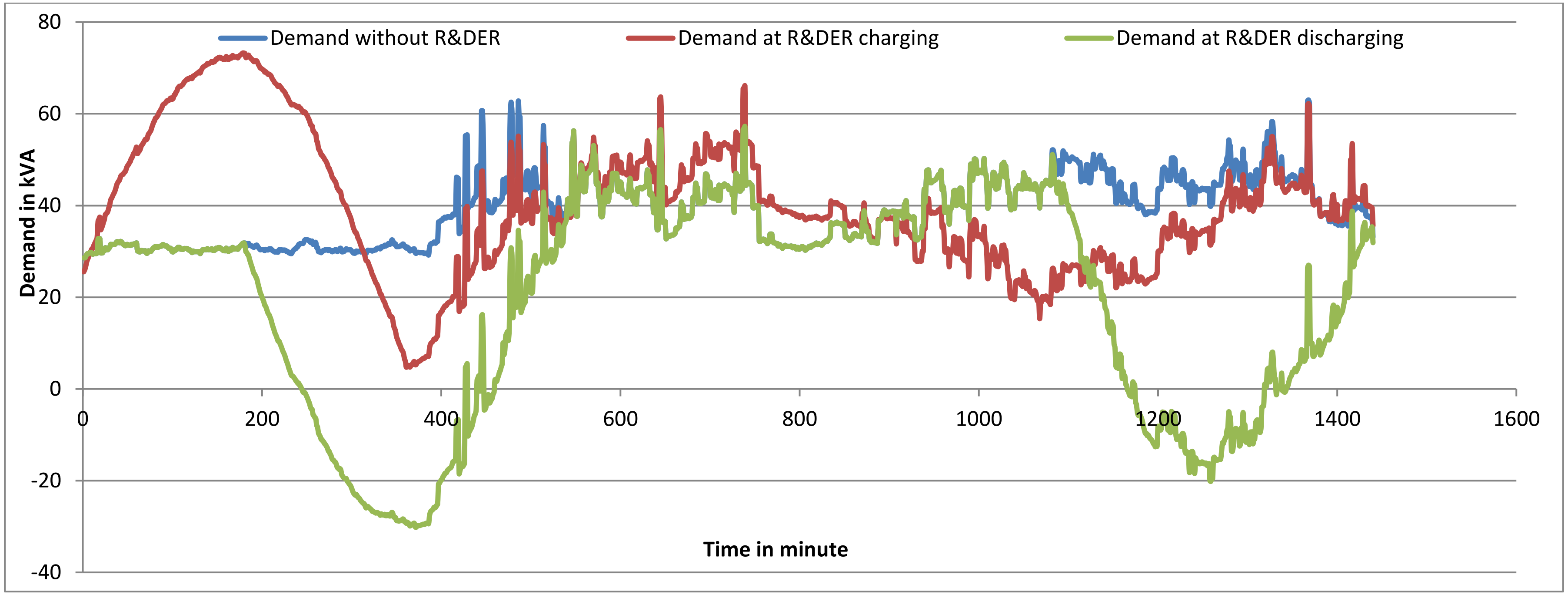


Figure 3.7: Load curve of domestic load node N52

Historically, load variability for domestic consumers can be predictable. However, wide-scale roof mounted Photovoltaic solar panels including modern electronic devices have been changing this practice. Load variability increased in uncountable number, load rejection has been taking place at Photovoltaic solar panels are on generation, reverse power flow causing islanding of loads, demand has increased due to change in modern life as shown in figures 3.7-3.10.

Node N53: Domestic loads

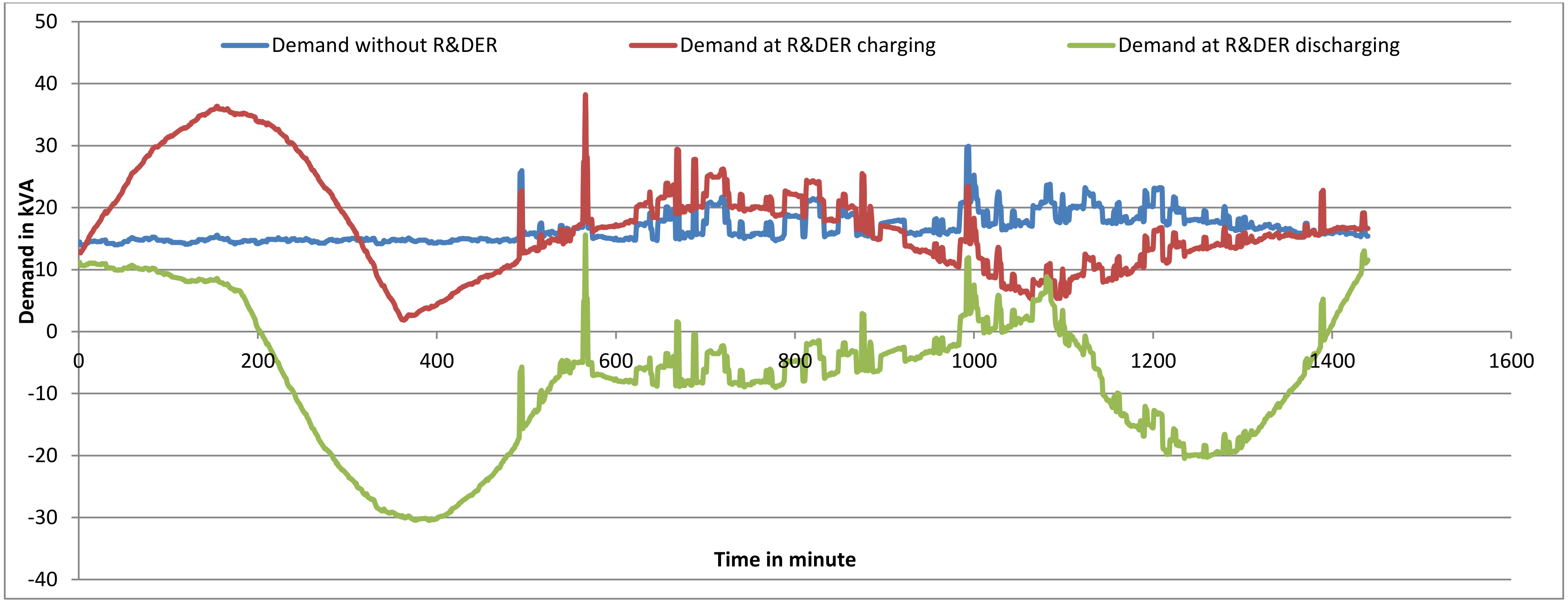


Figure 3.8: Load curve of domestic load node N53

Node N54: Domestic loads

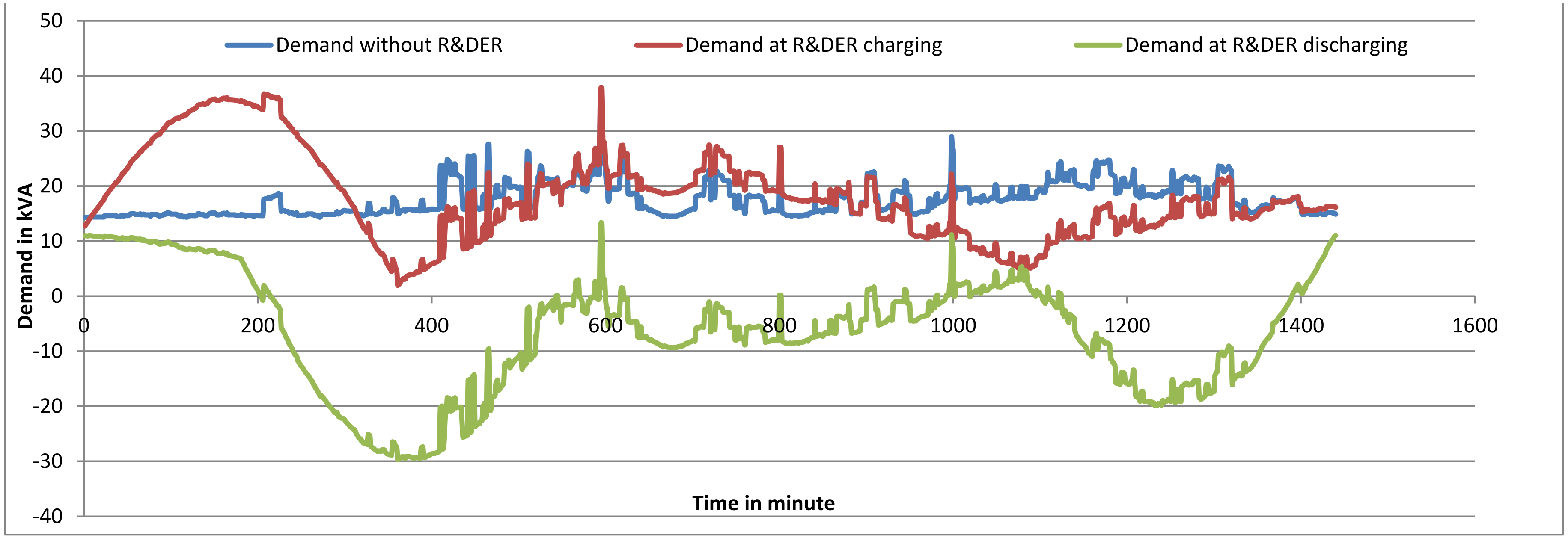


Figure 3.9: Load curve of domestic load node N54

Node N55: Domestic loads

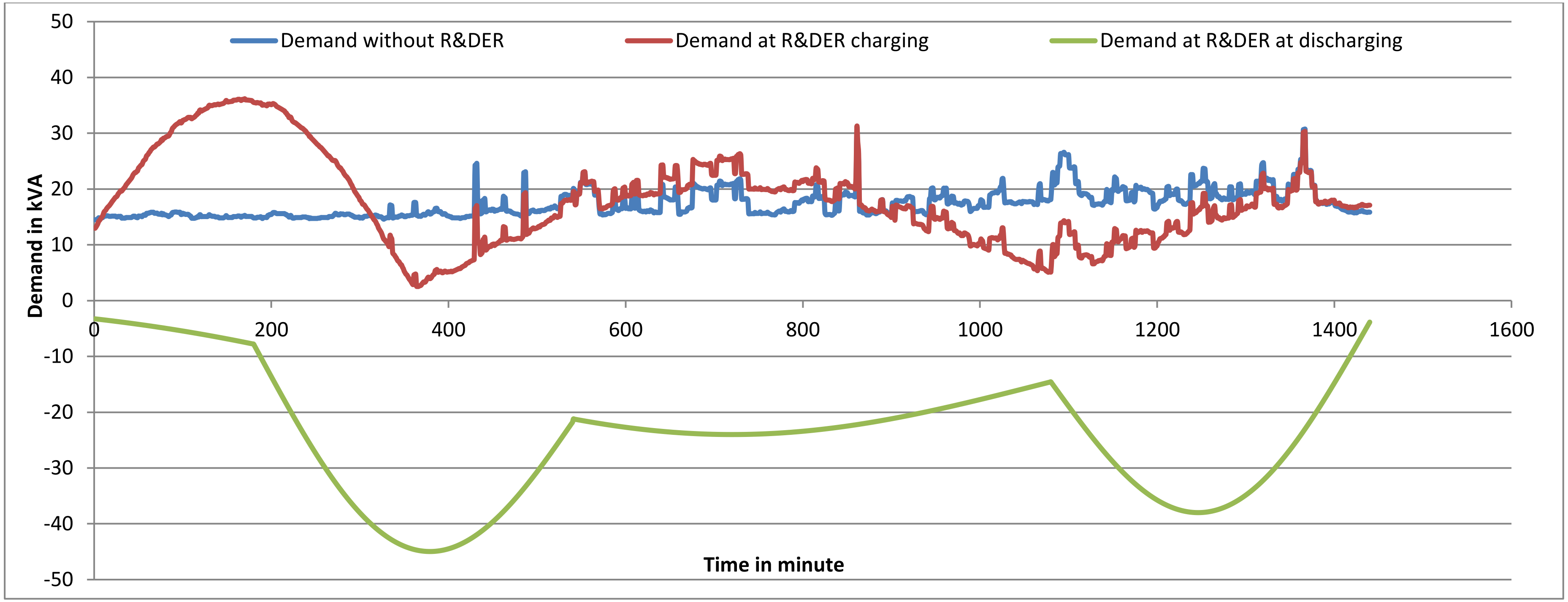


Figure 3.10: Load curve of domestic load node N55

However, total impacts on load curve for F10 (where Node N49 to N55 located) are noticeable as shown in figure 3.11. The supply-demand unbalance is distinguishable, reverse power flow occurs, and distribution transformer goes underload and no load conditions. The results of such causes are still unknown to the power industry across the world. These make optimal control and efficient operation algorithm for future sustainable, reliable and secure electricity supply inevitable.

Load curve of proposed SGDS:

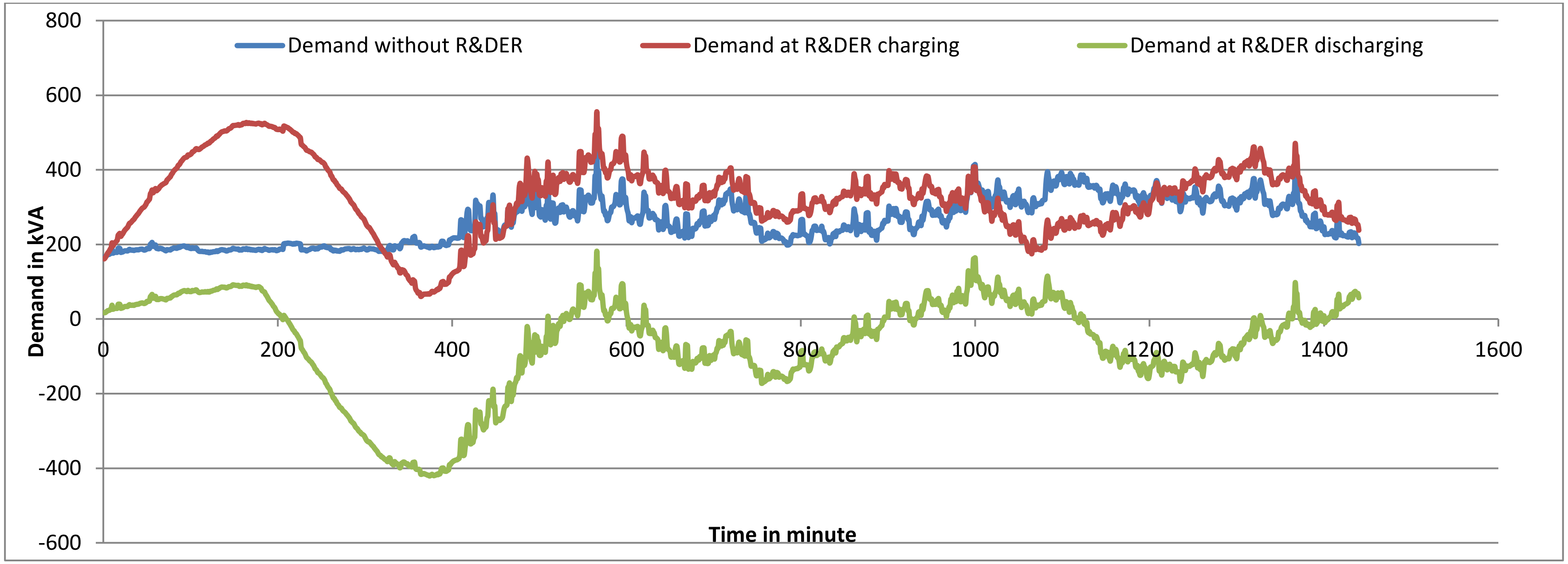


Figure 3.11: Load curve of F10 (proposed SGDS)

Additionally, in practice, load curves for load variability in conventional electric distribution system plot for the substation for Distribution Management System (DMS). In order to mitigate peak demand or large disturbances, some substation install diesel generator due to its rapid response time. It has been shown that load variability is predictable over the day. This is due to predictable consumer behaviour for example, demand is maximum in the morning (e.g.: between 5:00am to 8:00am) and in the afternoon (e.g.: 6:00pm to 10:00pm). Although, load variability is rapid, however, it can wisely be managed due to forecast of loads. However, this has been changing for wide-scale R&DER integration as presented in chapter 5. The connected load is considered for wide-scale R&DER integration increased from 68kVA to 178kVA compared with figure 3.4 to 3.10. It was found that the lower limit of demand is increased but exceeded maximum capacity (for example 598kVA) of distribution transformer (630kVA). Additionally, connected load does not represent the load variability due to wide-scale R&DER integration.

In the contrary, load variability in proposed Smart Grid Distribution System is diverse as shown in figure 3.4-3.11 and is not predictable without using advanced technologies. It is found that demand fluctuation is completely diverse and rapid during the time between 6:00am and 11:00pm. Moreover, demand reached its minimum between 11:00am and 3:00pm when Photovoltaic solar panels are in generation. It also exceeded the maximum limit between 6:00am and 9:00am and between 6:00pm and 10:00pm when Electric Energy Storage and Hybrid Electric Vehicle intended to charge. This leads reverse power flow in each node. The impacts of such multi-directional power flow, minimal load and rapid load variability within a small distribution area are unknown yet.

In summary, one of the significant impacts for proposed Smart Grid Distribution System is found as supply-demand unbalance as shown in figure 3.4 to 3.11. Not only for rapid changes in demand but also its magnitude for example demand exceeded than distribution transformer capacity, no-load condition of distribution transformer could potentially reduce lifetime of distribution system equipment, lead plant failure and eventually reduces overall reliability. The reliability benchmarks are found from several factors such as load factor, diversity factor, demand factor and plant capacity factor. Therefore, load factors, diversity factors and demand factor for the proposed SGDS compare with an electric distribution system (i.e.: IEEE EU LV feeder data) is calculated in the following section.

3.2.1 Load factor:

Load factor is defined as the ratio of average load to the maximum demand during a given period. In practice, load curves plot for demand against time for daily, weekly, monthly and annually that represents graphical presentation of demand variation over specified time.

Mathematically,

$$Load\ factor\ = \frac{Average\ load}{Maximum\ demand}$$

In principle, load factor is always less than one. This is because the average load is always smaller than maximum demand. It plays a key role in determining the overall cost per unit generated. The relationship between load factor and per unit tariff is inversely proportional, i.e. higher load factor provides cheap per unit electricity generated and vice versa. However, conventional electric distribution system is considered as a sink in traditional power system. In the contrary, concepts of Smart Grid Distribution System would change this tradition. Load factor for distributed & renewable energy resources based Smart Grid Distribution System would be much higher and consistent than conventional electric distribution system.

It is found that for conventional electric distribution system

Maximum demand = 142kW

Average demand=95.39kW

It is also found that for Smart Grid Distribution System

Maximum demand = 600kW

Average demand=294.48kW

Conventional electric distribution system:

$$Load\ factor = \frac{95.39kW}{142kW} = 0.6717 = 67.17\% \cong 67\%$$

Smart Grid Distribution System:

$$Load\ factor = \frac{294.48kW}{600kW} = 0.4907 = 49.07\% \cong 49\%$$

It can see that the load factor is decreased by 18%

3.2.2 Diversity factor

It is defined as the ration of the sum of individual maximum demands to the maximum demand.

Mathematically,

$$Diversity\ factor\ = \frac{Sum\ of\ individual\ maximum\ demand}{Maximum\ demand\ on\ substation}$$

Historically, a substation supplies load to various types of customers whose maximum demands generally do not occur simultaneously. Greater the diversity factor cheaper the cost of generation of electricity. This is due to greater the diversity factor means lower maximum demand. It in turn means that lower plant as well as equipment capacity is required.

It is found that for conventional electric distribution system

Maximum demand = 142kW

Average demand=95.39kW

It is also found that for Smart Grid Distribution System

Maximum demand = 600kW

Average demand=294.48kW

Conventional electric distribution system:

$$Diversity\ factor = \frac{587.65kW}{142kW} = 4.14$$

Smart Grid Distribution System:

$$Diversity\ factor = \frac{587.65kW}{600kW} = \ 0.98$$

It can see that the diversity factor decrease by 3.16

3.2.3 Demand factor

Demand factor is defined as the ratio of maximum demand to the connected load for a power system.

Mathematically,

$$Demand\ factor = \frac{Maximum\ load}{Connected\ load}$$

It is usually less than one as maximum demand is always less than the connected load. The knowledge of demand factor for a plant is vital as it determines the capacity of the plant equipment.

It is found that for conventional electric distribution system

Maximum demand = 142kW

Average demand=95.39kW

It is also found that for Smart Grid Distribution System

Maximum demand = 600kW

Average demand=294.48kW

Conventional electric distribution system:

$$Demand\ factor = \frac{142kW}{567kW} = 0.2504 = 25.04\% \cong 25\%$$

Smart Grid Distribution System:

$$Demand\ factor = \frac{600kW}{567kW} = 1.05 = 105\%$$

It is found that the demand factor increased by 80%

3.2.4: Summary of load curves

Table 3.3: Summary of Load factor, Demand factor, and Diversity factor

	Conventional Electric Distribution System	Smart Grid Distribution System without SHC	Variation	Reliability	Impact
Load factor	67%	49%	18% (decreased)	Decreased	Reverse power flow & overvoltage
Diversity factor (p.u)	4.14	0.97	316% (decreased)	Severely decreased	Transient instability
Demand factor (p.u)	0.25	1.05	80% (increased)	Decreased	Overload

Finally, it is found that Smart Grid distribution System experiences predicted and unpredicted events. The predicted events can be investigated by using statistical model. However, unpredicted events for examples reverse power flow, voltage fluctuation, overload, over voltage, rapid changes in demand require Self-healing and robust control in order to mitigate such large disturbances. One of the significant unpredicted events for Smart Grid Distribution is transient disturbance. Rapid changes in demand and PV generation fluctuation and R&DER condition changes are the key factors that results transient voltage and current in proposed Smart Grid Distribution System that has been discussed in the following section.

3.3 Transient analysis of proposed Smart Grid Distribution System

Widespread use of non-linear and electronics in everything from consumer electronics to the sensitive, expensive and massive industrial processes has raised the awareness regarding quality of power. Modern technology demands quality of power that is free from disturbance or interruption. Disturbance is generally defined as any changes in power, more specifically voltage, current or frequency that interferes with normal operation of electrical equipment. Most common disturbances in electric power distribution system are:

- Transient instability
- Over voltage
- Under voltage
- Overload
- Harmonics
- Voltage fluctuations
- Frequency variations

Amongst all, transient is considered as potentially the most damaging type of disturbance. Transient could be impulsive or oscillatory. Impulsive transient is defined as a sudden high peak event that raises the current or voltage or both in either a positive or a negative direction. It could be fast, medium or slow from five nanoseconds to fifty nanoseconds [112-113]. It is also known as surge or spike. The switching of inductive loads, poor grounding, reclosing operation during fault clearance and electrostatic discharge are the most common causes for impulsive transient. The oscillatory transient on the other hand is a sudden change in steady-state condition of a voltage or a current signal or both signals at both the negative and positive limits. It occurs when an inductive or capacitive load i.e. a motor or a capacitor bank installed along the radial feeder to regulate voltage turn off. Several technologies have been used to protect sensitive loads, plant and its equipment from the transients for example installation of line reactor for capacitor tripping and voltage suppressors at the sensitive load terminals for impulsive transient. However, line reactors are generally installed on medium or high voltage line and voltage suppressors have a limit of tolerance. Rapidly switching changes of Photovoltaic solar panels inverters or unpredictable demands cannot be solve by voltage suppressors not only the transient voltage or current magnitudes but also its duration. Therefore, transient behaviour of proposed SGDS is discussed in contrast with conventional electric distribution system in the following section.

In general, transient analysis of power system conducted through generator-load model as shown in figure 3.12 where distribution system is considered as the load (sink). Therefore, it is critical to analyse transient stability for small and large disturbance and is impractical to use generator-load model for electric distribution system or microgrid. It is also impractical to justify transient power-angle for distribution transformer as a synchronous machine. The significant impact of proposed Smart Grid Distribution System on generator-load model is its bidirectional power flow that contradicts with the conventional power flow analysis methods. However, to understand the transient stability analogy, a simple generator-load model is used in this section. Transient stability for bidirectional power flow has been discussed in later sections by means of Self-Healing Control.

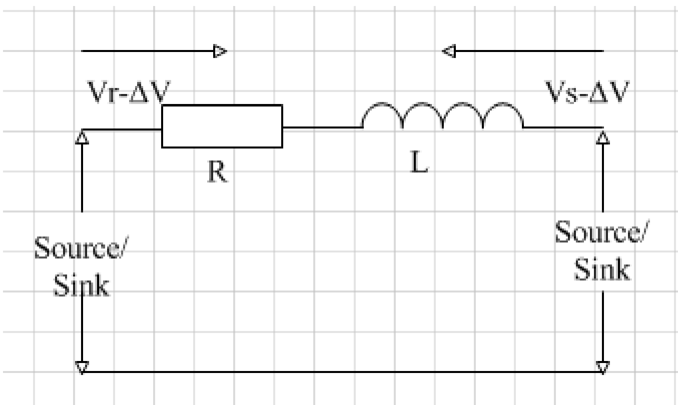


Figure 3.12: Source (generator)-load model for proposed SGDS in circuit model

Figure 3.13 shows a source-load model used for transient analysis of proposed Smart Grid Distribution System by simplifying figure 3.3 (as shown in section 3.1). It consists of a plant i.e. bus B2 (as shown in figure 3.3), Electrical Energy Storage and Photovoltaic solar panel that is supplying power to an equivalent resistive-inductive (R-L) load i.e. motor, R1+jωL1 fed at 400V (r.m.s voltage) from a distribution transformer with 11kV primary voltage rating. Where ω is the angular velocity whose magnitude is $2\pi f$. Here, f is the frequency and is 50Hz.

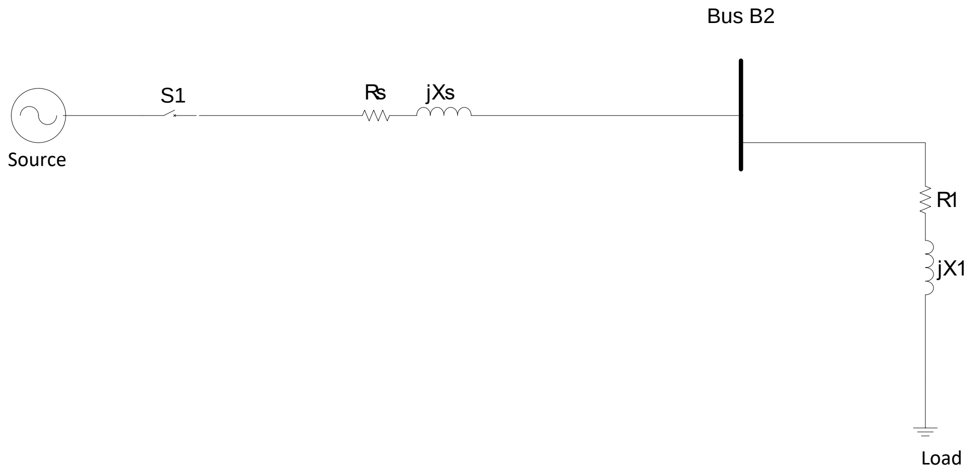


Figure 3.13: Source-load model for proposed SGDS in single line diagram

The Rs+Xs are the total feeder resistance and reactance respectively and measured in Ω/km. The R_1+jωL_1 represents the equivalent resistive-inductive loads (i.e. the combination of induction motor, air-conditioning and the resistive loads, i.e. lighting, heating). The average power factor (p.f) for the system is assumed as 0.9.

The All Aluminium Alloy Conductor (AAAC) with 4x120mm^2 main wire has used to model the line. Since Al has a resistivity of 2.62x10^{-8}Ω-m, length of the wire from source to load is assumed 35km, and cross-section area of the wire is 120mm^2, the resistance Rs and Xs is found as:

$$R_s = 0.284\ \Omega/\text{km and } X_s = 0.083\Omega/\text{km [58]}$$

The voltage limit of $\pm$ 10% provides bus 1 voltage range between 440V and 360V. Therefore, voltage profile must record upper threshold voltage as 438.416V and lower threshold voltage 358.704V for bus2 rather than 440V and 360V. Distribution transformer considered as a constant voltage source supplying electricity from the substation to the customer meter. It steps down voltage from 11kV to 400V. The customer consumes 400V line to line and 230V line to neutral. PV, EEV and HEV act as variable sources during generation and discharging. Inverters provided output to the loads from the PV generations. Hence, PV modelled as voltage controlled current source. EES charges either in PV at surplus generations or overnight or during the off-peak and super off-peak time. Current supplied by the distribution transformer at 400V secondary voltage can be found as:

Current, I = $\frac{VA}{\sqrt{3}.V} X1000$

When distribution transformer at full load, full load current:

$$I_{FL} = \frac{630VA}{\sqrt{3}\,.\,400V} X1000$$

I_{FL} = 909.326674 A for three phase and about 300A per-phase

Initially (i.e.: at t< 0), it is assumed that the system is not energised and switch S1 is opened. The current at t<0 the current flow through the line is $i(0^-)=i(0)=i(0^+)=0$ A.

At $0 \leq t \leq t_{sw}$, switch S1 (e.g.: substation circuit breaker) closed so that current flow begins in the system. Where, t_{sw} is transient voltage duration. The power supplies from substation transformer through distribution transformer to the customer devices. At t=0, when switch S1 in closed, system voltage is in transient state. In principle, transient state dies out over time. The transient time should be less than or equal to half cycle of the input current or voltage wave.

Let switch S1 closes forever. The current flow can be given as:

$$i(\infty) = \frac{v1(t)}{Rs+R_1} \qquad [3.1]$$

Where the time constant $\tau = \frac{L_T}{R_T}$

Therefore, i(t) = $i_{transient} + i_{steady\text{-}state}$

$$\text{Or, } i(t)= [i(0)-i(\infty)]\, e^{-\frac{t}{\tau}} + i(\infty) \qquad [3.2]$$

Rearranging equations [3.1] and [3.2], current response for $0 \leq t \leq t_{sw}$ can be found as:

$$i(t) = \frac{v1(t)}{R_S+R_1}\left[1 - e^{-\frac{t}{\tau}}\right] \qquad [3.3]$$

At steady state operation, the bus 2 voltage is stable. System transient does not last for more than 50ms as shown in figure 3.14. The details of theoretical analysis results are presented in the table 3.4.

Table 3.4: Transient parameters for system analysis

Power (kW)	P.F (cosΦ)	Nominal bus B2 voltage (V)	Resistance (Ω)	Reactance (Ω)	Time (ms)	Transient voltage at bus B2
0	0.95	0	1.667338667	0.548027718	0^- to 0^+	0
150	0.95	400	1.667338667	0.548027718	t≥0	179.8047493
189	0.95	400	1.323284656	0.434942633	5	420.6458531
200	0.95	400	1.250504	0.411020788	10	421.0514389
250	0.95	400	1.0004032	0.328816631	15	421.0525093
300	0.95	400	0.833669333	0.274013859	20	421.0526039
350	0.95	400	0.714573714	0.234869022	25	421.0526218
400	0.95	400	0.625252	0.205510394	30	421.052627
450	0.95	400	0.555779556	0.182675906	35	421.052629
500	0.95	400	0.5002016	0.164408315	40	421.0526299
504	0.95	400	0.496231746	0.163103487	45	421.0526314
550	0.95	400	0.454728727	0.149462105	50	421.0526315

Figure 3.16 shows equivalent transient circuit of smart Grid distribution System under normal operation. It shows that at t=0, transient begins and it expects that system should be stable within 50 ms. Hence, $t_{sw} \leq 50ms$. However, at t≥50ms, equipment as well as

the plant experiences severe threats in terms of possibility of equipment failure, brownout and power outage. It happens during a normal operation as well. If system switch (i.e.: S1) on while heavy connected loads are on or auto-start induction motors are connected, the magnitude and duration of transient increases. Thus, possibility of equipment as well as plant failure increases. These reduce reliability of the entire system.

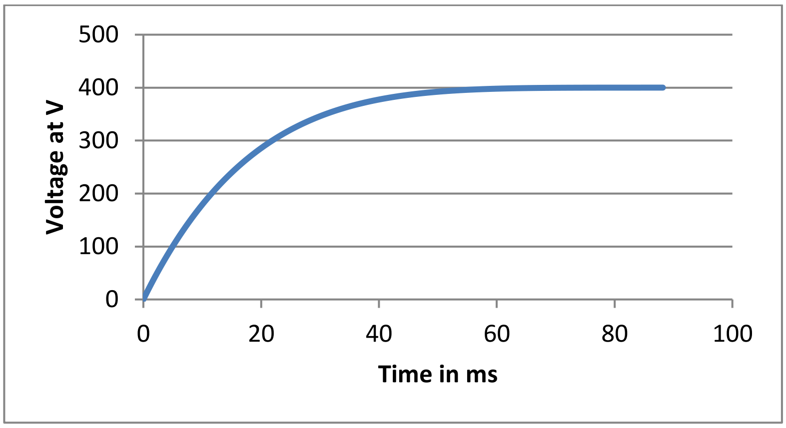


Figure 3.14: voltage response of the circuit under normal operation condition [found in MS-Excel]

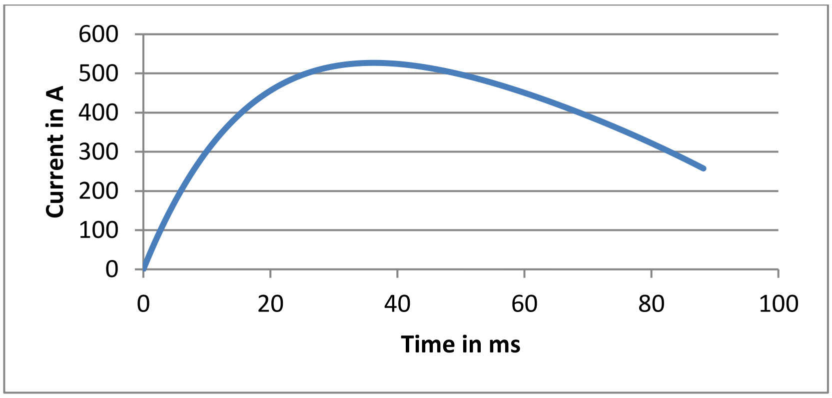


Figure 3.15: Current response of the circuit under normal operation of the system [found in MS-Excel]

It is found that steady state voltage achieved in 50ms as expected and per phase current has achieved in 70ms to the steady state condition. Current transient took longer due to current lags voltage. In order to further investigate transient behaviour of the proposed Smart Grid Distribution System, figure 3.16 has simulated in OrCAD PSPICE using table 3.4 parameters and several simulated results has presented in figure 3.17 to 3.19 and found similar results as figure 3.14 and figure 3.15.

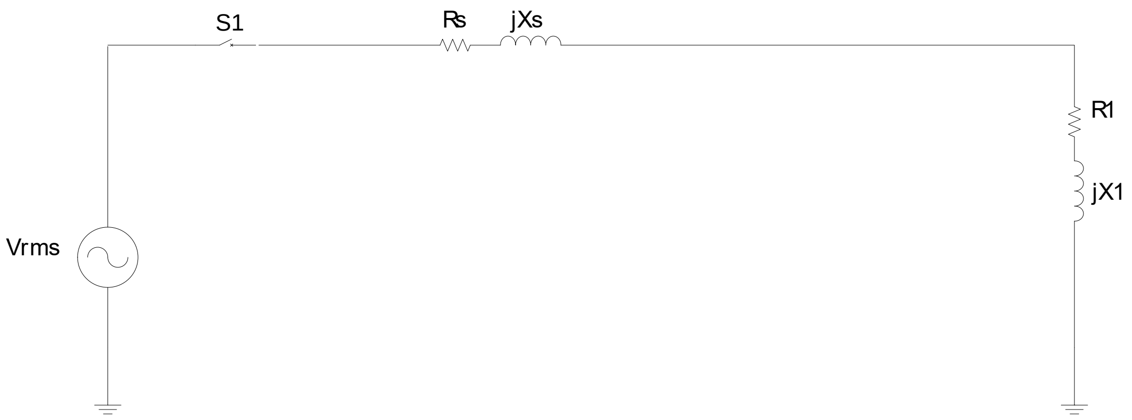


Figure 3.16: Circuit diagram for proposed SGDS in OrCAD PSPICE

Transient settings for time constant is shown in figure 3.17.

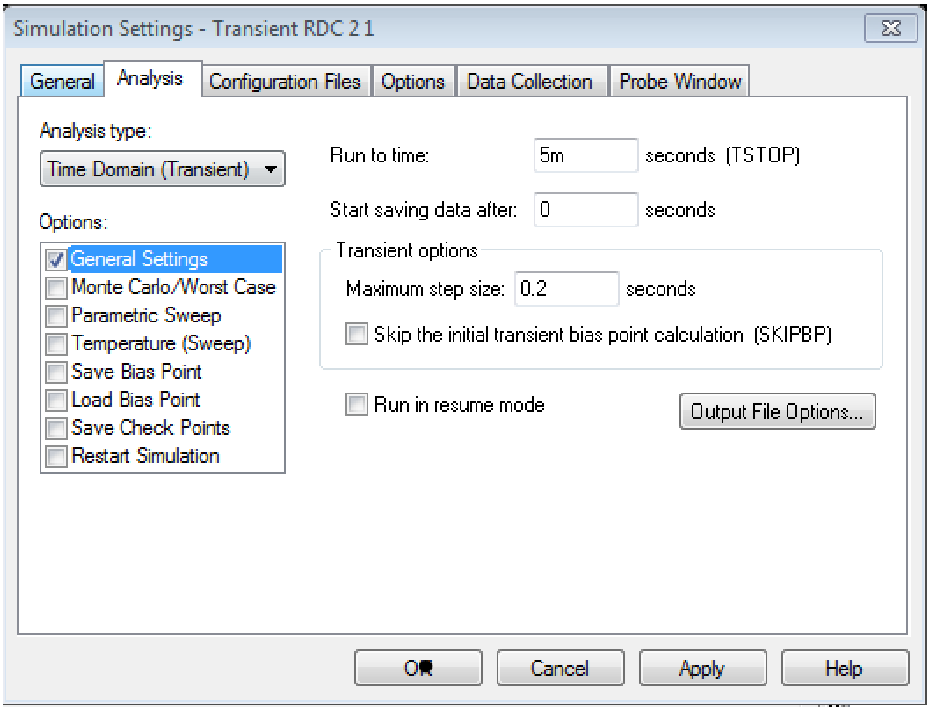
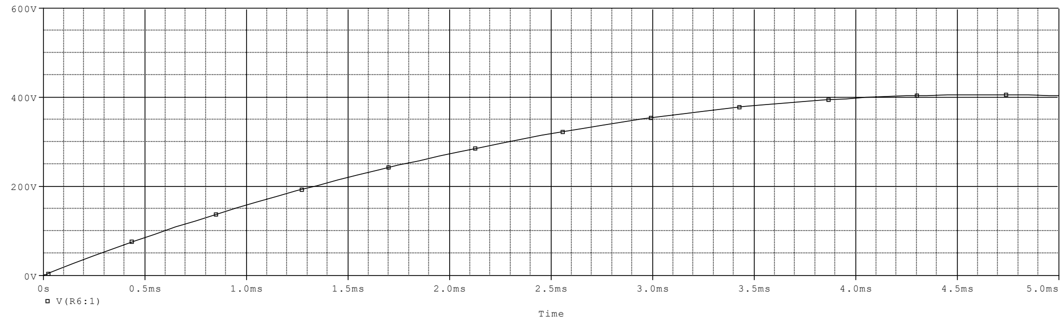
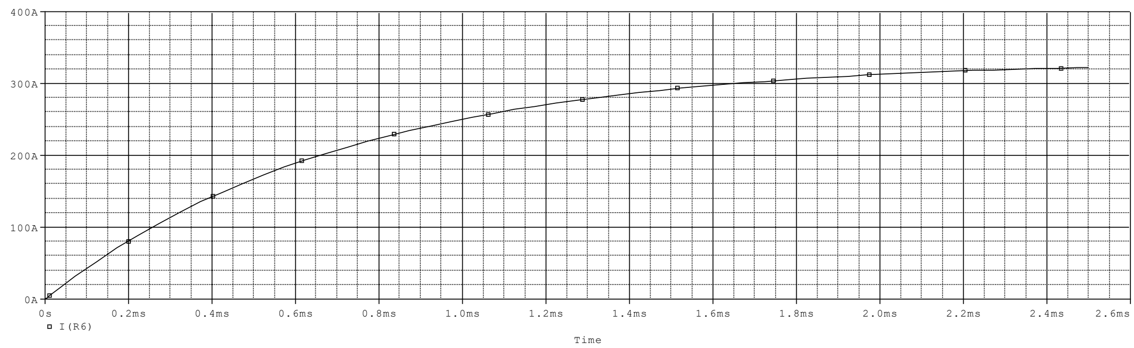


Figure 3.17: Transient settings in OrCAD PSPICE for 5ms with 0.2s step size



Y-axis=voltage in V and X-axis=time in ms

Figure 3.18: Voltage response found from OrCAD PSPICE simulation



Y-axis=current in A and X-axis= time in ms

Figure 3.19: Current response found from OrCAD PSPICE simulation

It has found that per phase current is equal to the calculated value of 300A. Such events may have severe impacts on radial feeder voltage profile for example voltage at bus B_2 of the proposed SGDS. As a result, the following section has presented the possible impacts on bus voltage for transient events related to MAIFI.

3.3.1 Impacts of modification on bus voltage (V_{B2}):

Let maximum demands occurs and the Photovoltaic solar panel generation is not available during an afternoon between 6:00pm and 10:00pm. Charged Electric Energy Storage and Hybrid Electric Vehicle started discharging in order to response peak demand instead of conventional diesel generator as shown in figure 3.20. The EES and HEV are similar in nature except their capacity. However, an equivalent storage is connected in the circuit to investigate the impacts of discharging on low voltage feeder. Let equivalent storage is controlled by switch S2.

If load variability occurs for example demand increases, storage switch S2 closed. However, initially, bus B2 voltage will decrease due to time delay in synchronisation of storage. Hence, the entire system experiences voltage dips as well as transient instability.

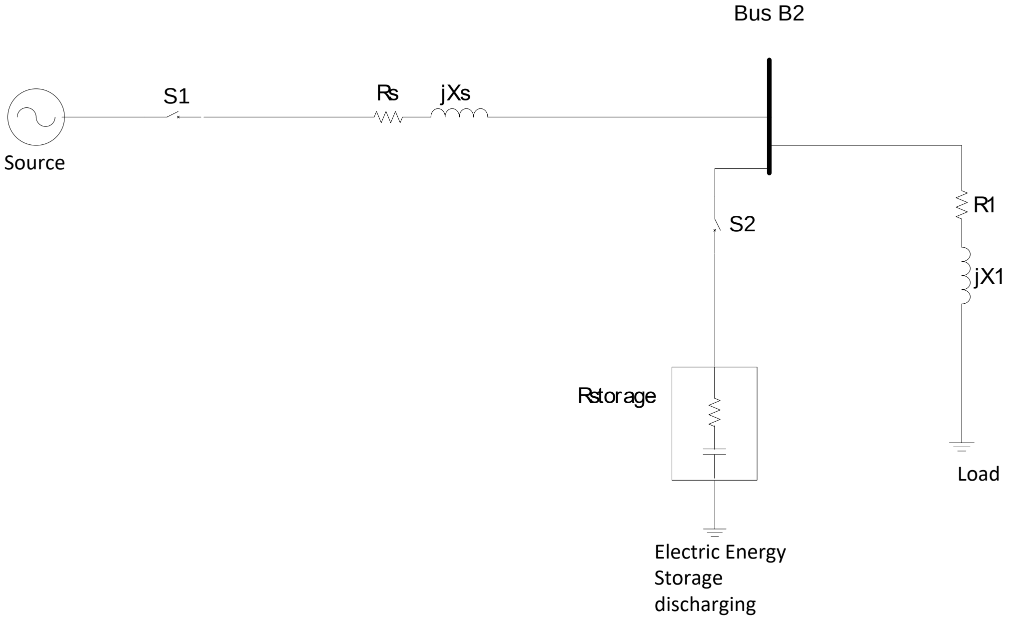


Figure 3.20: Proposed smart Grid Distribution System with Electric Energy Storage

Assume that at $t \geq t_{sw}$ (t_{sw} is the switching time of Electric Energy Storage) demand increases suddenly and distribution transformer is not sufficient to satisfy the increasing demand. The Electric Energy Storage needs to response to satisfy the demand as well as to provide stability to the system. Delay in response can collapse the voltage that leads the plant failure. A proper switching duration is significant to retain electricity supply at the customer meter. The switching response in terms of voltage and current determine how system behaves in different switching schemes. If switch S2 closes at $t=t_{sw'}$, voltage source v2(t) connects and circuit behaviour changes. However, this sudden change does not affect inductive load current because the storage element current cannot change abruptly. Hence, current at $t=t_{sw}$ can express as:

$$i(t_{sw}) = \frac{v1(t)}{R_1+R_2}\left[1 - e^{-\frac{t}{\tau}}\right] \qquad [3.4]$$

at $t>t_{sw}$ voltage transient begins and at $t_{sw}<t\leq\infty$ system have to gain stability (steady state) from the transient. Hence, current at $t_{sw}<t\leq\infty$ is:

$$i(t) = i_{transient} + i_{steady\text{-}state}$$

$$i(t) = i(\infty) + [i(t_{sw}) - i(\infty)].e^{-(t-tsw)/\tau 2}$$

$$i(\infty) = \frac{1}{R_2}\left[\frac{\frac{V1(t)}{R1}+\frac{V2(t)}{Rst}}{\left(\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R_{st}}\right)}\right] \qquad [3.5]$$

and

$$(t) = \frac{1}{R_2}\frac{\frac{V1(t)}{R1}+\frac{V2(t)}{Rst}}{\left(\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R_{st}}\right)} + \left[\left\{\frac{v1(t)}{R_1+R_2}\right\}\left[1 - e^{-\frac{tsw}{\tau 1}}\right] - \frac{1}{R_2}\left\{\frac{\frac{V1(t)}{R1}+\frac{V2(t)}{Rst}}{\left(\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R_{st}}\right)}\right\}\left[1 - e^{-\frac{t-tsw}{\tau 2}}\right]\right] \qquad [3.6]$$

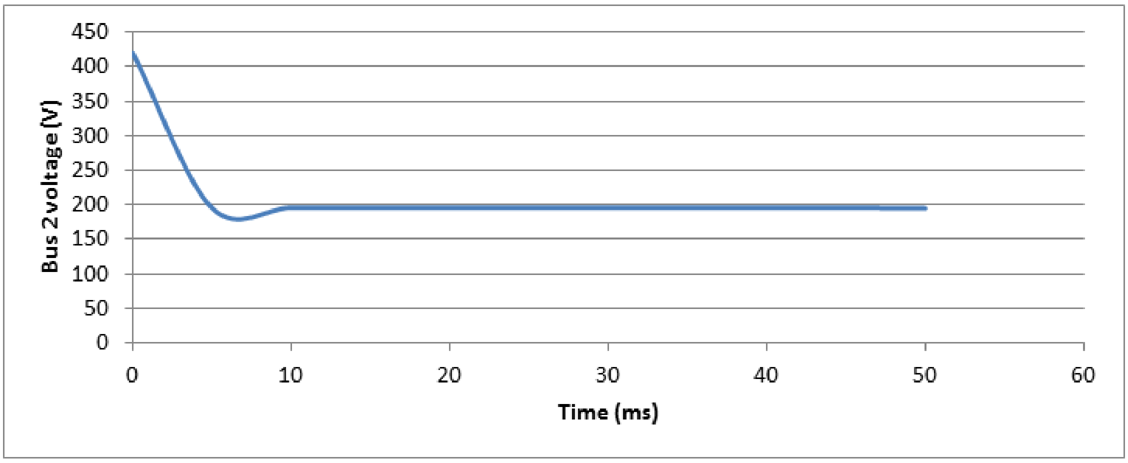


Figure 3.21: Bus 2 voltage (V) during peak demand

Figure 3.21 shows sufficient voltage instability (both in magnitudes-below -10% of rated voltage and duration and last for over 25ms) that resulted permanent failure of distribution equipment or plant. Hence system reliability will be reduced.

In order to response with peak demand, conventional electric distribution system installs diesel generator or use spinning reserve from the transmission system. Diesel generator is expensive and produces greenhouse gases. Its maintenance cost is expensive. Spinning reserve at transmission and generation system is an additional power station or temporary storage. These generators must run with minimum loads. Hence, streetlight during the day need to turn on which is completely waste of electrical energy.

This circuit has been simulated in OrCAD PSPICE for further investigation. An r.m.s voltage source has used for generator, a lithium-ion battery with variable internal resistance has used for Electric Energy Storage that charge and discharge through an AC/DC converter and DC/AC inverter respectively. The circuits and simulated results has presented in figure 3.22 to 3.26 as below.

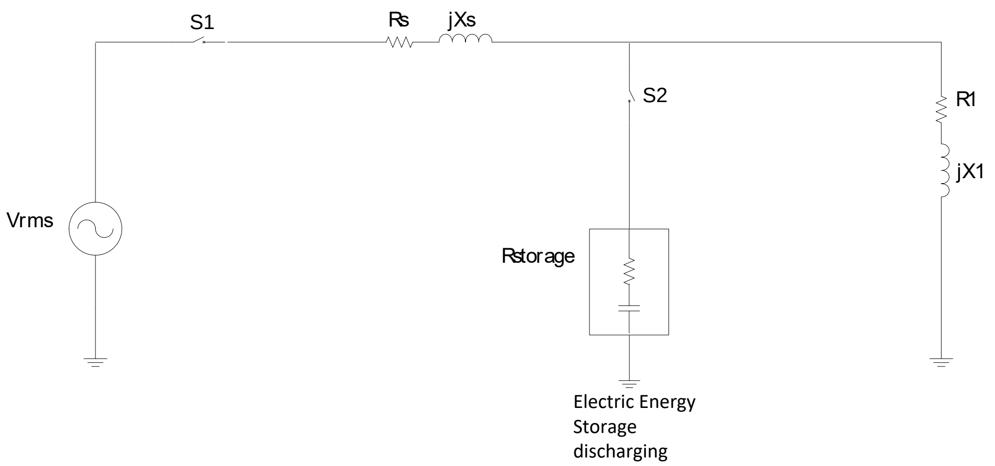


Figure 3.22: Circuit in OrCAD PSPICE for further investigation

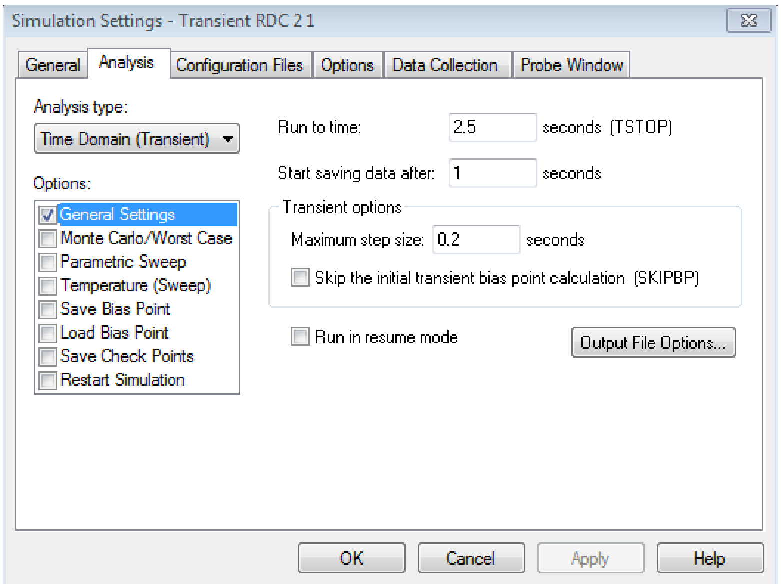
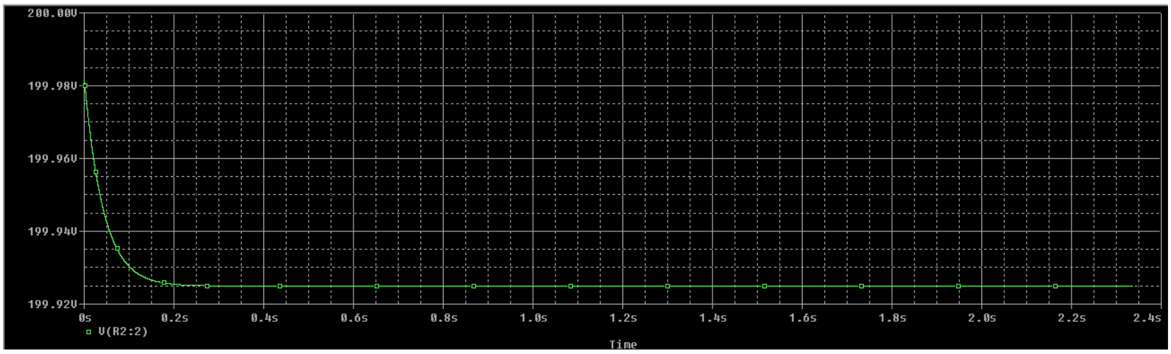


Figure 3.23: Transient settings in OrCAD PSPICE

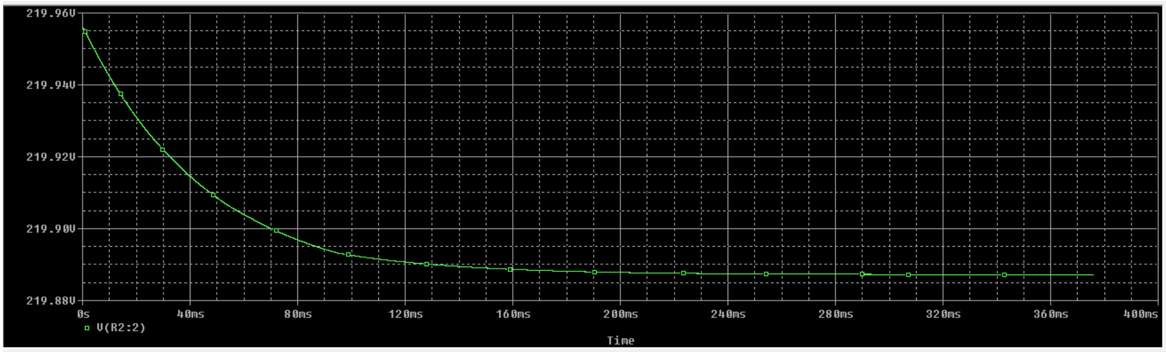
The circuit was simulated for 2.5 seconds while Photovoltaic solar panels generations are assumed to be dropped down. The voltage at Node 51 has found to 199.92 V which is 50.02% lower than rated voltage as shown in figure 3.24.



Y-axis= Voltage in V; X-axis=time in ms

Figure 3.24: Voltage response at PV generation dropped

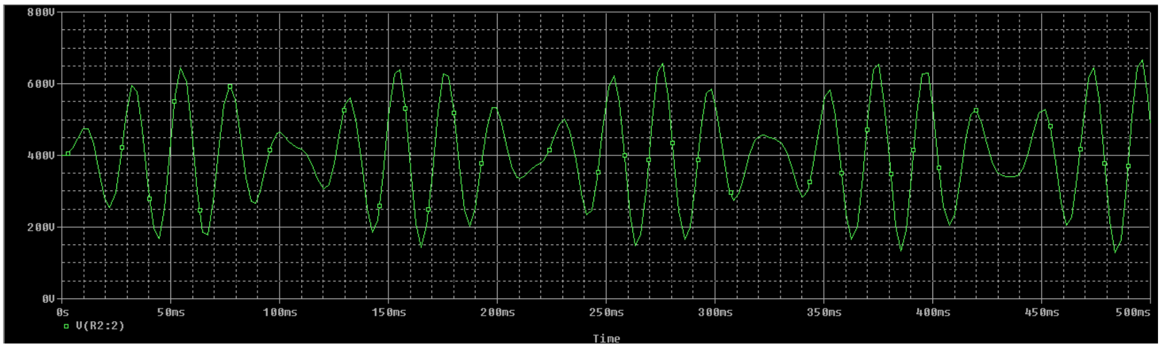
At Node 49, 50kW Electric Energy Storage was installed. The voltage at Node 49 was measured while storage charge was running out gradually and has found that voltage dropped to 45.03% from the rated voltage. However, the drop was gradual as shown in figure 3.25.



Y-axis= Voltage in V; X-axis=time in ms

Figure 3.25: Voltage drop at EES charge running out

It was assumed that PV generations are fluctuating in a cloudy day as shown in figure 3.26. The Distribution Network Operators set HEV to charge when PV generation is at maximum mode or substation load is under steady state or least demand. Therefore, due to PV generation fluctuation, HEV will switchover (on-off) in order to response with supply-demand variances. It has found that voltage fluctuation is noticeable for every one cycle as shown in figure below. The voltage magnitude and its fluctuation is noticeable. If it sustains for more that 25ms, plant failure occurs or protective devices trips.



Y-axis= Voltage in V; X-axis=time in ms

Figure 3.26: Voltage fluctuation HEV charging on and off (assumed that PV generations are fluctuating)

3.3.2 Summary of impacts of wide-scale R&DER integration

It has been shown through an investigation in the previous sections that wide-scale R&DER integration results a supply-demand unbalance as presented in figure 3.4 to 3.11. This unbalance causes transient voltage instability not only in magnitude but in duration and frequency. It has also been shown that such transient results in equipment as well plant failure as shown in figure 3.14 and 3.26. Hence, overall equipment or plant efficiency decreased. Additionally, the experiments and investigations were identified that modifications of existing electric distribution into Smart Grid Distribution System would have impacted control and operation of the system. As a result, the reliability of the system decreased. However, R&DER provides sustainable green energy. Therefore, it is inevitable to optimally manage integrated R&DER rather than restrict it.

However, to ensure the sustainability and reliability, a novel control technique along with its algorithm would be required for optimal control and efficient operation of the SGDS. The novel control technique is to be capable of applying intelligence on sources, DPN and loads respectively. At present, loads are uncontrolled and out of monitoring. However, it has been found from aforementioned investigations that some loads must be monitored as well as remotely controlled prior to implementation any intelligence. Therefore, this research now proposes an intelligent control named Self-Healing Control using an Intelligent Power Switch. Several experiments and investigations are carried to evaluate feasibility of SHC in order to achieve optimal control and efficient operation for proposed SGDS. The following chapters demonstrate investigations and experiments for SHCA respectively.

Chapter 4: Self-Healing Control Algorithm

4.1 Introduction

Self-Healing Control (SHC) is a form of intelligent control technique that uses modern control theory together with various computer-based artificial intelligence approaches. More precisely, it is an intelligent control technique that uses state-space control, optimisation techniques such as genetic algorithm, artificial neural network algorithm, Bayesian Probability and several computing artificial intelligence approaches simultaneously. The proposed SHC, will consists of a combination of time-variant modern control (i.e.: state-space control) technique, Genetic Algorithm optimisation technique and Bayesian inference in order to analyse the reliability for the proposed Smart Grid Distribution System

One of the key objectives of SHC technique is to enhance SGDS reliability. The enhanced reliability is achieved by providing resilience in optimal control and efficient operation to the SGDS. The self-learning and self-adaptability capabilities of SHC technique provided resilience in control and operation to proposed SGDS. In self-learning process, SHC used historical events such as overvoltage or overload received through the input signals. Typical input signals are current from current transformers, voltage form potential transformers and real-time energy consumptions by smart meters, smart sensors and many more intelligent electronic devices installed across the network.

In self-adaptability process, SHC technique used optimisation technique and probability distribution in order to tune system to the next best equilibrium state (i.e.: stable-state). The stable-state included parallel operations of R&DER and NG as well as autonomous islanded operation of healthy parts of the network after successful optimisation had taken place. One of the key advantages of SHC technique was that it incorporated with existing protection and control schemes (i.e.: selectivity), Supervisory Control and Data Acquisition (SCADA), Distribution Management System (DMS) and Remote Terminal Unit (RTU).Thus the greatest resilience was achieved in order to improve reliability in optimal control and efficient operation to the system.

The following section has discussed details about Self-Healing Control technique followed by an overview of Self-Healing Control over classical control system. It has also been associated with DSO (Distribution System Operations) such as Supervisory Control and Data Acquisition (SCADA), Distribution Management system (DMS), Remote Terminal Unit (RTU) to perform switching operations for Self-Healing Control Algorithm.

4.2 Self-Healing Control: an overview and background

The classical or frequency-domain feedback control technique is based on converting a system's differential derivative to a transfer function for generating a mathematical model of the system that algebraically relates a representation of the output to a representation of the input [114]. The primary demerit of this approach is its limited applicability as it can only be applied to linear time-invariant (LTI) systems or such systems that can be approximated as appropriate.

Classical control theory is suitable for linear system. It uses mathematical model to analyse static and dynamic system behaviours. A mathematical model of a dynamic system is defined as a set of equations that represents the dynamics of the system accurately or at least fairly well. However, a mathematical model is not unique to a given system. A system may be represented in many different ways and therefore may have many mathematical models depending on one's perspective. For example, in optimal control problems, it is advantageous to use State-space representations. On the other hand, for the transient-response or frequency-response analysis of single-input single output (SISO), linear time-invariant (LTI) systems, the transfer function representation may be more relevant than any other. The dynamics of many systems may be described in terms of differential equations. Such differential equations may be obtained by using physical laws governing a particular system, for example, Faraday's law for electromagnetic induction, Fourier series for waveform and harmonic analysis and so on. By all means, deriving reasonable mathematical models is the most important part of the entire analysis of the classical control system.

Additionally, in obtaining a mathematical model, we must make a compromise between the simplicity of the model and the accuracy of the result of the analysis. In deriving a reasonably simplified mathematical model, we frequently find it necessary to ignore certain inherent physical properties of the system for example to analyse real and reactive power flow in a generator-motor model, line resistance always been ignored. In particular, if a linear lumped-parameter mathematical model (that is, one employing ordinary differential equations) is desired, it is always necessary to ignore certain nonlinearities and distributed parameters that may be present in the physical system. If the effects that these ignored properties have on the response are small, good agreements will be obtained between the results of the analysis of a mathematical model and the results of the experimental study of the physical system.

In general, in solving a new problem, it is desirable to build a simplified model so that we can get a general feeling for the solution. A more complete mathematical model may then be built and used for a more accurate analysis. We must be well aware of the fact that a linear lumped-parameter model, which may be valid in low-frequency operations, may not be valid at sufficiently high frequencies since the neglected property of distributed parameters may become an important factor in the dynamic behaviour of the system. For example, the switching losses may be neglected in low-frequency system, but it becomes an important property of the system at high frequencies. (For the case where a mathematical model involves considerable errors, robust control theory may be applied).

Intelligent Control technique on the other hand uses modern time-variant control system including computer-based artificial intelligence approaches that considers both constraint and unconstraint variables. Thus it is suitable for both linear and non-linear system with or without any governing mathematical model. Since electric power system is a non-linear system and its dynamic include both constraint and unconstraint variable, intelligent control technique was found as most appropriate for demonstrating various static and dynamic linear and non-linear time-invariant and time-variant characteristics of the proposed Smart Grid Distribution System.

However, intelligent control technique has uncountable numbers of form based on applications and research area. Thus this research outlined intelligent control in terms of Self-Healing Control technique for proposed Smart Grid Distribution System. As defined the SHC technique in section 4.1, Self-Healing Control is an automatic restoration method that observes disturbances in real-time, spontaneously tunes system to a desire state by controlling disturbances, bounds uncertainties in order to prevents system from anomaly and automatically restores system to a stable condition (e.g.: from transient-state to steady-state) with or without optimisation network and its assets as appropriate.

Moreover, SHC technique uses advanced robust control theory whose approach is to design robust controllers (e.g.: SH Controller) explicitly deals with uncertainty. To design a robust controller, SH Controller uses Digital Controller which has embedded Digital Signal Processor. The key issue with SH Controller is uncertainty or disturbance and how the SH Controller can deal with this problem. There is uncertainty in the model of the plant (feeder, laterals and components). There are disturbances that occur in the plant system (entire SGDS including substation, SCADA, RTU). Also there is error which is read on the sensor (CT/PT/PMU) inputs. Each of these uncertainties can have an additive or multiplicative component. In the contrary, SH Controller seeks to bound the uncertainty rather than express it in the form of a probability distribution. Given a bound on the uncertainty, the control can deliver results that meet the control system requirements in all cases. Therefore, SHC technique might be stated as a worst-case analysis (i.e: worst case circuit analysis) method rather than a typical case method.

In addition, SHC technique categorises standby, continuous, non-critical, critical, sensitive and emergency loads by interacting with Smart Meter, AMI, Smart Sensor and Smart Socket. Interactive software in SH Controller interfaces both digital controller and digital signal processor in order to maintain accuracy and sensitivity of the system. Interactive software also enables SHC to incorporate with SCADA and RTU. SHC assessment methods i.e. adaptive islanding, optimisation, reconfiguration and restoration play the key role to enable incorporation with SCADA and RTU. Additionally, SHC technique predicts system voltage magnitude at each node at a specified loading condition. The key objective of SHC technique is to achieve system voltage is equal to the node voltages at each node. The system resilience is achieved by implementing interactive software in SH Controller. In programming, set of specified instructions and commands are written and implemented by the controller. However, SH Controller rearrange program loops in order to control system under any circumstances and protect from permanent failure or equipment damage. One of the significant features of SHC is to provide resilience to the system. The resilience for the SGDS is achieved by providing robustness to the system, implementing advanced control techniques and optimisation techniques.

Moreover, one of the key objectives of SHC technique is to improve system reliability for SGDS. This is described in reconfiguration of highly meshed transmission system in various literatures. Reconfiguration of laterals and feeders is directly linked with reliability of the system. A successful reconfiguration enables automatic service restoration in conventional electric distribution system. However, reconfiguration in a single-loop radial circuit (as shown in figure 3.1) is not applicable due to its physical model. Therefore, the future distribution system reliability will be measured in terms of SHC technique in this chapter.

Advancement of modern sensor and actuator, advanced control and modern optimisation theory and computer-based system analysis enable Self-Healing Control technique for power system. The following section has discussed details about proposed Self-Healing Control technique to clarify its function into proposed Smart Grid Distribution System to achieve optimal control and efficient operation.

4.3: Operation of Self-Healing Control

As discussed, Self-Healing Control technique has been developed as a multi-agent system combining state-space control system, Genetic Algorithm optimisation technique and Bayesian probability for proposed Smart Grid Distribution System. As consequences, voltage instability has considered as a disturbance for proposed SGDS. Figure 4-1 shows a simplified Self-Healing Control technique block diagram where green blocks would be demonstrated in this research for reliability analysis. Details of this block diagram is followed throughout this and next chapter. Eventually, a Self-Healing Control Algorithm will be proposed for proposed SGDS in terms of optimal control and efficient operation by optimising voltage profile of the proposed nodes N49 to N55. The

SHCA would be presented as a centralised control algorithm in chapter 5 in order to justify its validity by means of Intelligent Power Switch

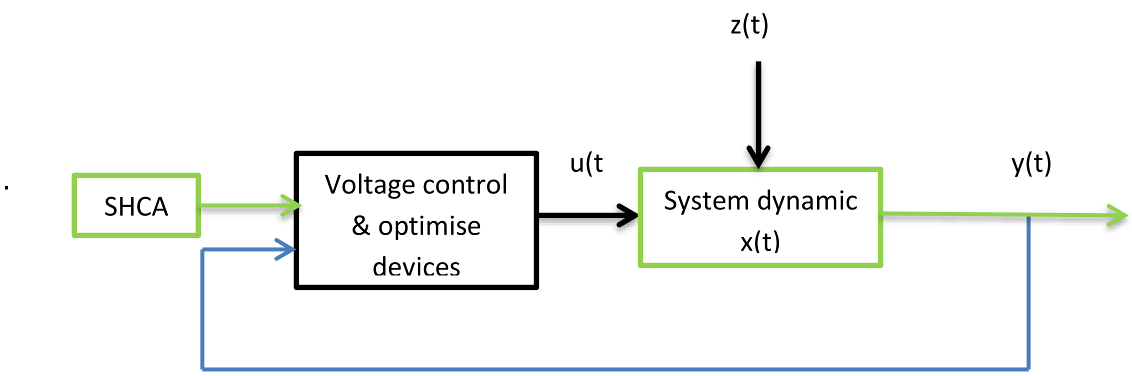


Figure 4-1: Simplified block diagram of Self-Healing Control technique

SHCA is the Self-Healing Control Algorithm

x(t) is the system dynamic

u(t) is the control signal

y(t) is the output signal and

z(t) is the disturbances.

4.3.1 Self-Healing Control system in state-space

State-space control concerns with input variables, output variables and state variables. The state variables and the system state settings are quite significant to formulate for formulating a system model [115]. The state variables are the minimum set of linearly independent system variables that uniquely define the system state [116]. A system is static when its state variables are time invariant and dynamic when its state variables are functions of time. The state of any system is the minimum set of state variables by which the knowledge of these variables at $t=t_0$ along with the knowledge of the input for $t \geq t_0$, completely determines the behaviour of the system any time $t \geq t_0$ [117]. The system state delineates operations of the system. Generally, the power flow solution in SGDS predicts the operational state of the electrical network subject to a specified loading condition. The result of real and reactive power flow is the voltage magnitudes and angles at each of the SGDS nodes. These nodes, hence bus voltage magnitudes and angles are defined as the state variables (or independent variables) [118]. The voltage and angle magnitudes allow SGDS to determine real power flows, reactive power flows, voltage drops, current flows and power losses.

If nodes voltages are expressed as a vector x(t) = [v_1, v_2, v_3,……….v_n and δ_1, δ_2, δ_3 ……. δ_n]^T where x(t) is referred to state vector, input voltage u(t)= v_s, output variables y(t)=v_0, and u(t) is the control signal that affects the system to achieve a desired behaviour, y(t) is the output signal that serves to assess whether or not the control achieved the desired goal Thus state-space equation for SGDS can be written as:

$$\dot{x} = F(x, u) \qquad [4-1(a)]$$

$$y = G(x, u) \qquad [4-1(b)]$$

for non-linear analysis of SGDS and

$$\dot{x} = Ax + Bu \qquad [4-2(a)]$$

$$y = Cx + Du \qquad [4-2(b)]$$

for linear analysis of SGDS

Linear system has one equilibrium point refer to the steady-state point (a stationary point) whereas non-liner system has more than an equilibrium points and refer to the optimum points (more than one stationary point).

Where

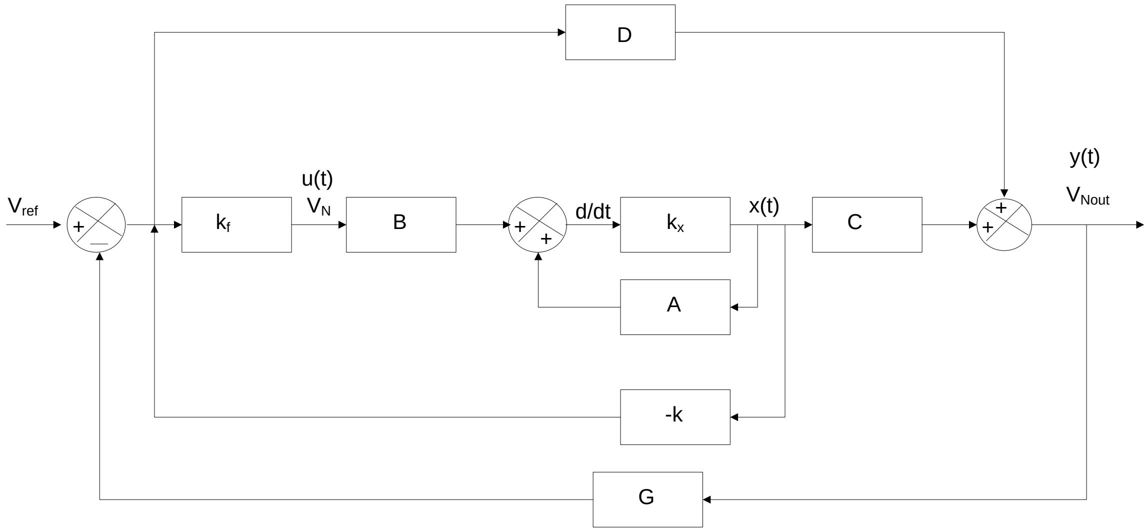
A = system matrix

B = input matrix

C = output matrix

D = feedforward matrix

Thus, the state-space control can be modelled as shown in figure 4-2. The proposed control block shaped a closed loop state-variable control system. Hence, automatic control can be evaluated from the block.



Reference signal r(t) = V_{ref}, Output signal y(t) = $V_{N\text{-}out}$

Figure 4-2: Self-Healing Control model in state-space

The input matrix, B^T is a set of sensor data. Smart sensors data form this matrix and exert through control devices. The output matrix C^T is a set of actuator outputs and feed to comparator reference port/(s). The feedforward matrix D^T is the result of interaction of reference signals of comparator port and feedback sensor signals. The system matrix A^T is the systems' self-learning and self-diagnosis capability that is a set of either Internet of Things (IoT) data or historical data. State vector is a vector whose elements are state vector such as bus and node voltages.

The state-space equation of SGDS response can develop in first-order differential equations as follow:

$$\frac{dx_1}{dt} = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \cdots + a_{1n}x_n + b_{11}u_1 + b_{12}u_2 + \cdots + b_{1m}u_m$$

$$\frac{dx_2}{dt} = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \cdots + a_{2n}x_n + b_{21}u_1 + b_{22}u_2 + \cdots + b_{2m}u_m$$

$$\frac{\mathrm{d}x_3}{dt} = a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + \cdots + a_{3n}x_n + b_{31}u_1 + b_{32}u_2 + \cdots + b_{3m}u_m$$

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$$\frac{dx_n}{dt} = a_{n1}x_1 + a_{n2}x_2 + a_{n3}x_3 + \cdots + a_{nn}x_n + b_{n1}u_1 + b_{n2}u_2 + \cdots + b_{nm}u_m \qquad [4-3]$$

These sets of equations can be converted into matrix equation as follows:

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} a11 & a12 \ldots\ldots & a1n \\ a21 & a22 \ldots\ldots & a2n \\ \cdot & \vdots & \vdots \\ \cdot & \cdot & \cdot \\ \vdots & \cdot & \cdot \\ an1 & a2n & ann \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} b11 & \cdots & b1m \\ \vdots & \ddots & \vdots \\ bn1 & \cdots & bnm \end{bmatrix} . \begin{bmatrix} u_1 \\ u_2 \\ \cdot \\ \vdots \\ u_n \end{bmatrix} \qquad [4-4]$$

Where B (b11, b12, b31……bnn) can be found from IEDs (i.e.: SHCPS) data/state information around the network that enable controller to distribute sources-loads in order to achieve desire C (i.e.: c11, c12, c13….cnn) state. Genetic Algorithm ensures the best next C state for every B distribution. A is the IoT and sensor-measured values (i.e.: voltage and current) which is used by controller for self-learning and self-diagnosis capabilities. The following section demonstrated how B and C could be achieved under different source and load conditions. D is the comparator outputs with respect to sensor and IoTs. Thus, controller controls its tuning duration to provide best steady-state condition of the SGDS.

The concept of observability and controllability play a significant role in the design of state-space control system. In fact, the conditions of observability and controllability govern the existence of an absolute solution to the control system design problem. ''A system is completely observable if and only if there exists a finite time T such that the initial state x(0) can be determined from the sensor and IoT data (i.e.: observation history) y(t) given the control u(t), $0 \leq t \leq T$''. A system is completely controllable if there exists an unconstrained control u(t) that can transfer any initial state x(t_0) to any other desired location x(t) in a finite time, $t_0 \leq t \leq T$ [74].

4.3.1.1 Controllability

Consider the state-space equation for the proposed SGDS.

$$\dot{x(t)} = Ax(t) + Bu(t) \qquad [4-5]$$

Where,

x(t) is the state vector whose variables are time-variant

u(t) is the time-variant control signal

A is the system matrix that is an eigenvalues defines the roots of the characteristic equation

B is the input matrix whose variables are time-variant

The control signal governs the control laws for proposed system. If the control system is closed-loop, the relationship between control signal u(t) and the state-feedback gain matrix, k can be expressed as:

$$u(t) = -kx(t) \qquad [4-6]$$

The control signal u(t) is determined by instantaneous state from the state-feedback gain matrix, -k and state-variable x(t). In controllability, it has assumed that all state variables were available to feedback and all control signals were unconstrained. Therefore, it has assumed that equation [4-5] was state controllable at any time $t \geq t_0$ as it was possible to construct an unconstraint control signal that has transferred from an initial state to a final state in finite time interval$t_0 \leq t \leq T$. The controllability has developed by assuming a reference signal r(t) and an output signal y(t) as shown in figure [4-1].

The objective of designing controllability was to maintain a constant output signal for a specific input signal. However, the disturbances such as photovoltaic solar panel generation fluctuation, state-of-charge of electric energy storage, plug-in characteristics of hybrid electric vehicle were deviating output from equilibrium point (or points). The state-feedback matrix was used in order to reinstate output signal back to specified equilibrium point (or points). Solving equation [4-1] for control signal, the state-space equation can be expressed as:

$$\dot{x(t)} = Ax(t) - Bkx(t)$$

$$or, \frac{dx(t)}{dt} = Ax(t) - Bkx(t)$$

$$or, \quad \int_{x(t_0)}^{x(T)} \frac{dx(t)}{x(t)} = (A - kB) \int_{t_0}^{T} dt$$

$$or, [ln\{x(T)\} - ln\{x(t_0\}] = (A - kB)[T - t_0]$$

$$or, ln\left[\frac{x(T)}{x(t_0}\right] = (A - kB)[T - t_0]$$

$$or, x(T) = x(t_0)e^{-(A-kB)[T-t_0]} \qquad [4-7]$$

Here, $x(t_0)$ is the initial state caused by an external disturbance. The voltage stability and transient-response of the system was determined from A-kB matrix (eigenvalue matrix) as system states were known. Thus state-space representation of figure [4-1] was modified with control law as shown in figure [4-2].

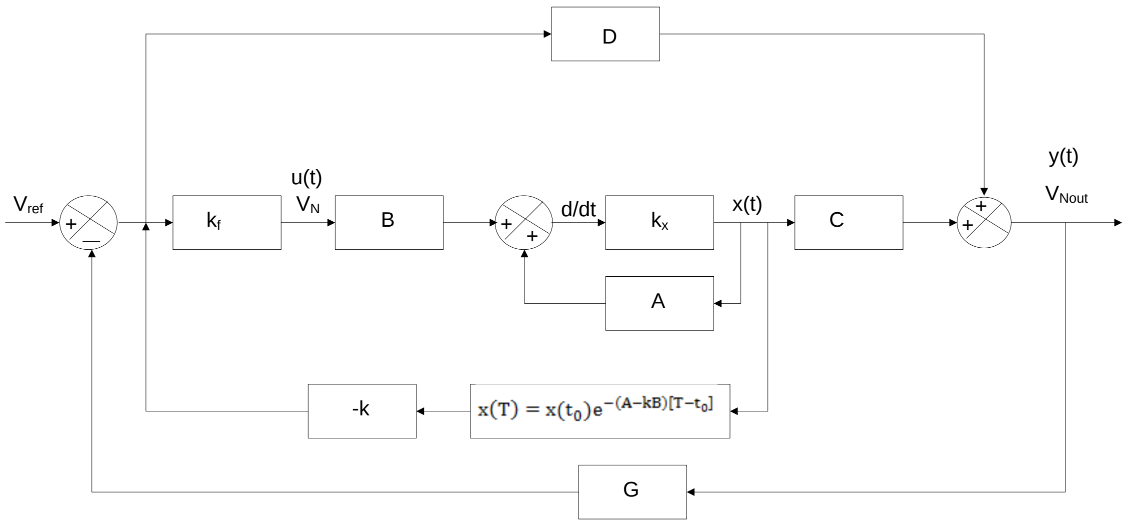

Figure 4-3: State-space controller with controllability

4.3.1.2 Observability

It is assumed that the system is linear and expressed by the following state equation:

$\dot{x(t)} = Ax(t)$

$or, y(t) = Cx(t)$

Where

x(t) is the state-variable

y(t) is the output variable

A is the system matrix and

C is the output matrix

It was investigated that whether the system is completely observable if its output variables y(t) were observable over finite time interval $t_0 \leq t \leq t_1$. The concept of observability is significant for restoring system by predicting unmeasurable output states from measurable output states. In general, when a system encountered to access to measure direct states of the output states, it becomes necessary to justify on output states in order to protect system from anomaly. The system observability function is therefore derived as:

System-state as:

$$\frac{dx(t)}{dt} = Ax(t)$$

$$or\ \frac{dx(t)}{x(t)} = Adt$$

$$or\ \int_{x(0)}^{x(t)} \frac{dx(t)}{x(t)} = \int_{t_0}^{t} Adt$$

$or\ x(t) = x(0)e^{-A(t-t_0)}$ and

Output state as:

$y(t) = Cx(t)$

$$or\ y(t) = C\left[x(0)e^{-A(t-\ t_0)}\right] \qquad [4-8]$$

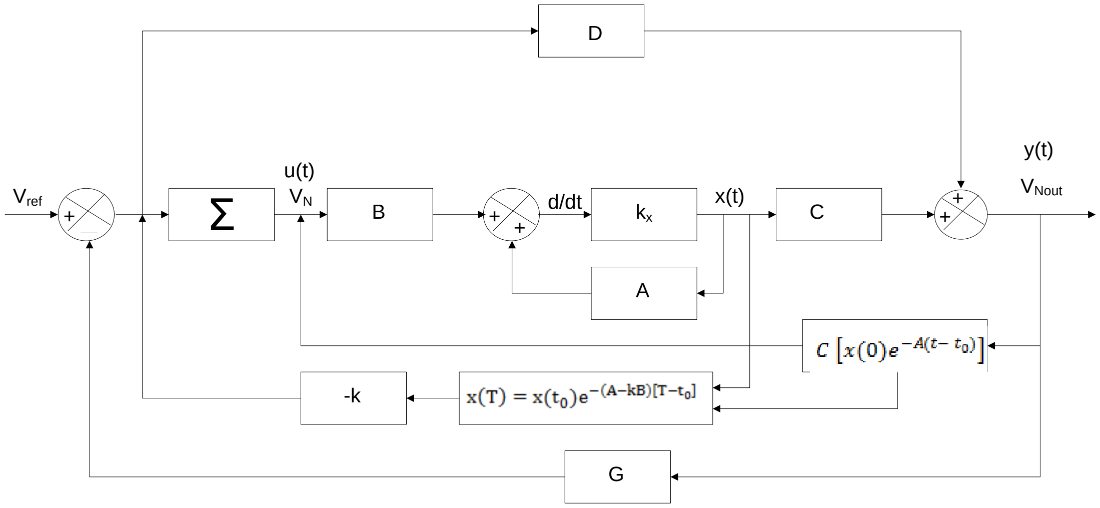

Figure 4-4: State-space control with full observer

4.3.2: Bayesian probability theorem and self-Healing Control

Bayesian probability offers a mathematical skeleton for performing hypothesis using probability. It is very often use in engineering disciplines to justify the relative validity of hypothesis for the system that deals with uncertainties in order to adjust parameters of a specific model. As Self-Healing Control for Smart Grid Distribution System mitigate uncertainty based on hypothesis, an overview of it Bayesian probability has been discussed in this section in related to Self-Healing Control.

4.3.2.1: Bayesian rule

According to the Bayesian Probability theory, assume R is the research hypothesis and S is the sensors and IEDs data, the relative fact of the hypothesis with respect to the given data can be expressed as:

$$P\left({}^{R}/_{S}\right) = \frac{P\left({}^{S}/_{R}\right).P(R)}{\sum P(S)} \qquad [4-9]$$

Where,

$P(^S/_R)$ is the likelihood function that assesses the probability of the observed data from the observer of the state-space controller

P(R) is the prior data that reflects system's prior knowledge from historical data (i.e.: voltage profile) before real time data are considered (D is the feed-forward state-vector control system model that is real time data of sensor. System matrix A, compare with D for optimum control action to be taken. P(R) is the state variables of system matrix A)

$\sum P(S)$ is the algebraic sum or integration of events functions occurred and is limit by minimal and maximum settings of sensors and controllers.

$P(^R/_S)$ is the posterior function that reflects the probability of the hypothesis after consideration of the data

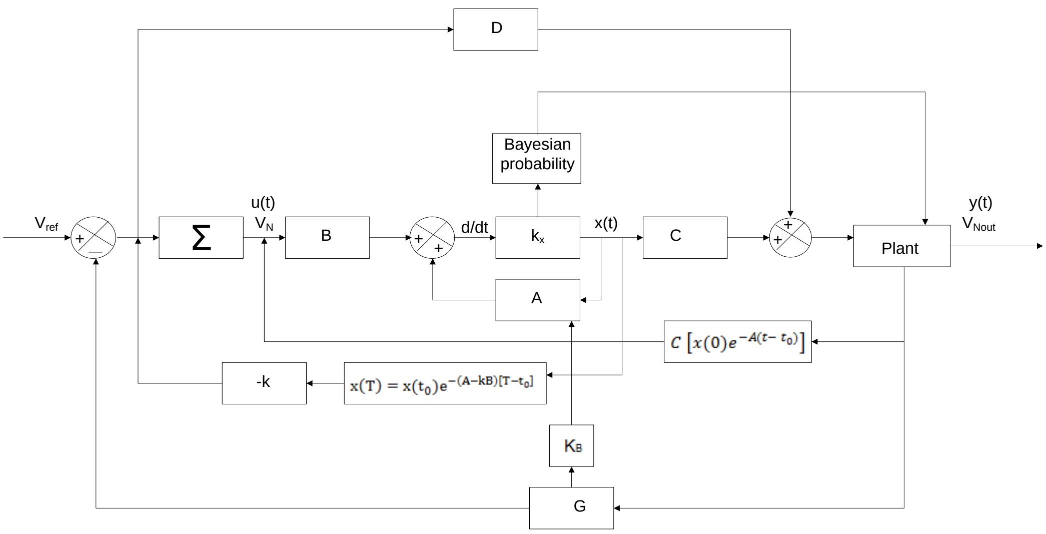

Figure 4.5: Integration of Bayesian probability into Self-Healing Control technique

Thus the Bayesian probability can be formulated as:

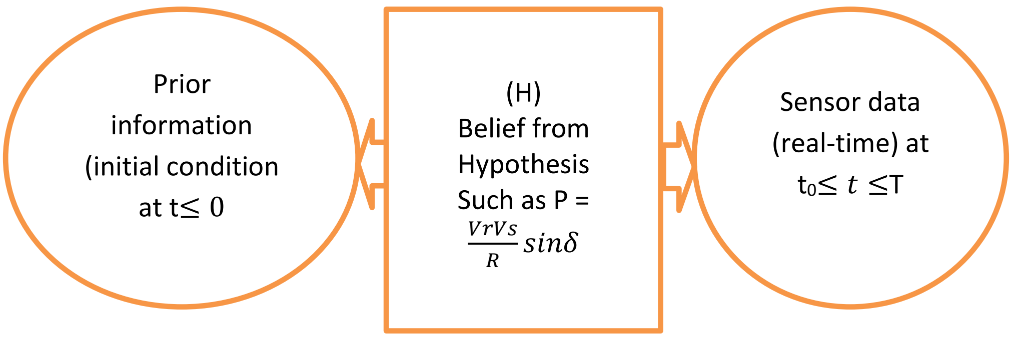

Figure 4.6: Bayesian inference for hypothesis against sensor data

Hypothesis defines that voltage stability can be gained at receiving end voltage and phase angle equal to sending end voltage and phase angle.

4.3.3 Genetic algorithm optimisation technique

Historically, electric distribution relies on automation for optimal control and efficient operation. In principle, automation technique consists of several stages from substation to customer end such as monitoring, analysis, optimisation, reconfiguration and restoration. Optimisation acts as one of the key indicators in the distribution automation for obtaining the best outcomes under given circumstances. The ultimate goal of optimisation for distribution automation is to maximise the efficiency and minimise the negative impacts of disturbances on the distribution system. Thus optimisation for SGDS can be described as the process of identifying minimum and maximum limits for optimal control and efficient operation under given circumstances for example node voltage magnitudes for voltage stability.

There is not a single optimisation technique that can solve all problems. Different optimisation techniques are suitable for different applications. This research has carried out investigation both on traditional and modern optimisation techniques for voltage profile optimisation in Smart Grid Distribution System. Linear programming (i.e.: traditional), Genetic Algorithm (GA) and Artificial Neural Network (ANN) (i.e.: modern) optimisation techniques were found as the best suit for Smart Grid distribution System. However, GA was identified as the most appropriate in particular for medium (e.g.: 11kV) and low voltage (e.g.: 0.4kV) distribution system for voltage profile optimisation and used in Self-Healing Control technique.

4.3.3.2 Application of Genetic Algorithm in proposed network

The principle of natural genetics and natural selection process govern Genetic Algorithm optimisation. Design problems that are characterised by nonconvex, discontinuous and continuous-discrete design variables are best-suited for resolving by Genetic Algorithm optimisation technique. GA uses natural genetics such as reproduction (link with –to optimise output y(t) signal), crossover (link with –to learn probability distribution for voltage optimisation) and mutation (link with control law to modify state variable x(t) = -ku(t)) as objective function in search procedure. A specific design vector for corresponding objective function plays role of fitness function in natural selection. Fitness function is the function that maximise the objective function. Usually, the relationship between objective function and the fitness function is given by:

$$F(x) = \frac{1}{1 + f(x)}$$

Where,

F(x) is the objective function

f(x) is the fitness function

The GA was implemented on single-line diagram of SGDS as shown in figure 4-7.

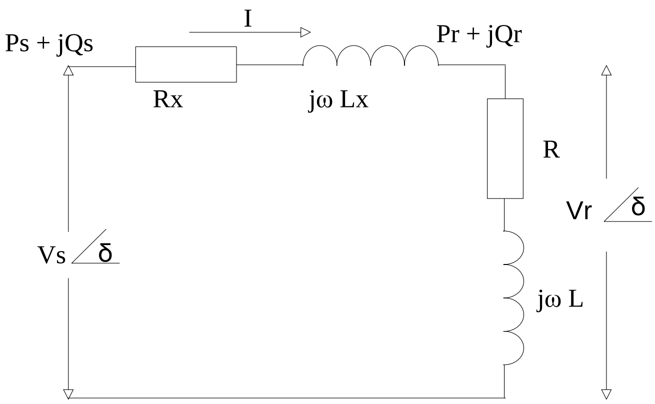

Figure 4.7: Simplified proposed SGDS

It was assumed that power flow study was the objective function, sending and receiving end voltage magnitudes were the fitness function. GA was applied to reproduce voltage profile under given circumstances such as supply-demand unbalance during PV fluctuation or HEV charging variations, to estimate voltage variations and to work out adaptive voltage magnitudes at receiving end. For real power flow study it was assumed that line X/R ratio is much more less than unity and following real power derivative was used:

For real power demand,

$$f(x) = P(x) = \frac{Vr(x).Vs(x)}{R}.sin\delta$$

For reactive power demand,

$$f(x) = Q(x) = \frac{Vr(x).Vs(x)}{R}.(1 - cos\delta)$$

Where,

P(x) is the real power

Vr(x) is the voltage at receiving end

Vs(x) is the voltage at sending end

X is the line reactance and

δ is the phase angle (angle between voltage and current waveform)

The fitness function was analysed in order to formulate optimal control and efficient operation condition for proposed network. Thus F(x) is the optimal control and efficient operation function (i.e.: objective function).

The constraints were applied for proposed network as follows:

$$V_s = 400 \qquad [4-10]$$

$$440 \leq V_r \leq 360 \qquad [4-11]$$

$$a_1 V_s + b_2 V_r \geq 798 \qquad [4-12]$$

$$Objective\ function, \quad F(x) = plant\ function = y(t) = \begin{cases} optimal\ control \\ efficient\ operation \end{cases}$$

Therefore, the relationship between objective function and fitness function for proposed network can be given as:

For real power demand,

$$y(t) = \frac{1}{1 + \frac{V_s V_r}{X}.sin\delta} \qquad [4-13]$$

For reactive power demand,

$$y(t) = \frac{1}{1 + \frac{V_s V_r}{X}.(1 - cos\delta)} \qquad [4-14]$$

The sending end voltage V_s and line reactance X remains unchanged in the network. Hence, optimal control and efficient operation for proposed network can be estimated once maximum and minimum node voltage magnitudes obtained. Figure 4-8 represents SHC with GA optimisation for such node voltage optimisation.

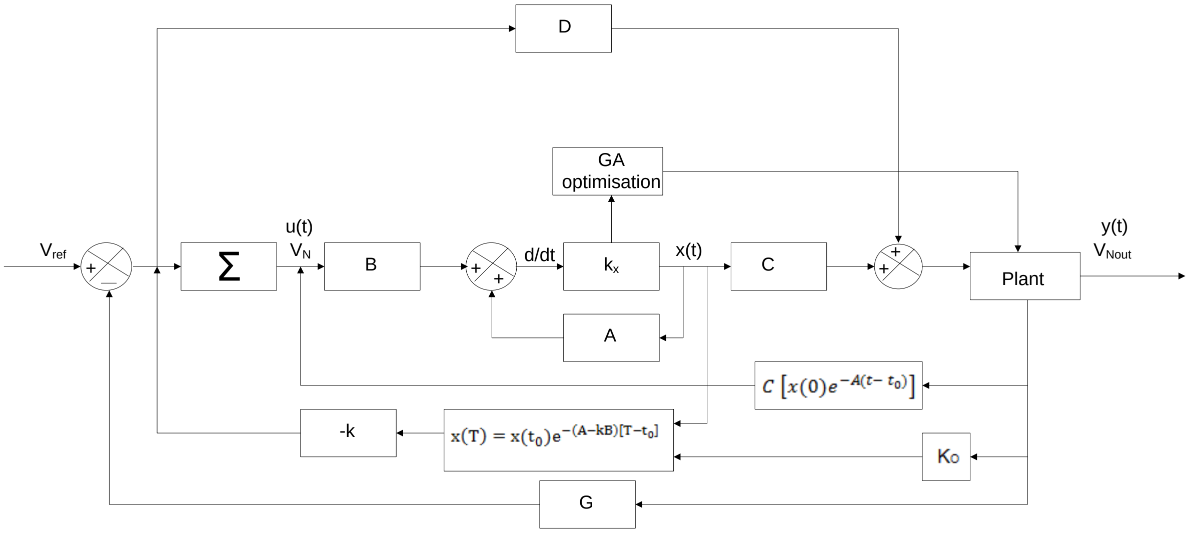

Figure 4.8: Self-Healing Control with GA optimisation

4.4: Self-Healing Control Algorithm for voltage profile optimisation

The theory of Self-Healing Control was developed in the previous section. It was shown that intelligent control for Self-Healing Control technique was achieved by integrating Bayesian probability, Genetic algorithm optimisation technique within the state-space modern control system. Thus Self-Healing Control Algorithm can now be modelled for proposed Smart Grid Distribution System to optimise voltage profile. Eventually, the Self-Healing Control Algorithm for voltage profile optimisation can be

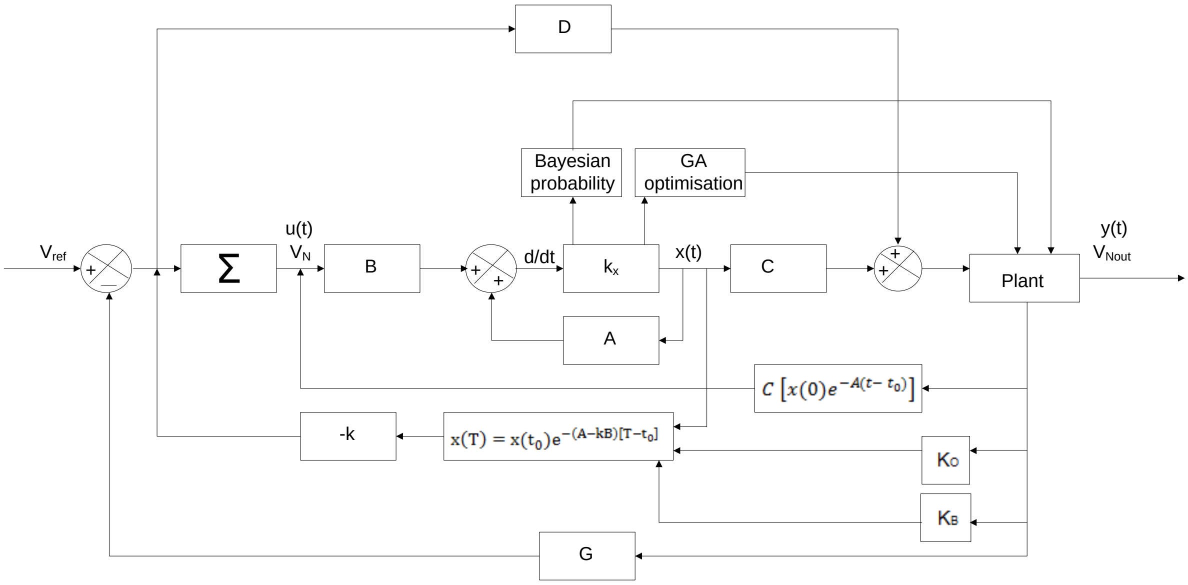

Figure 4.9: SHC with BP, GA and state-space model

Let us place SGDS into this control block for further investigation.

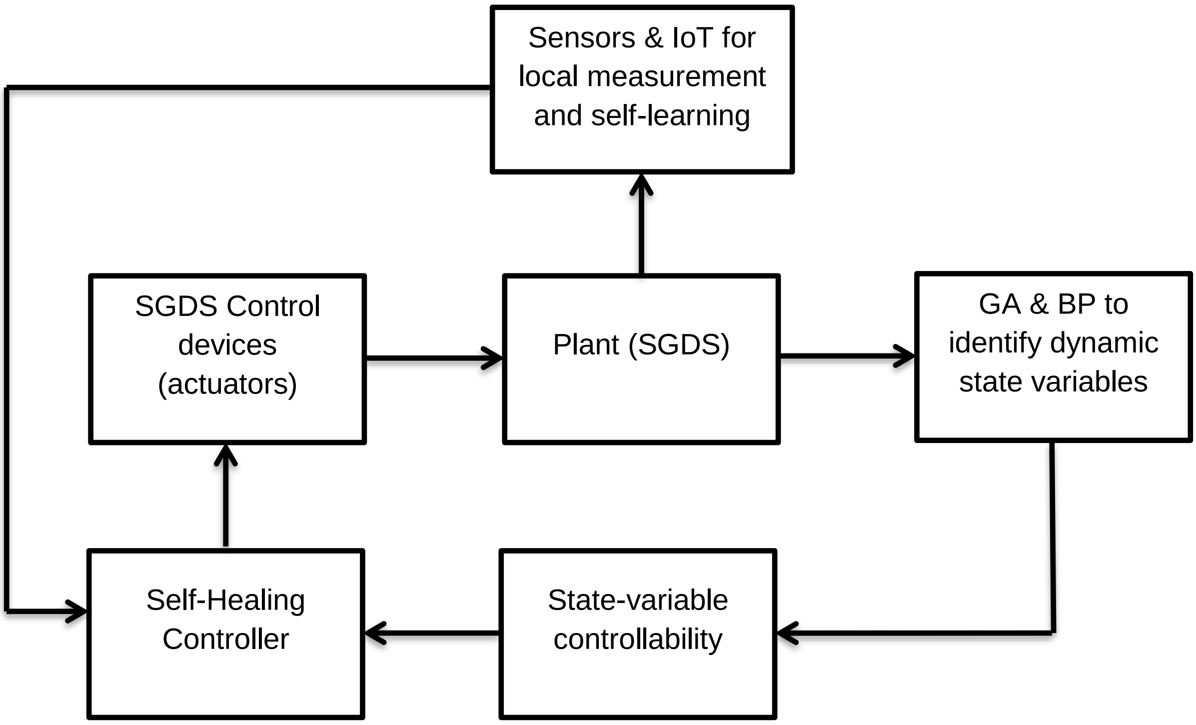

Figure 4.10: SHC in flow/block diagram

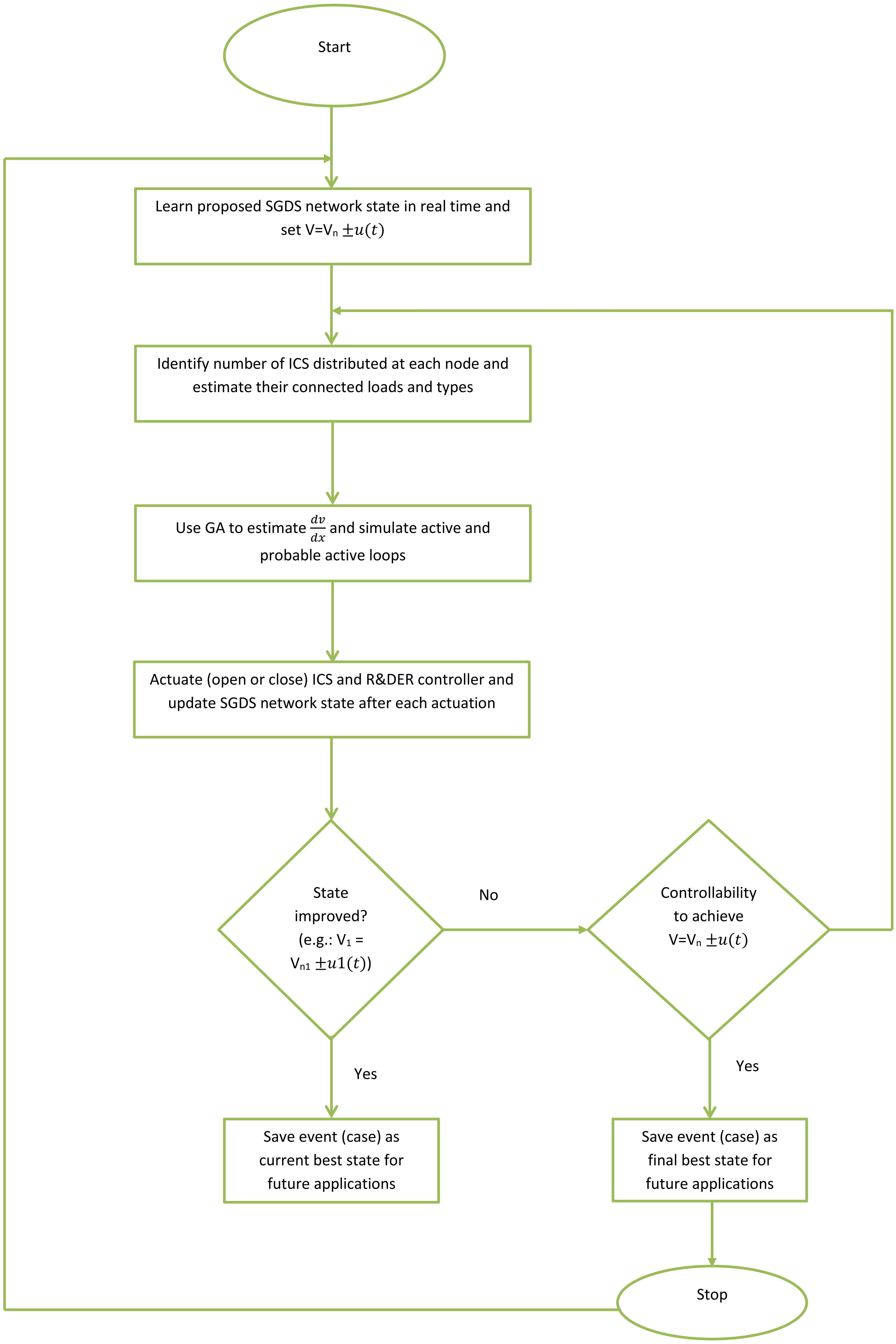

Figure 4-11: Self-Healing Control Algorithm

4.5: Summary of SHCA

At the end, it was developed that Self-Healing Control technique implement intelligent control approaches for proposed SGDS. The multi-agent system consists of state-space control, Bayesian probability and Genetic Algorithm worked for unidirectional locus that is the optimal control and efficient operation. They all intended to act on voltage profile so that algorithm can obtain the best optimised profile while retaining reliability at a constant level.

System matrix consists of critical values of node voltage magnitudes, real and reactive power demand. Critical by means of maxima, minima, withstand, voltage immunity values and so on. Bayesian rule provides probability of supply-demand probability whereas Genetic Algorithm identifies the best equilibrium point(s) for the radial feeder node voltage(s) from the Bayesian distribution. Integration of state-space system matrix, Bayesian rule and Genetic Algorithm forms the Self-Healing Control techniques and provides intelligence to tune SGDS to the best or nearest equilibrium point(s). In addition, it can also summarise that SHC not only optimises supply-demand proportion but also optimises the number of ICPS required for a specific node. This provides SGDS resilience in operation and controls its assets and network. It bounds uncertainties to protect system from anomaly.

Additionally, GA deals voltage constraints, Bayesian probability distributes possible node voltages both from constraints and unconstraint and time-variant state-space control signal for desire output signal. These operations take place simultaneously. Thus SHCA can be called as an intelligent control technique. State-space representation by means of controllability and observability provide a skeleton for analysing voltage profile optimisation for SGDS. Bayesian probability enhances real and reactive power distribution along with R&DER distribution for voltage profile optimisation. Optimisation deals both constraint and unconstrained variable in power system. Withstand voltage and voltage immunity for equipment is constraint variables. Disturbances are unconstrained variables in power system. Traditional control and protection equipment trips-off for controlling networks from unconstrained variables such as line to ground faults, arc, surges and overload.

However, optimisation technique optimises network operation and minimise trips-off or find alternative solutions rather that outage such as islanding, autonomous operation, power flow optimisation and so on. Intelligent Control approaches for SGDS with multi-dimensional control and operation techniques established SHC as a unique solution for voltage profile optimisation in order to provide optimal control and efficient operation in SGDS networks.

In the contrary, it is important to outline the differences between SHC and ADA. As mentioned in literature survey, ADA has been using for distribution automation, protection and control for over a decade. ADA uses conventional power flow study to implement automation, protection and control in order to enhance energy and network management of electric distribution system while SHC uses multidirectional power flow with R&DER integration within SGDS. The concept of ADA was motivated by the evolution of information and communication technology. However, SHC was motivated from the technical drawbacks for wide-scale R&DER integration, multi-directional power flow, microgrid and nanogrid concepts for the future electricity power network (i.e.: Smart Grid). ADA uses various existing technologies to enhance the operating performance, energy management and control of electric distribution system whereas SHC used advanced robust control theory, continuously improving intelligence and various probability and optimisation theory to upgrade existing distribution system to an active distribution system, smart energy management, and optimum control of the SGDS. ADA defines as a technology to enable remote monitoring, coordination and operation of electric distribution components that never considered R&DER within the network. SHC on the other hand not only monitor and control SGDS but also predict an optimum R&DER integration for smart energy monitoring, real-time monitoring, and enhanced controlled and reliability to the SGDS. Eventually, several case studies have been investigated for optimal control and efficient operation in SGDS network and two experiments are presented in the following chapter.

Chapter 5: Implementation of Self-Healing Control Algorithm (SHCA)

5.1 Introduction

The SHCA was implemented on the secondary distribution system (i.e.: 400V line-line system) and demonstrated in this chapter. In order to implement SHCA, intelligent power switches were installed across the controlled load terminals. Since SHCA tunes R&DER, sources and controlled loads controllers based on state of the SGDS, the results were found as expected and aimed according to this thesis aim and objectives. The reasons of SGDS were not working without SHCA are conventional power flow study, real and reactive power demands, power quality analysis and energy management and control operations in traditional distribution systems. Historically, traditional distribution systems were designed for one-way power flow and most of its demands were real power as demonstrated in chapter 3 and in research literature. Thus distribution equipment such as circuit breaker, reclosing switches and powergui block shows simulation errors in MATLAB Simulink. This is true for practical applications due to nature of secondary distribution feeder and its assets. Additionally, R&DER controllers and IPS were not functioning with powergui block parameters. This means the SGDS required an advanced control algorithm such proposed SHCA which was the main aim of this thesis. Thus the contribution to knowledge is made in developing a novel SHCA.

Additionally, the main objective of SHCA was to improve reliability of proposed SGDS by means of optimal control and efficient operation that has been presented with sufficient experimental and analytical results. It will also been shown that SHCA not only optimises the control and operation but also optimises the number of Intelligent Power Switches required for each proposed SGDS or node by considering reliability, costs, power losses and annual load growth. The following sections have been organised by carrying out experiments presented in chapter 3 equipped with IPS and implemented SHCA on the proposed SGDS. The results are critically analysed for such a system in terms of real-world challenges, opportunities and applications.

5.2: Experiment 1: Generator-Motor-R&DER model for proposed SGDS

Figure 5.1 shows a single-line diagram simplified from proposed SGDS presented in chapter-3 figure 3.1and 3.2. Since the traditional electric distribution system has now been changed from consumer to prosumer, a Generator-Motor model is no longer valid for proposed SGDS. Therefore, Generator-Motor model has transformed into Generator-Motor-R&DER model as shown in figure 5-1.

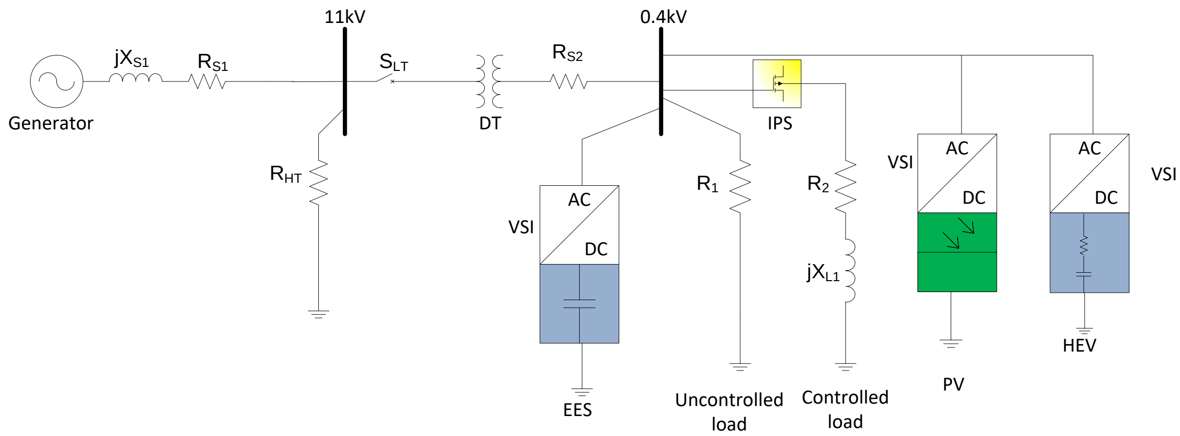

Figure 5.1: Generator-R&DER-Motor model of proposed SGDS

The proposed system consists of an 11kV generator, an 11kV bus, a 11kV/0.4kV distribution transformer and a secondary distribution system connected with 0.4kV low voltage feeder. The Electric Energy Storage and Photovoltaic solar panel were integrated on 0.4kV feeder. A controlled resistive-inductive (R-L) load and an uncontrolled resistive (R) load were connected that demands real and reactive power to the sources. PV and EES were connected with feeder through voltage source inverters (VSI). Controlled load was connected with an Intelligent Power Switch (IPS). The power was fed from a 10MVA generator through an 11kV/0.4kV distribution transformer. The distribution transformer was rated as 630kVA two-winding transformer with 5% X/R ratio. The 11kV system is simulated by a high-tension resistive (R_{HT}) load. The high-tension end facilitated to isolate by a low-tension switch (S_{LT}). It has been assumed that a real-time communication has been established among Self-Healing Controller (i.e.: to implement SHCA), IPS, node sensors and voltage control devices.

The system was designed in such a way that EES and HEV would be charging when PV generation is at MPPT or 11kV generator is on off-peak or super off-peak demand state. The EES and HEV would be discharged at peak demand or to respond a disturbance. The IPS across water pump, central heating and other ancillary services would automatically turn on to respond to achieve supply-demand balance by SHCA. The IPS across washing machine, fridge-freezer lift, air conditioner and escalator would turn off within a pre-determined time to respond to achieve supply-demand balance by SHCA. These sound a complex engineering task that has been demonstrated in the following section with simulated results and analytical findings.

At first, the system was modelled in MATLAB Simulink as shown in figure 5-2. PV, EES and HEV were integrated into proposed SGDS in Simulink model. SHCA were implemented, IPS were optimised and installed as appropriate in the Simulink model. The first case studied about a scenario when PV was at MPPT for example 11:00 hours to 15:00 hours, EES and HEV were charging in a sunny day. According to the investigation discussed in chapter 3, section 3.6, power intended to flow in reverse direction towards the 11kV system through distribution system. However, it is impractical that power flows reverse from 0.4kV to 11kV system in Simulink model as well as in practice. Therefore, Simulink model was designed for supply-demand balance state by incorporating and implementing SHCA and IPS.

Figure 5.2 (a) shows proposed SGDS system for Generator-Motor-R&DER model by integrating photovoltaic solar system, Battery Electric Energy System and Hybrid Electric Vehicle within an existing grid-tied electric distribution system. Figure 5.2(a) was a bulk model to simulate as it crossed one-thousand nodes/connections which was incompatible for student version of Simulink. Thus, the system was converted into a simplified Generator-Motor-R&DER model by creating subsystems and presented in figure 5.2(b) without SHCA and 5.2(c) with SHCA respectively.

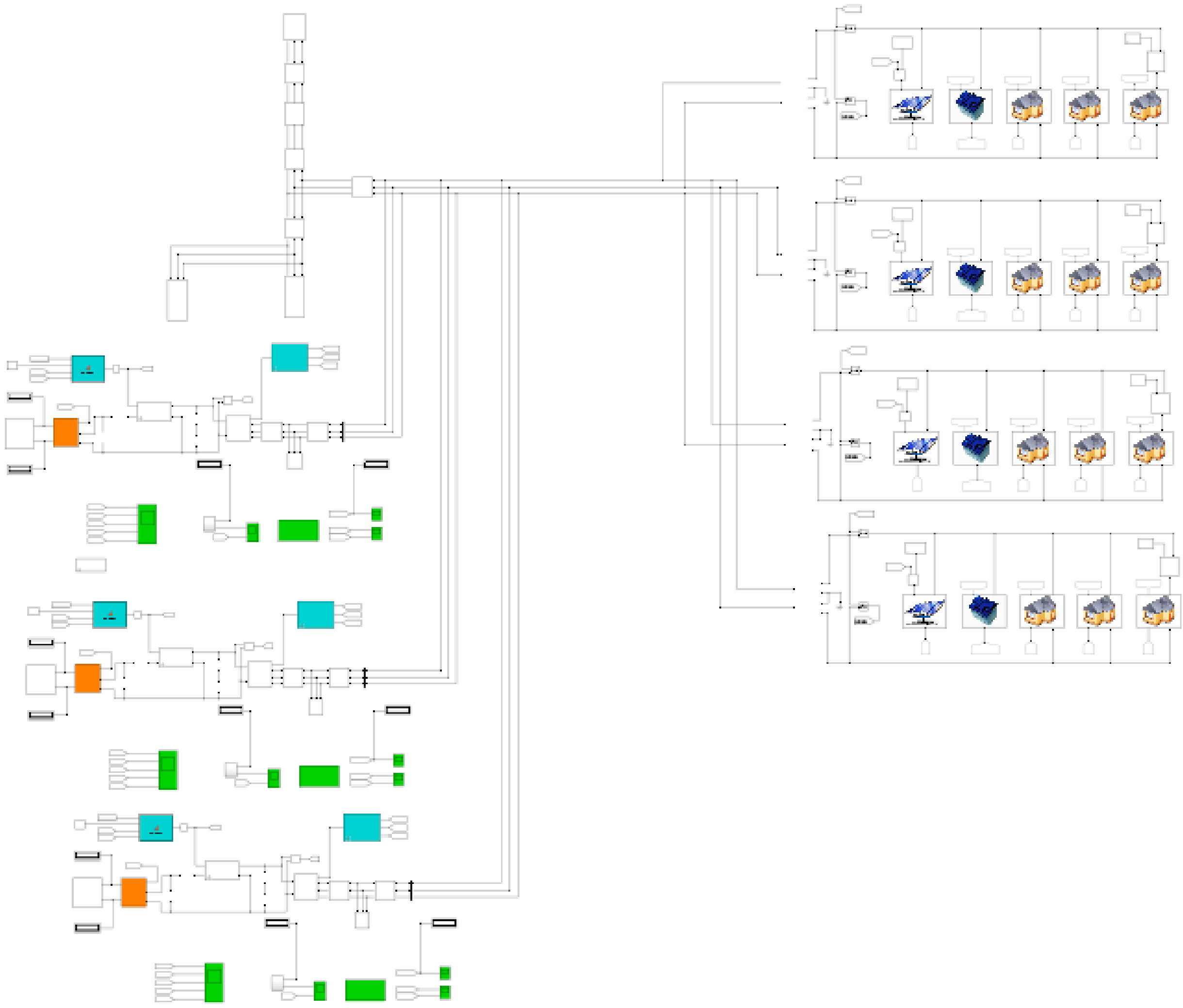

Figure 5.2 (a): Proposed SGDS system for Generator-Motor-DR&DER model in MATLAB Simulink

Figure below shows MATLAB Simulink model of the proposed SGDS including voltage control devices and IPS without SHCA. It shows that IPS that is connected across controlled loads are open-circuited as no tuning controllers are available.

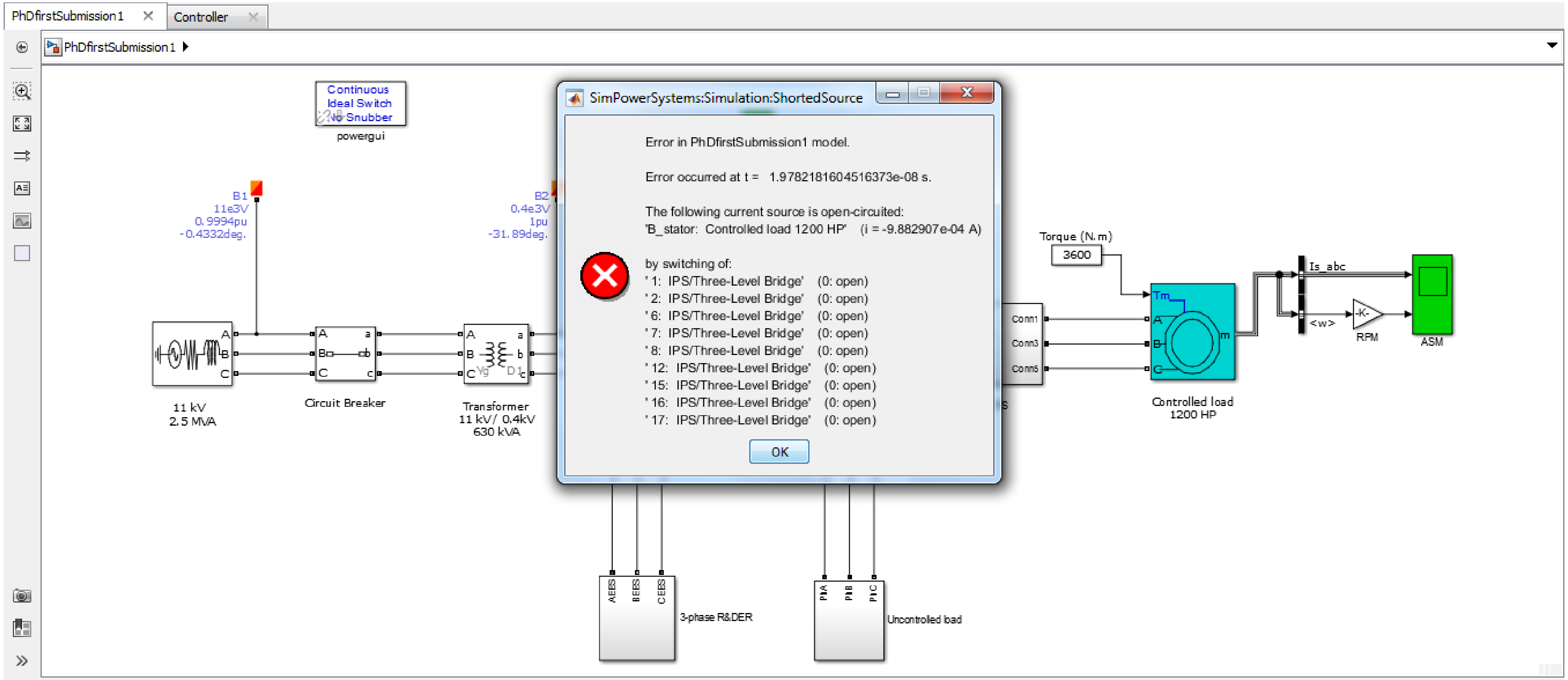

Figure-5-2 (b): Generator-Motor-R&DER model without SHCA

SHCA implemented on Generator-Motor-R&DER model and proposed SGDS works as expected and results are described in the following sections.

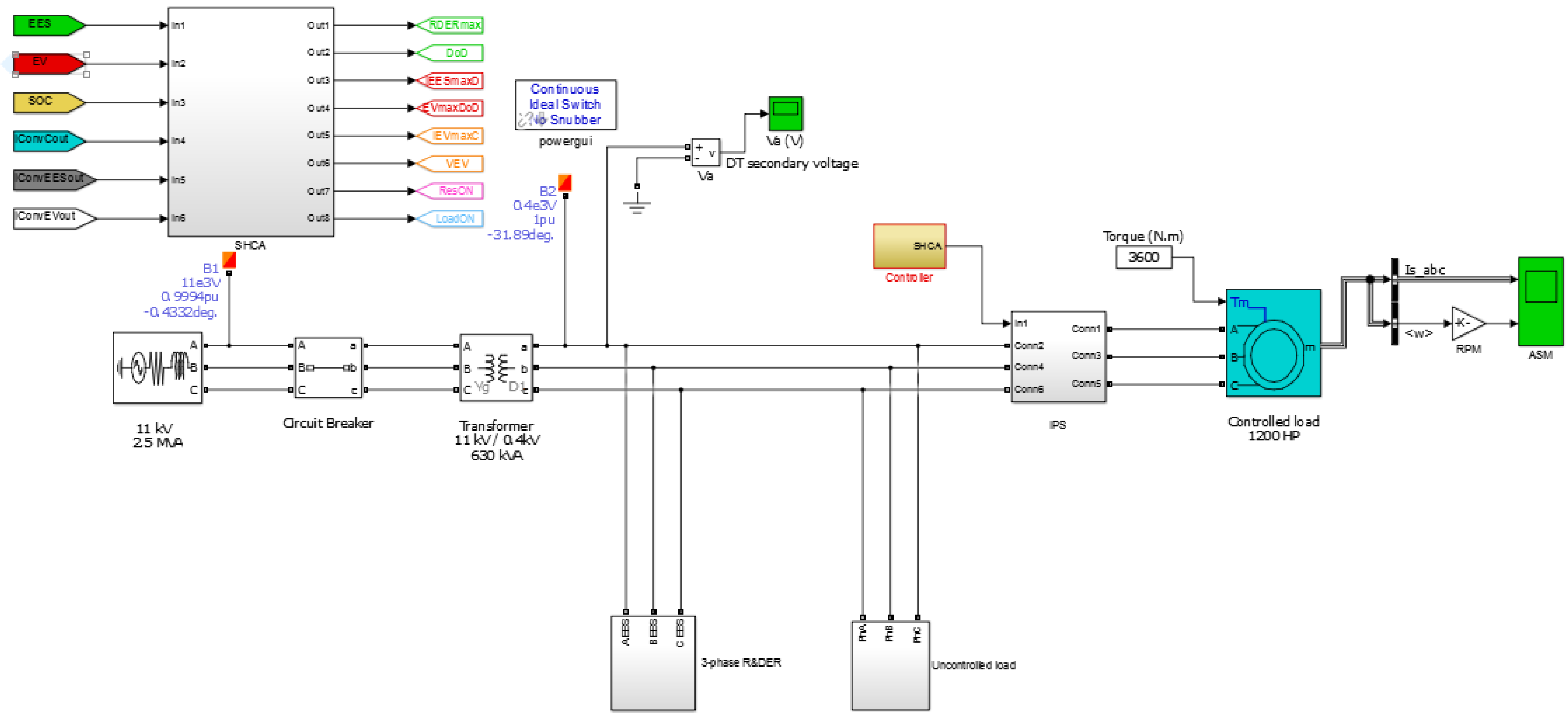

Figure 5-2 (c): Generator-Motor-R&DER model with SHCA

The following section demonstrates step by step procedure to show how supply-demand balance was achieved by SHCA and IPS. Recalling that Self-Healing Control technique is a multi-agent intelligent system combined with state-space control, Bayesian probability and Genetic Algorithm optimisation technique. Thus, the above system at first analysed in terms of state-variable approach. Secondly, an equivalent Bayesian network was developed. Finally, Genetic Algorithm optimisation technique was demonstrated. Simultaneous operation of all three techniques and methods were implemented on voltage profile and demonstrated how voltage profile was optimised in order to achieve supply-demand balance hence optimal control and efficient operation of the proposed SGDS. The circuit was run in MATLAB Simulink and measured voltage drops at the bus B_2. To respond to sudden demand, EES turns on to discharge electricity in order to mitigate voltage drops below the minimum values (i.e.: 360V). The SHCA simultaneously applied state-variable approach, Bayesian inference and Genetic Algorithm optimisation technique in order to achieve optimal control and efficient operation for the proposed SGDS. Hence, each of these steps are analysed in the following sections. However, implementation of an IPS in MATLAB Simulink is presented here prior to present detailed SHC steps.

5.2.1: An Intelligent Power Switch

Intelligent Power Switch is an automatic switch that enables remote monitoring and control operations of electronics equipment. It consists of switching element and switching control mechanism. The switching element is simply an on-off switch while its control mechanism operates the nature and duration of switching states. This research embedded SHCA as a switching control mechanism to turn on or turn off the IPS as shown in figure-5.3.

The main power supply and R&DER power supply sources are represented by S-1 and S-2 respectively. m_SHCA represents SHCA signal that tune switch to change its states from open to close and vice versa. Loads such as washing machine, air conditioner, lift, and so on operations can control by m_SHCA control signal based on availability of R&DER as well customer demands.

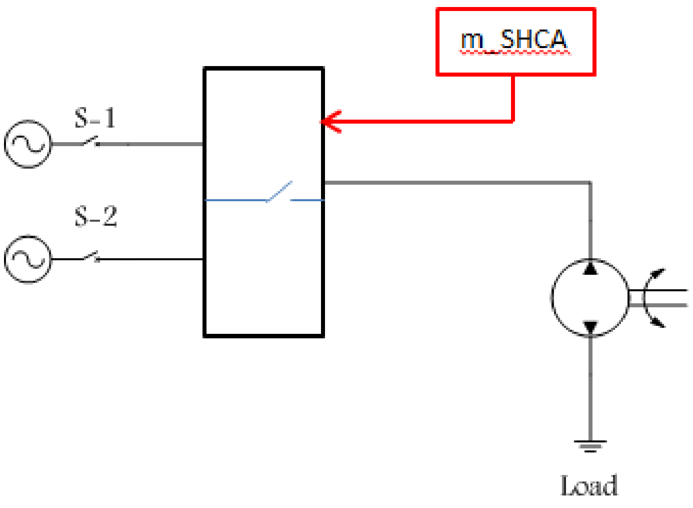

Figure 5-3: (a) Block diagram of IPS

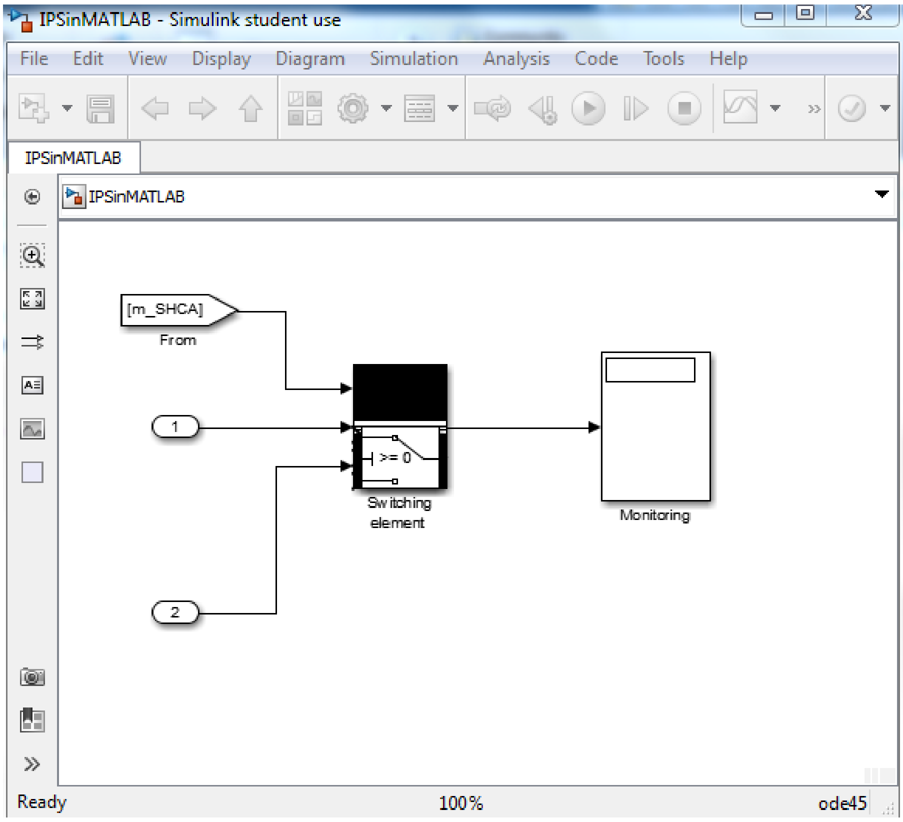

Figure 5-3: (b) IPS implementation in MATLAB Simulink

A wired protocol UART is implemented to communicate with neighbouring IPS through switching control mechanism (i.e.: SHCA). UART also enables real-time demand, power rating of the equipment and load forecast to the SHC. This real-time information enhances SHCA to learn about input parameters. This is how SHCA makes decision intelligently for closing or opening IPS in different power system dynamic stages.

5.2.2 (a): State-variable approach for SHCA

A simplified single-line diagram for each node of proposed SGDS is considered as shown in figure 5-3. The real and reactive power demand varies according to IEEE EU Low-Voltage feeder data under steady-state as discussed in chapter-3. The variations in real and reactive power demands that impacts feeder voltage, are presented by ΔP_r and ΔQ_r which are the key parameters to investigate.

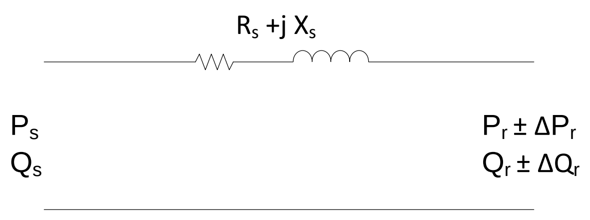

Figure 5-3: Real and reactive power supply and demand

Here,

R_1 is the equivalent resistance of the loads demands for real power P_r

$j\omega X_{L1}$ is the equivalent reactance of the loads demands for reactive power Q_r

Q_s is the reactive power demand at the receiving state at steady-state

P_r is the real power demand at the receiving end at steady-state

ΔP_r is the variations of real power demand at the receiving end

ΔQ_r is the variations of reactive power demand at the receiving end

To simplify the expression, let i(t) is the state variable for that the state-space equation will be developed and solved. Once i(t) is determined, the actual state-variable v(t) can be determined from $V_R(t)$ = i(t).R and $V_L(t)$= i(t).X_L.

Applying Kirchhoff Voltage Law (KVL), the state-space equation for figure 5-3 can be found as:

$$v(t) = R.i(t) + L\,\frac{di(t)}{dt} \qquad [5-1]$$

Equation [5-1] is the time-domain representation of voltage and current of the proposed system where initial conditions are ignored.

Applying Laplace transformation equation [5-1] can express as:

V(s) = R.I(s) + sL.I(s)

Where, s is the Laplace operator.

Considering the initial condition, it is found that

V(s) = R.I(s) + L[s.I(s) + i(0)]

If the input V(s) is a unit step function u(t) whose Laplace transform is, V(s) = u(t) = 1/s, the above equation can solve for current flow through the network as follow:

$$\frac{1}{s} = R.I(s) + L\,[sI(s) - \,i(0)]$$

$$\text{or } \frac{1}{s} = (R + sL).I - L.i(0)$$

$$or, \frac{1}{s} + L.i(0) = (R + sL).I(s)$$

$$or, I(s) = \frac{1}{s(sL + R)} + \frac{L.i(0)}{(sL + R)}$$

$$or, I(s) = \frac{1}{R}.\frac{sL + R - sL}{s(sL + R)} + \frac{i(0)}{s + \frac{R}{L}}$$

$$or, I(s) = \frac{1}{R}\left(\frac{1}{s} - \frac{1}{s + \frac{R}{L}}\right) + \frac{i(0)}{s + \frac{R}{L}}$$

Applying inverse Laplace transformation, the state-space equation is determined as:

$$i(t) = \frac{1}{R}\left(1 - e^{-\left(\frac{R}{L}\right)t}\right) + i(0)e^{-\left(\frac{R}{L}\right)t} \qquad [5-2]$$

The current flow through the circuit, i(t) is thus the state variable function that is a subset of all possible variable of the SGDS. If the initial condition of current flow i(0) and inpout voltage v(t) that happen in transient state can be determined or known, all other state variables along with power flow, network losses, voltage drops and so can be determined. Eventually, the state-space equation for figure 5-5 is being derived in equation [5-2] in terms of state variable i(t).

Therefore, voltage drop across the resistive loads V_R(t) would be:

$$V_R(t) = R.i(t) = \left(1 - e^{-\left(\frac{R}{L}\right)t}\right) + R.i(0)e^{-\left(\frac{R}{L}\right)t}$$

And voltage drop across the inductive loads would be:

$$V_L(t) = v(t) - V_R(t) = v(t) - \left(1 - e^{-\left(\frac{R}{L}\right)t}\right) + R.i(0)e^{-\left(\frac{R}{L}\right)t}$$

It can be summarised that if current flow i(t) and input voltage v(t) are known all possible state-variables such as node voltages can be determined.

Let us extend the proposed SGDS in order to realise the actual state-variables. Since R and X_L were assumed to be the equivalent resistance and reactance respectively, the subset of resistance and reactance can be written in matrix equations as follows:

$$R = \begin{bmatrix} R49-1 & \cdots & R55-1 \\ \vdots & \ddots & \vdots \\ R49-n & \cdots & R55-n \end{bmatrix}$$

And

$$X_L = \begin{bmatrix} X49-1 & \cdots & X55-1 \\ \vdots & \ddots & \vdots \\ X49-n & \cdots & X55-n \end{bmatrix}$$

Following the R and X_L matrix values the simulation have run for 10 minutes and found the following results.

Result-1: Measurements at synchronous motor terminals

- The demand increased hence overload occurred
- Overload caused voltage drops
- EES responded to mitigate demands
- EES responds resulted voltage transient
- System restored to steady-state shortly followed by sufficient power supply from EES which provided parallel operation of EES and main grid provides better stability and demand response in SGDS

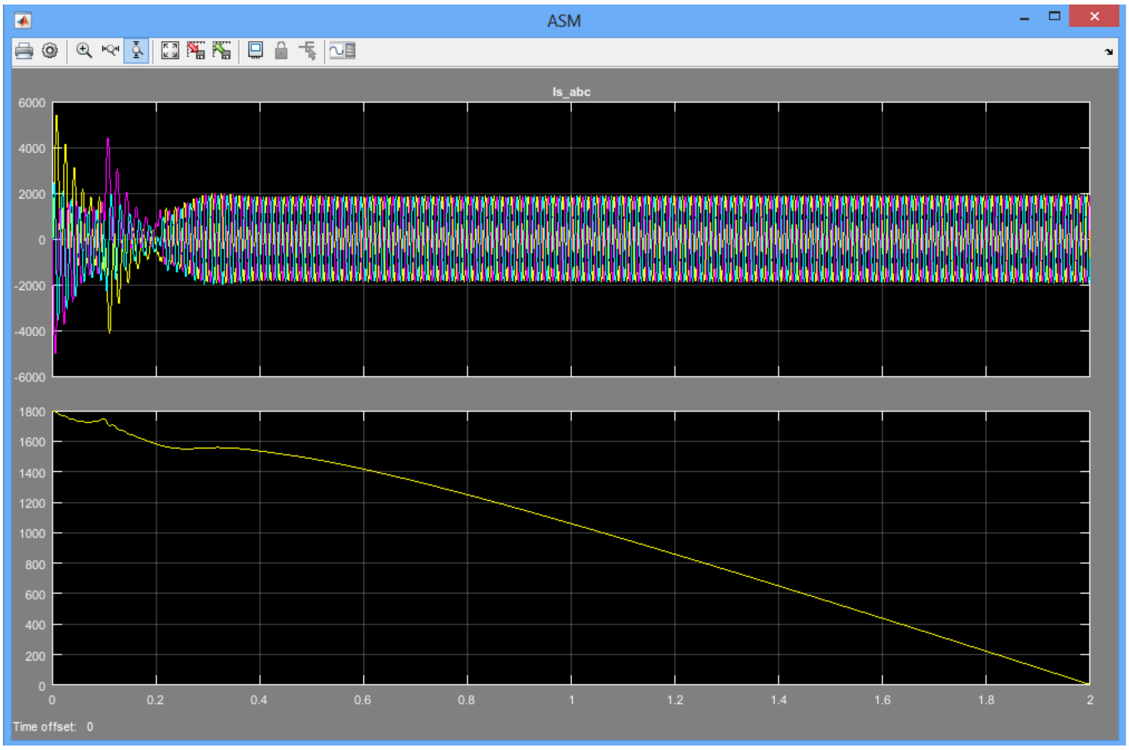

Figure 5-4: Simulation result-1 [Y-axis= power consumption/kW & RPM; X-axis= time in second]

Result-2: Measurements across R&DER terminals

- Oscillation occurred at the generator terminals and transient voltage emerged
- Generator (typically an asynchronous machine) experienced impulse and oscillation both for a short-period of time
- Bus B_2 voltage reduced to around 60% (0.6p.u) during overload
- 60% voltage drops causes brown-out of the equipment (cannot detect in Simulink environment. It shows simulation error only though equipment fails in such disturbance)

- Oscillation occurred across the load terminals and transient voltage emerged

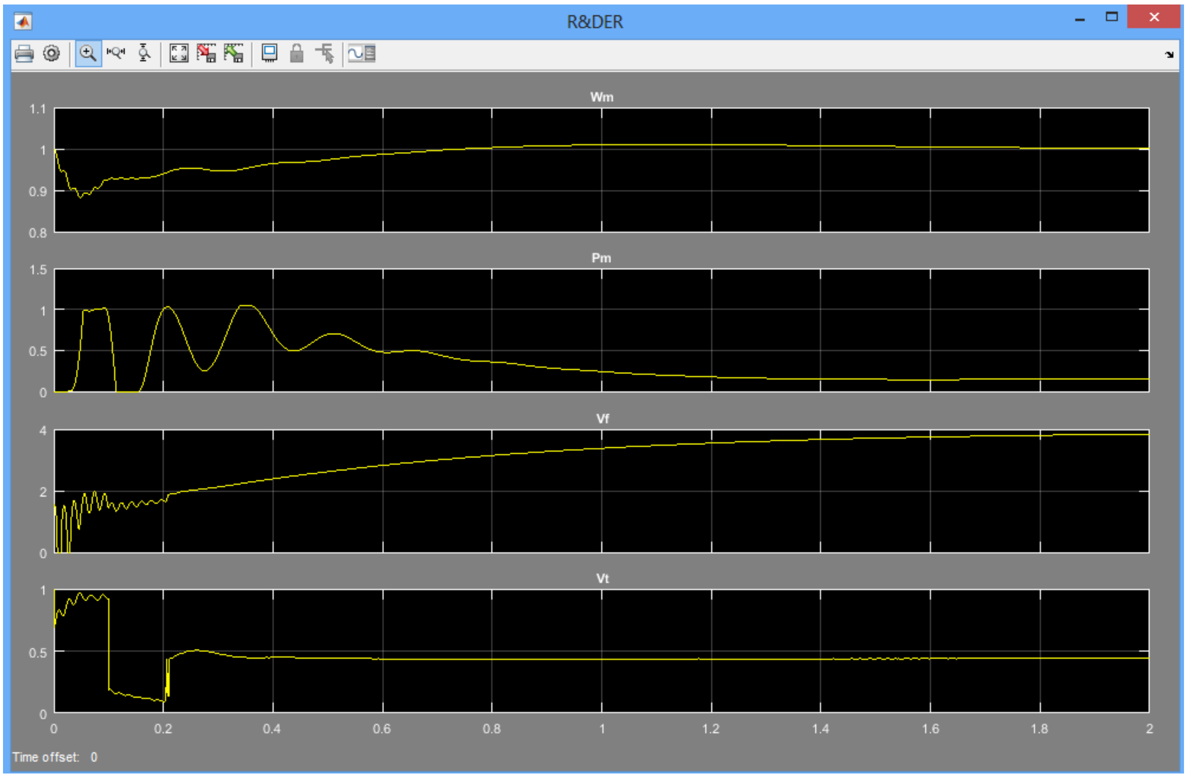

Figure 5.5: Simulation result-2 [Y-axis= energy dispatchability kVA/s; R&DER voltage in p.u.; Bus voltages at generator and Bus B_2; X-axis=time in second]

Result-3: Measurement at Bus B2

- R&DER experience overvoltage during its turned on
- If voltage increases above 6V of rated voltage, R&DER isolates from the grid that means R&DER are unable to supply power to the grid network and loads
- SHCA stopped from such isolation by providing resilience in the system
- Thus, voltage dropped for a short-time period while responding and
- Achieved steady-state and supplied power as required

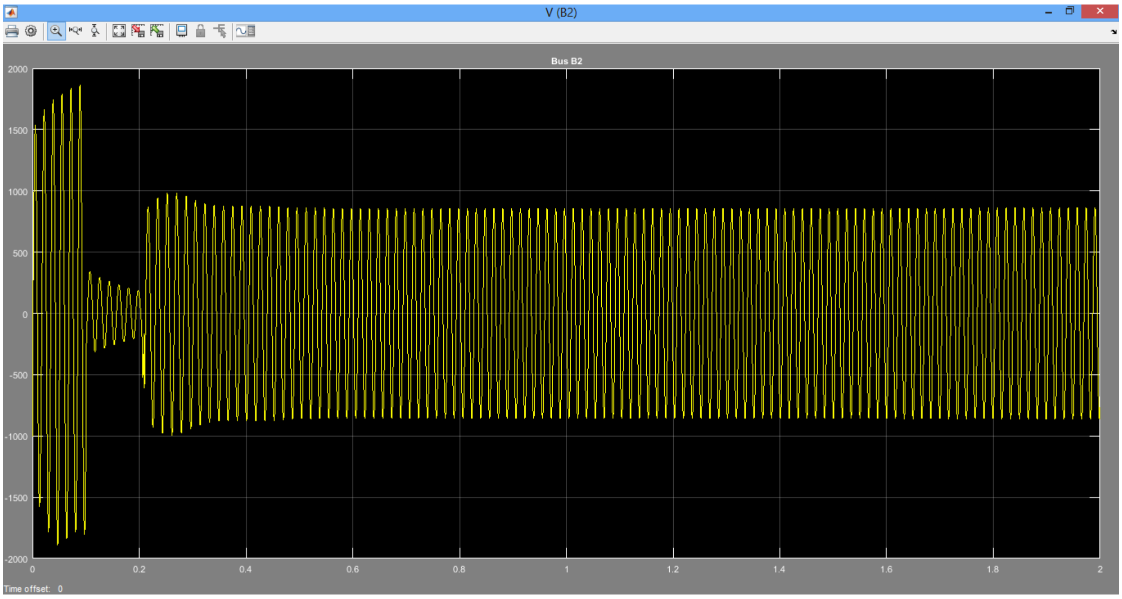

Figure 5.6: Simulation result-3 [Y-axis= voltage at Bus B_2; X-axis= time in second]

The results shown are based on control signal u(t) and state-variable x(t) as presented in chapter-4. The closed-loop state-space control has shown greater flexibility in order to maintain assessed nodal voltages as shown in above figure. However, some node voltages crossed the set limits (trajectory point). This is due to absence of required power electronics converter in electric distribution system unlike transmission system. Additionally, such state-space controllers perform location based automation and control operation. This control operation can be improved by including optimisation technique and probability distribution. As consequences, Self-Healing Control included Genetic Algorithm technique and Bayesian probability with modern control system (i.e.: state-space control) in order to provide resilience to the Smart Grid Distribution System. The Genetic Algorithm and Bayesian Probability have been presented in the following sections consecutively.

From the above discussion, it is clear that state-space control requires various computer approaches to simulate non-linear dynamics. Additionally, non-linear parameters have more than one-equilibrium point that requires optimisation. Thus, Self-Healing Control uses Bayesian Probability and Genetic Algorithm in order to realise an intelligent control for proposed SGDS.

5.2.2: Bayesian inference for SHCA

Bayesian probability offers a mathematical skeleton for performing hypothesis using probability. For instance, the hypothesis of this research is the supply-demand unbalance due to widespread R&DER presence in the proposed SGDS; is the fact. If supply-demand unbalance event occurs, sensor data or measured voltage magnitude must be beyond (above upper limit or below lower limit) the voltage profile magnitude; is the cause. Bayesian probability is very often used in engineering disciplines to justify the relative validity of hypothesis for the system that deals with uncertainties in order to adjust parameters of a specific model. As Self-Healing Control technique for Smart Grid Distribution System performs uncertainty analysis and control disturbance that results uncertainty based on hypothesis, an overview of Bayesian probability has been discussed in this section in related to Self-Healing Control.

5.5.2.1: Bayesian inference

According to the Bayesian Probability theory, assume R is the research hypothesis and S is the sensors and IEDs data, the relative fact of the hypothesis with respect to the given data can be expressed as:

$$P\left({}^{R}/_{S}\right) = \frac{P\left({}^{S}/_{R}\right).P(R)}{\sum P(S)} \qquad [5-3]$$

Where,

$P\left({}^{S}/_{R}\right)$ is the likelihood function that assesses the probability of the observed data from the observer of the state-space controller.

P(R) is the prior data that reflects system's prior knowledge from historical data (i.e.: voltage profile and self-learning) before real time data are considered (D is the feed-forward state-vector control system model that is real time data of sensor. System matrix A, compare with D for optimum control action to be taken. P(R) is the state variables of system matrix A)

$\sum P(S)$ is the algebraic sum or integration of events functions occurred and is limit by minimal and maximum settings of sensors and controllers.

$P(R/S)$ is the posterior function that reflects the probability of the hypothesis after consideration of the data

Hypothesis defines that voltage stability can be gained at receiving end voltage and phase angle equal to sending end voltage and phase angle.

5.2.2.2 Bayesian inference for loop flow effect

A literature survey was carried out on Bayesian probability for electric distribution system. No data were found for electric distribution system. However, it was found that Bayesian network based reliability analysis had been carried out in several publications. The legacy is due to nature of electric distribution system in a power system where it has been considered as a sink for years after years until Smart Grid by means of bidirectional power flow concept put forward.

Consequently, experiments were carried out on Bayesian probability in terms of following relationship to the proposed SGDS.

- Bayesian for linear regression and voltage profile
- Bayesian for logistic regression and voltage profile
- Bayesian for demand curve and voltage profile
- Bayesian for supply-demand relationship and voltage profile

Due to the research interest, this paper presented Bayesian probability in terms of supply-demand relationship. Figure 5-7 shows a simplified probabilistic model of figure 5-1. When PV, EES, HEV and main grid are available to dispatch power across the network, the model shows its greatest flexibility. Power can flow within the loop from high potential to low potential nodes through line segment-1 (LS1) and line segment-2 (LS2).

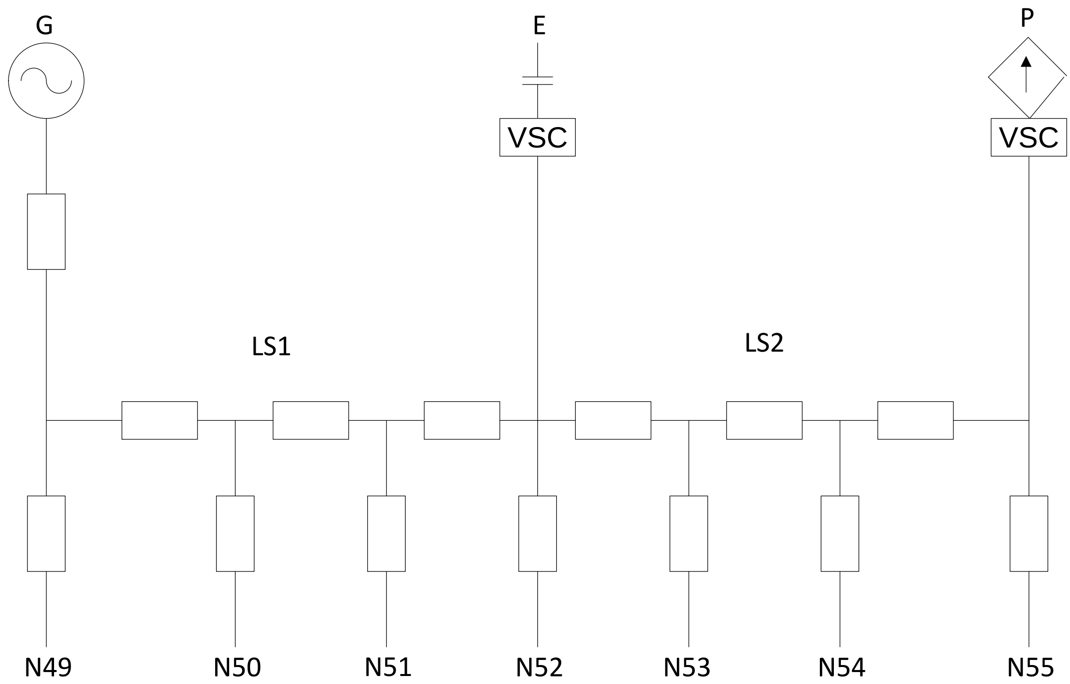

Figure 5.7: Proposed Bayesian network for supply-demand analysis

The analysis carried out based on figure 5-7 to investigate how to allocate sources to satisfy demand so that demand can be responded optimally. G, E and P represent generator source, electric energy storage and photovoltaic solar panel respectively. LS1 and LS2 were the line segment 1 and line segment 2 respectively. EES was installed across industrial loads, commercial loads and municipal loads respectively. PVs were installed throughout the network as shown in chapter-3.

Thus the analysis had taken place under various legislations. At first, it was assumed that all sources were belonged to DNOs. That means all source responded to the demand based on their availability. For example, a demand rose at node N51, there are three sources to response according to the hypothesis. But sensor data may feed zero reference for PV due to a cloudy day or unavailability of EES due to DoD. Therefore, a probability model for hypothesis against sensor data has presented by Bayesian probability in the following section.

The Bayesian probability has been demonstrated as follow:

P(G) is the probability of generator source to response for demand

P(E) is the probability of the EES to response for demand

P(P) is the probability of the PV to response for demand

$$P(G) + P(E) + P(P) = 1 \qquad [5\text{-}4]$$

$$P(G \cup E \cup P) = P(G) + P(E) + P(P) - P(G \cup E) - P(E \cup P) - P(P \cup G) + P(G \cap E \cap P) \qquad [5-5]$$

and

$$P\left(\frac{G}{E}\right)\frac{P\left(\frac{E}{G}\right).P(E)}{\cup_i^n P\left(\frac{G}{E}\right).P\left(\frac{G}{P}\right).P(\frac{E}{P})} \qquad [5-6]$$

Also, there were 2^N number of bridge nodal existed for such a system as shown in figure 5-7. Figure 5-8 shows the number of configuration possible to response to the demand.

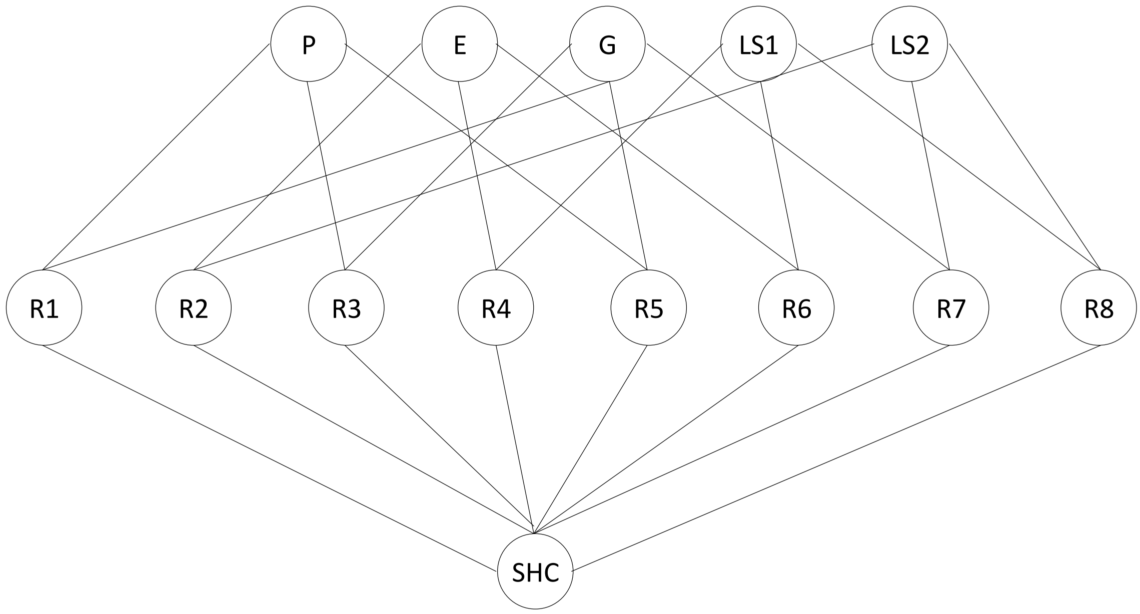

Figure 5.8: power flow loop in proposed SGDS

The power flow loop as shown in figure 5-8 provided number of possible routing to obtain Self-Healing Control technique for proposed SGDS network applying Bayesian probability network. If power flows according to the finding, there will be overvoltage and harmonics on two point of common coupling (PCC) as shown in figure 5-7. It was assumed that state-controllability together with GA optimisation technique mitigated overvoltage. Thus, the probability of power flows through the network was simulated in MATLAB and following result was found as shown in figure 5-8.

Secondly, at no PV generation during a cloudy day the hypothesis against sensor data is a certain event thus.

$$P(P') = 1 \text{ where } P(P) = 0$$

In this instance, the loop was changed as shown in figure 5-9 with two sources by assuming discharging of HEV in unpredictable. This provides Bayesian network to flow power through a single line segment-1 (LS1). The power dispatch duration will rely on system lumped parameter to compute time delay through the line.

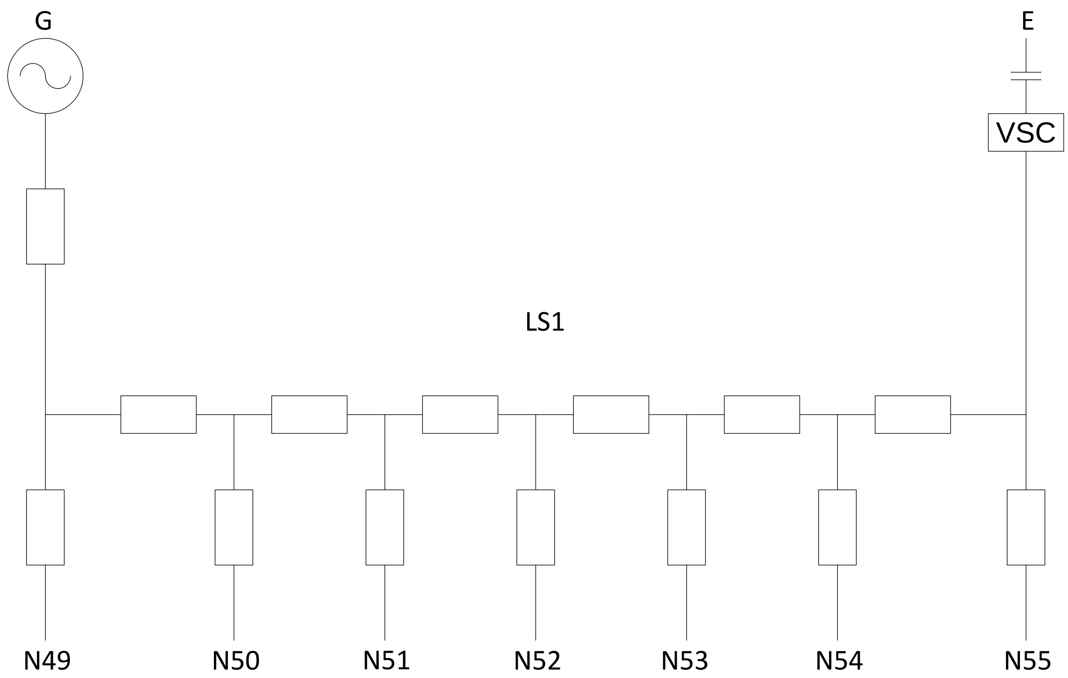

Figure 5.9: Bayesian loop for loop flow effect for proposed SGDS

The power flow loop to achieve SHC for G & E source was found as shown in figure 5-10.

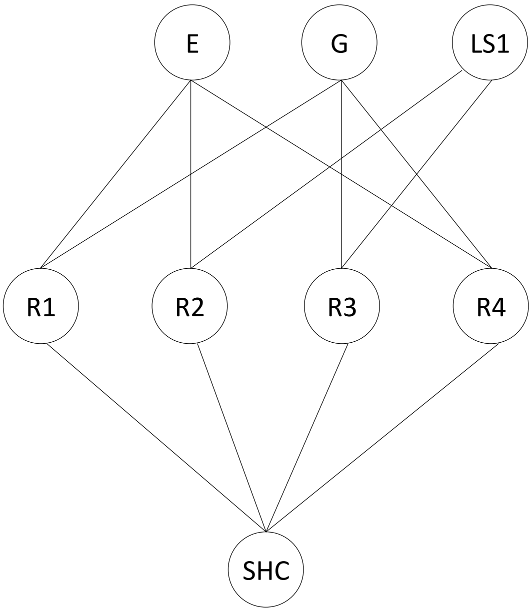

Figure 5.10: The destiny of SHC with Bayesian loop for loop flow

If power flows according to Bayesian probability distribution, optimal control and efficient operation would be achieved. Thus this statement was used to simulate probability distribution in MATLAB and result was presented in figure 5-11. The Simulink model was achieved as PV at MPPT, main grid is at steady-state, EES battery is ready to dispatch, load is under dynamic state, and State-of-Charge of batteries for discharging is controllable.

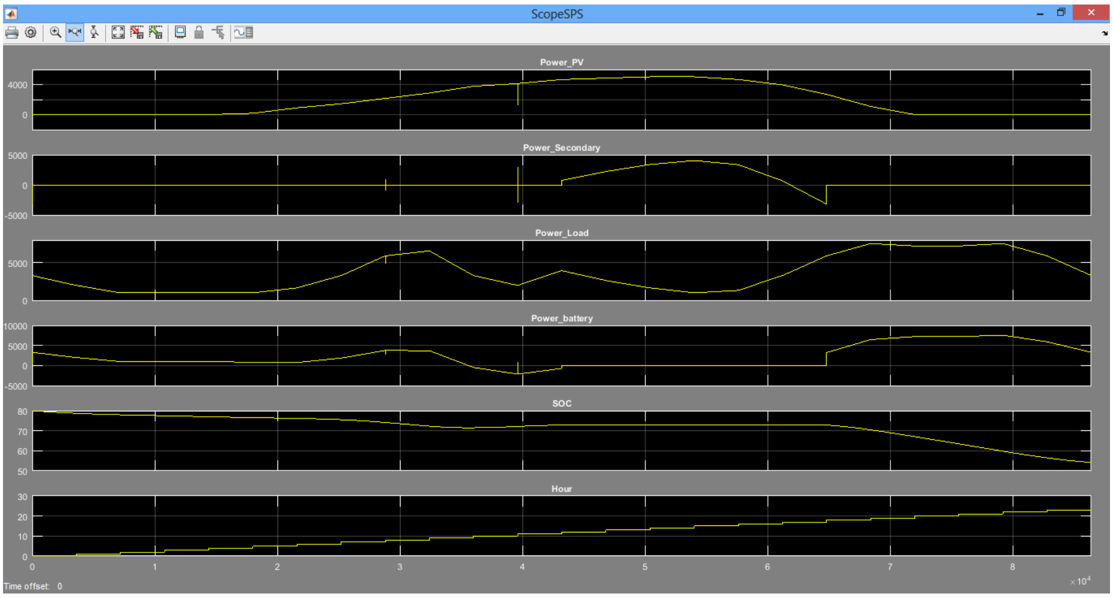

Figure 5.11: Power flow loop in proposed SGDS feeder. [Y-axes= corresponding values on the title; X-axes= time in second]

5.2.3: Genetic Algorithm for SHCA

The principle of natural genetics and natural selection process govern Genetic Algorithm optimisation. Design problems that are characterised by nonconvex, discontinuous and continuous-discrete design variables are best-suited for resolving by Genetic Algorithm optimisation technique. GA uses natural genetics such as reproduction (to optimise output y(t) signal), crossover (to learn probability distribution for voltage optimisation) and mutation (control law to modify state variable x(t) = -ku(t)) as objective function in search procedure. A specific design vector for corresponding objective function plays role of fitness function in natural selection. Fitness function is the function that maximise the objective function. Usually, the relationship between objective function and the fitness function is given by:

$$F(x) = \frac{1}{1+f(x)} \qquad [5-7]$$

Where,

F(x) is the objective function

f(x) is the fitness function

The GA was implemented on single-line diagram of SGDS as shown in figure 5-12.

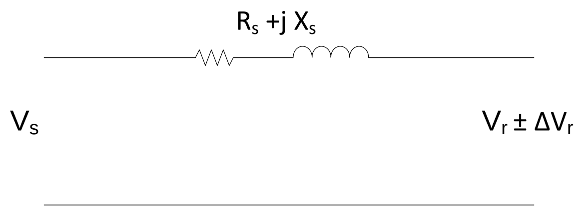

Figure 5.12: Generator-Motor-R&DER model for voltage optimisation of proposed SGDS

It was assumed that power flow study was the objective function, sending and receiving end voltage magnitudes were the fitness function. GA was applied to reproduce voltage profile under given circumstances such as supply-demand unbalance during PV fluctuation or HEV charging variations, to estimate voltage variations and to work out adaptive voltage magnitudes at receiving end. For real power flow study it was assumed that line X/R ratio is much more less than unity and following real power derivative was used:

For real power demand,

$$f(x) = P(x) = \frac{Vr(x).Vs(x)}{R}.\sin\delta \qquad [5-8]$$

For reactive power demand,

$$f(x) = Q(x) = \frac{Vr(x).Vs(x)}{R}.(1-\cos\delta) \qquad [5-9]$$

Where,

P(x) is the real power

Vr(x) is the voltage at receiving end

Vs(x) is the voltage at sending end

X is the line reactance and

δ is the phase angle (angle between voltage and current waveform)

The fitness function was analysed in order to formulate optimal control and efficient operation condition for proposed network. Thus F(x) is the optimal control and efficient operation function (i.e.: objective function).

The constraints were applied for proposed network as follows:

$$V_s = 400 \qquad [5-10a]$$

$$440 \le V_r \le 360 \qquad [5-10b]$$

$$a_1V_s + b_2V_r \ge 798 \qquad [5-10c]$$

Objective function, $F(x) = \text{plant function} = y(t) = \begin{cases} \text{optimal control} \\ \text{efficient operation} \end{cases}$

Therefore, the relationship between objective function and fitness function for proposed network can be given as:

For real power demand, objective function can be expressed as:

$$y(t) = \frac{1}{1 + \frac{V_s V_r}{X} . \sin\delta} \qquad [5-11a]$$

For reactive power demand, objective function power can be expressed as:

$$y(t) = \frac{1}{1 + \frac{V_s V_r}{X} . (1 - \cos\delta)} \qquad [5-11b]$$

The sending end voltage V_s and line reactance X_s remains unchanged in the network. Hence, optimal control and efficient operation for proposed network can be estimated once maximum and minimum node voltage magnitudes are obtained as shown in figure 5-13.

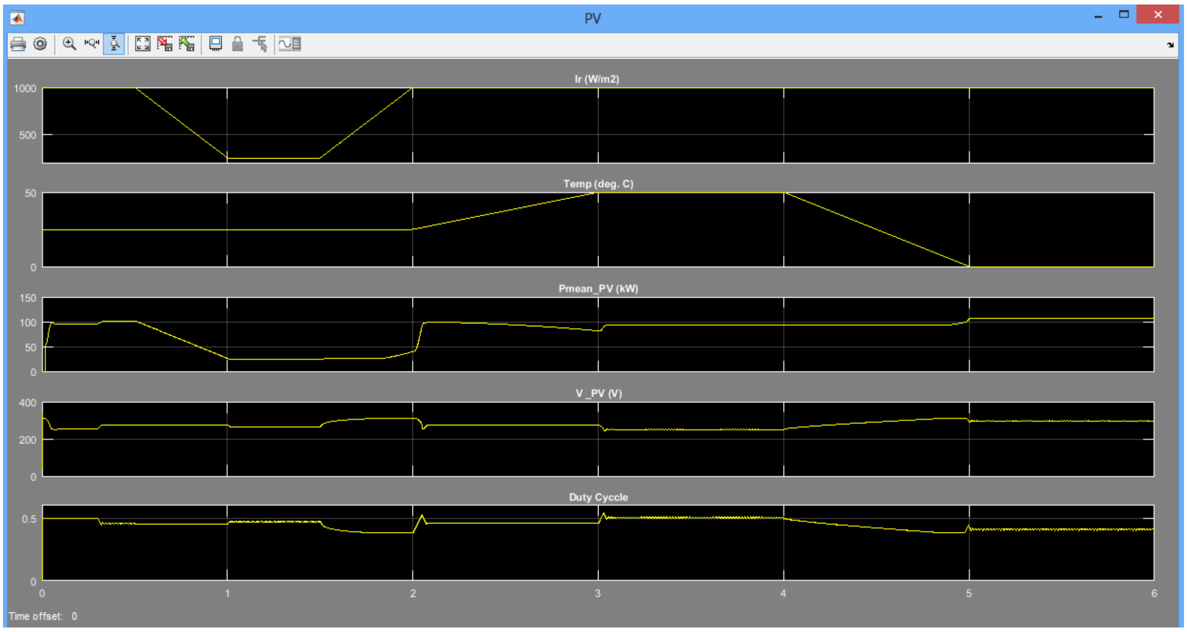

Figure 5.13: PV to responds voltage profile optimisation [Y-axes= corresponding title values; X-axes=time in second]

The extended components will mean the actual real and reactive power demand and their real-time variations. Hence, the time-variant voltage profile in real-time can be achieved. Figure 5-14 shows the proposed SGDS voltage profile for node 49 to node 55 (i.e.: N49 to N55 in figure).

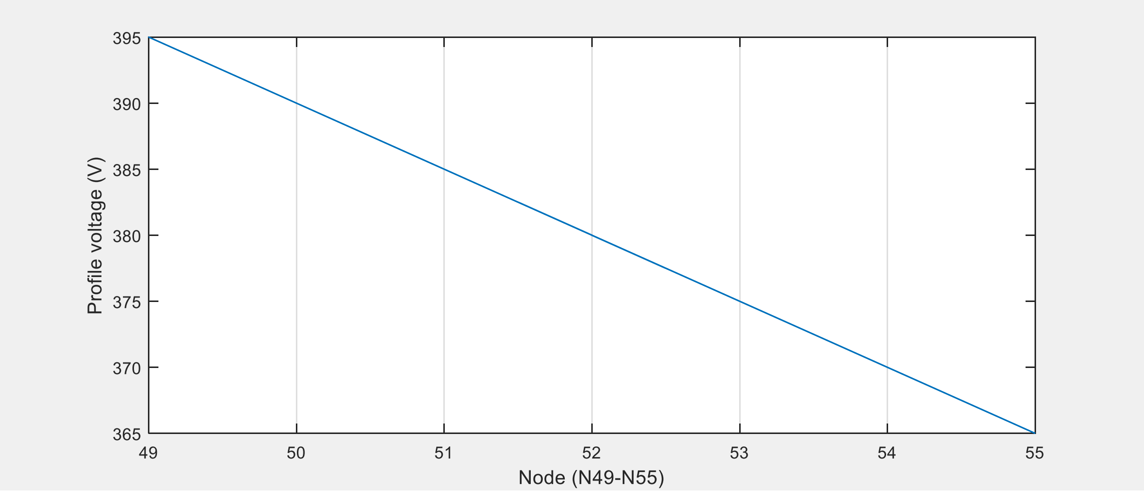

Figure 5-14: Voltage profile for proposed nodes N49 to N55 by state-space control

These assess voltages should be maintained under any conditions in order to failure the equipment or the system. Considering figure 3-17 discussed in chapter 3 at supply-demand unbalance, applying state-space control techniques, the voltage has evaluated in MATLAB and obtained results presented in figure 5-15.

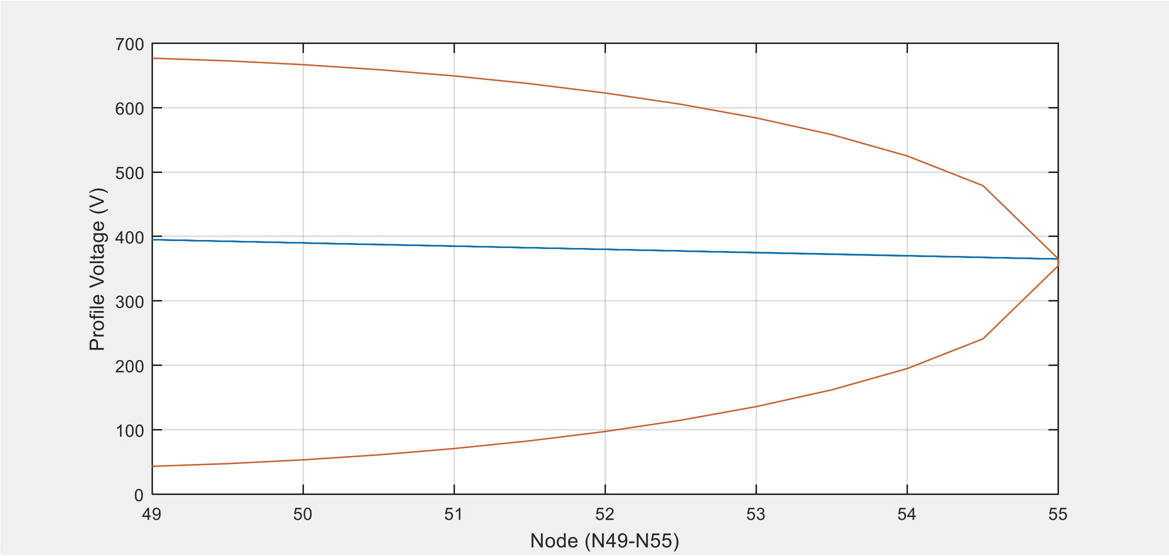

Figure 5-15: Bounded voltage profile with SHCA

5.2.4: Summary of experiment 1

At first the experiment was simulated for Electric Energy Storage. The simulation was set for 100% of State of Charge (SoC) and 20% Depth of Discharge (DoD) of EES. These means, the EES will discharge until SoC stays beyond 20% and stop discharging when SoC at any level below 20%. The EES response time was set below 10 micro-seconds. As discussed in chapter 3 section 3.10 (impacts on R&DER integration), EES response at peak hours. Thus the simulation carried out for peak hours at 6:00 pm and 10:00 pm. At first, EES was simulated in standalone mode to deliver power to AC loads. This provided concept of dynamics of EES. The experiment was used an AC generator to charge battery through a voltage source converter when SoC went below 20%. The following results were found for standalone mode EES for AC loads: EES later on connected with power-grid and investigated voltage dynamics as shown in figures above. Secondly, PV was simulated in standalone mode to deliver power to the same AC loads and following results were found. PV was connected to grid and carried out investigation of voltage and following results were found. Eventually, PV, EES and HEV were connected to bus 2 and carried out voltage dynamics investigation on proposed SGDS network by means of SHCA. In conclusion of parallel operation of R&DER with an existing electric distribution system, it was found that non-deterministic time-variant behaviour of PV generation along with location of HEV charging-discharging can be mitigated by means of SHCA with the aid of an IPS. The supply-demand balanced was achieved for the proposed SGDS network.

Additionally, in experiment 1, it has been found that photovoltaic solar panel integration should be proportional to the annual load growth. There could be more HEV or EES possible as PV integration increase but it cannot be rationale. The relationship between R&DER and IPS number for each bus should be quadratic. It has also been found that an optimum integration of R&DER and optimised IPS number would provide supply-demand balance by implementing SHCA which eventually mitigate overvoltage and overload issues hence improved optimal control and efficient operation and reliability. However, such operation may have impacts on load curve of the system. Therefore, an experiment carried out to investigate impacts of load curve and implemented SHCA to achieve supply-demand balance under any circumstances. This experiment presents in the following section.

5.3: Experiment-2: SHCA to optimise load curves

Self-Healing Control Algorithm uses real time information on both source and load. It limits upper and lower threshold of load curves. It uses Genetic Optimisation Algorithm technique to achieve desire upper and lower threshold. Figure 5-16 to 5-23 show how Self-Healing Control Algorithm limits maximum to minimum demand in order to achieve desire outcomes at node N49 to node N55 and proposed SGDS. Hence, an enhanced optimisation was achieved. Self-Healing Control Algorithm also used low-cost smart sensors, economic energy storages and power electronics controllers to ensure greater interaction to achieve improved reliability and resilience in operation.

N49 with SHCA

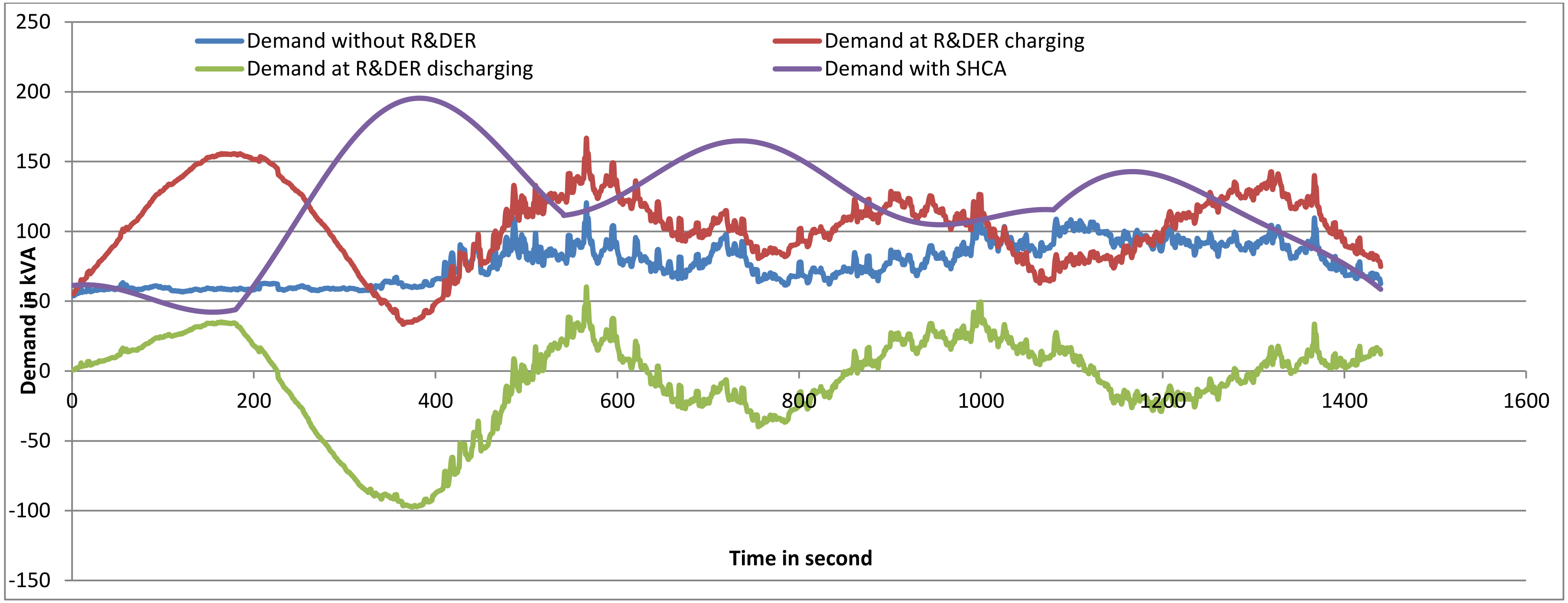

Figure 5.16: Implementation of SHCA on node N49

$$\text{Load factor} = \frac{169.85\text{kVA}}{197.5\text{kVA}} = 0.86 \quad \text{Diversity factor} = \frac{843.325\text{kVA}}{197.5\text{kVA}} = 4.27 \quad \text{Demand factor} = \frac{197.5\text{kVA}}{250\text{kVA}} = 0.79$$

Result analysis:

- Demand at node N49 increased up to 160kVA when EES and EV charged as shown in red line
- Increased demand caused overload at node N49
- Demand decreased up to -100kVA when EES and EV discharged as shown in green line
- Decreased demand resulted isolation of the node and then started reverse power supply towards the substation transformer
- Islanding and reverse power flow occurred
- Continuation of islanding and reverse power flow results substation reverse power relay to trip substation circuit breaker and switchgear, hence power outage occurs
- SHCA optimised amount of EES and EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV, EES and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.86), demand factor (4.27) and diversity factor (0.79) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Node 50 with SHCA

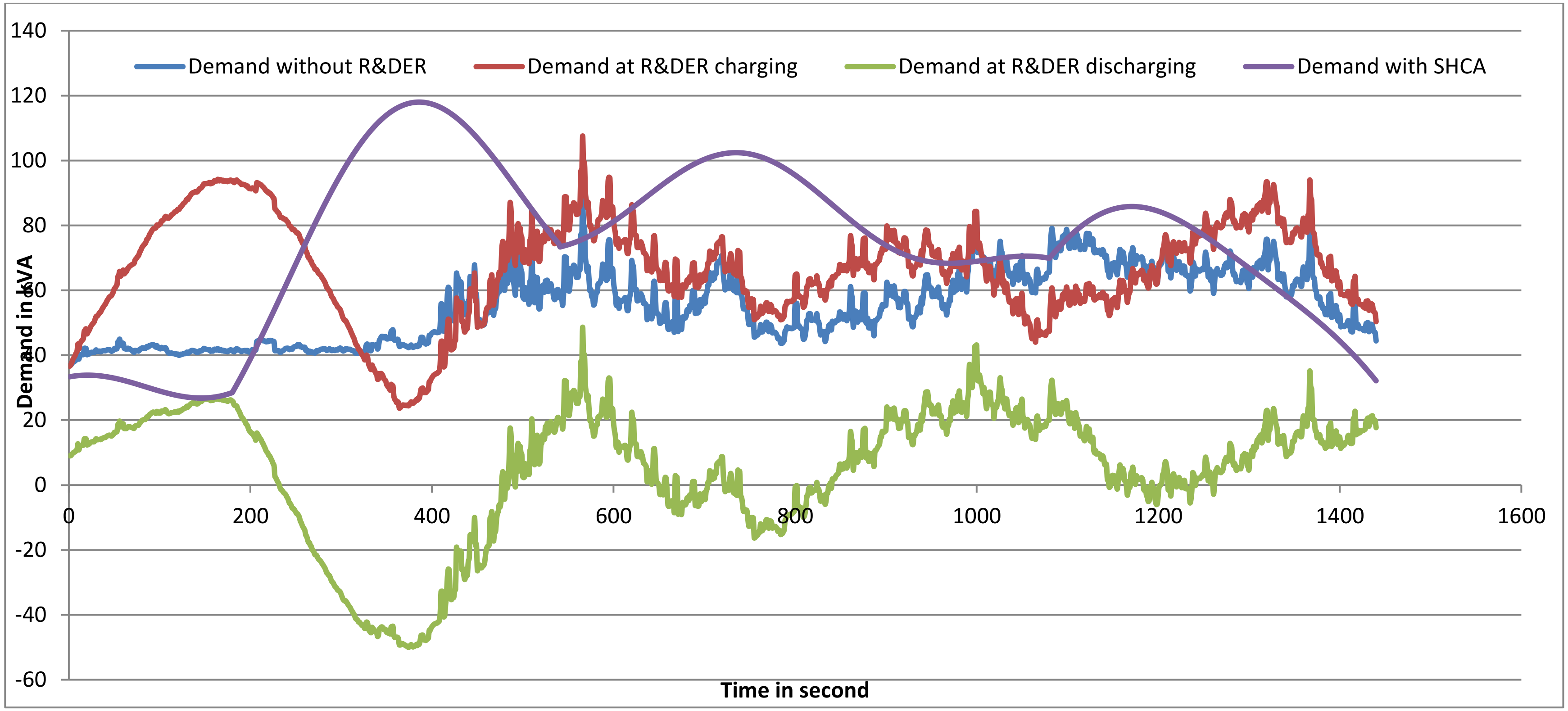

Figure 5.17: Implementation of SHCA on node N50

$$\text{Load factor} = \frac{169.325\text{kVA}}{197.5\text{kVA}} = 0.83 \text{ Diversity factor} = \frac{851.225\text{kVA}}{197.5\text{kVA}} = 4.31 \text{ Demand factor} = \frac{197.5\text{kVA}}{240.85\text{kVA}} = 0.82$$

Result analysis

- Demand at node N50 increased up to 115kVA when EES and EV charged as shown in red line
- Increased demand caused overload at node N50
- Demand decreased up to -42kVA when EES and EV discharged as shown in green line
- Decreased demand resulted isolation of the node and then started reverse power supply towards the substation transformer
- Islanding and reverse power flow occurred
- Continuation of islanding and reverse power flow results substation reverse power relay to trip substation circuit breaker and switchgear, hence power outage occurs
- SHCA optimised amount of EES and EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV, EES and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.83), demand factor (4.31) and diversity factor (0.82) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Node 51 with SHCA

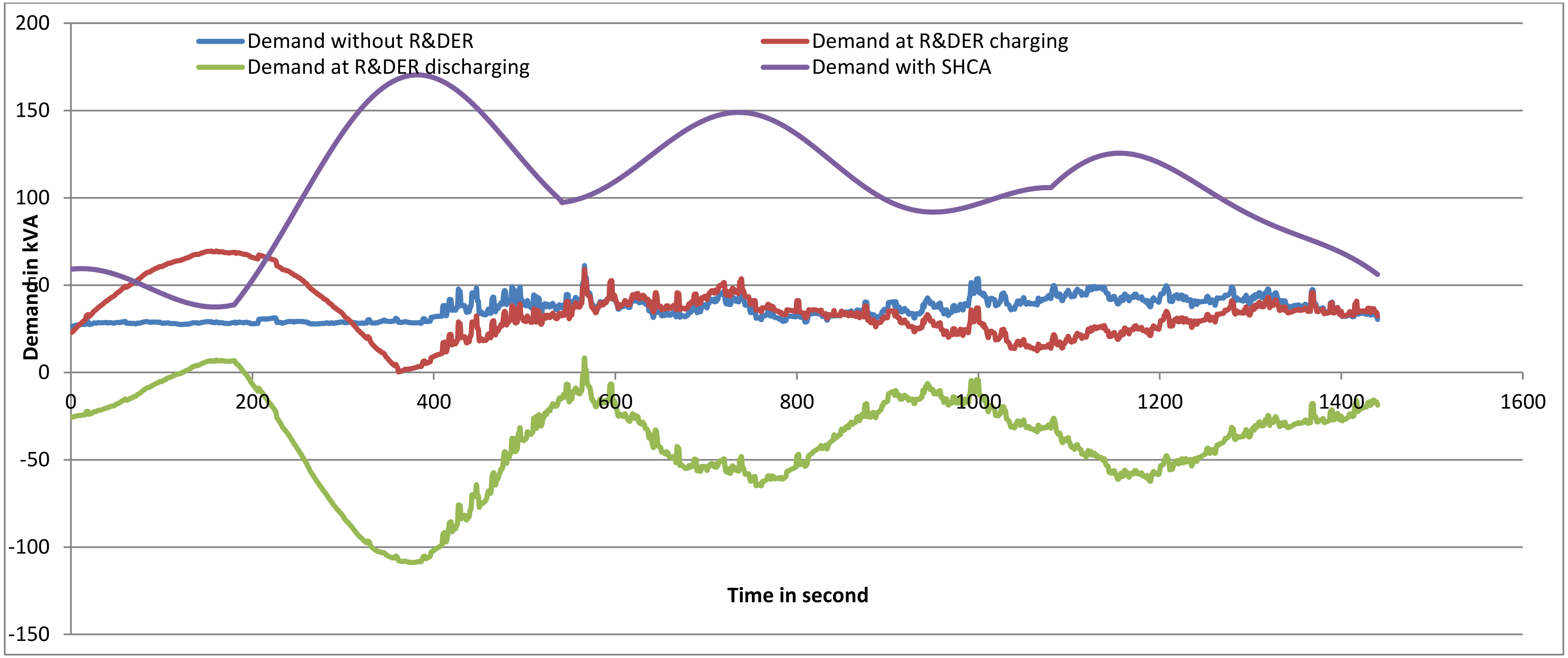

Figure 5.18: Implementation of SHCA on node N51

$$\text{Load factor} = \frac{173.8\text{kVA}}{197.5\text{kVA}} = 0.88 \ \text{Diversity factor} = \frac{841.35\text{kVA}}{197.5\text{kVA}} = 4.26 \quad \text{Demand factor} = \frac{197.5\text{kVA}}{232.35\text{kVA}} = 0.85$$

Result analysis

- Demand at node N51 increased up to 70kVA when EES and EV charged as shown in red line
- Increased demand caused overload at node N51
- Demand decreased up to -105kVA when EES and EV discharged as shown in green line
- When EV and EES discharged, the entire node stayed isolated that caused over voltage at the neighbouring nodes and at the substation
- Reverse power flow due to surplus energy at node N51caused two-way power flow in SGDS all time as shown in green line
- Voltage instability, islanding and reverse power flow occurred
- Continuation of islanding and reverse power flow results substation reverse power relay to trip substation circuit breaker and switchgear, hence power outage occurs
- SHCA optimised amount of EES and EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV, EES and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.88), demand factor (4.26) and diversity factor (0.85) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Node 52 with SHCA

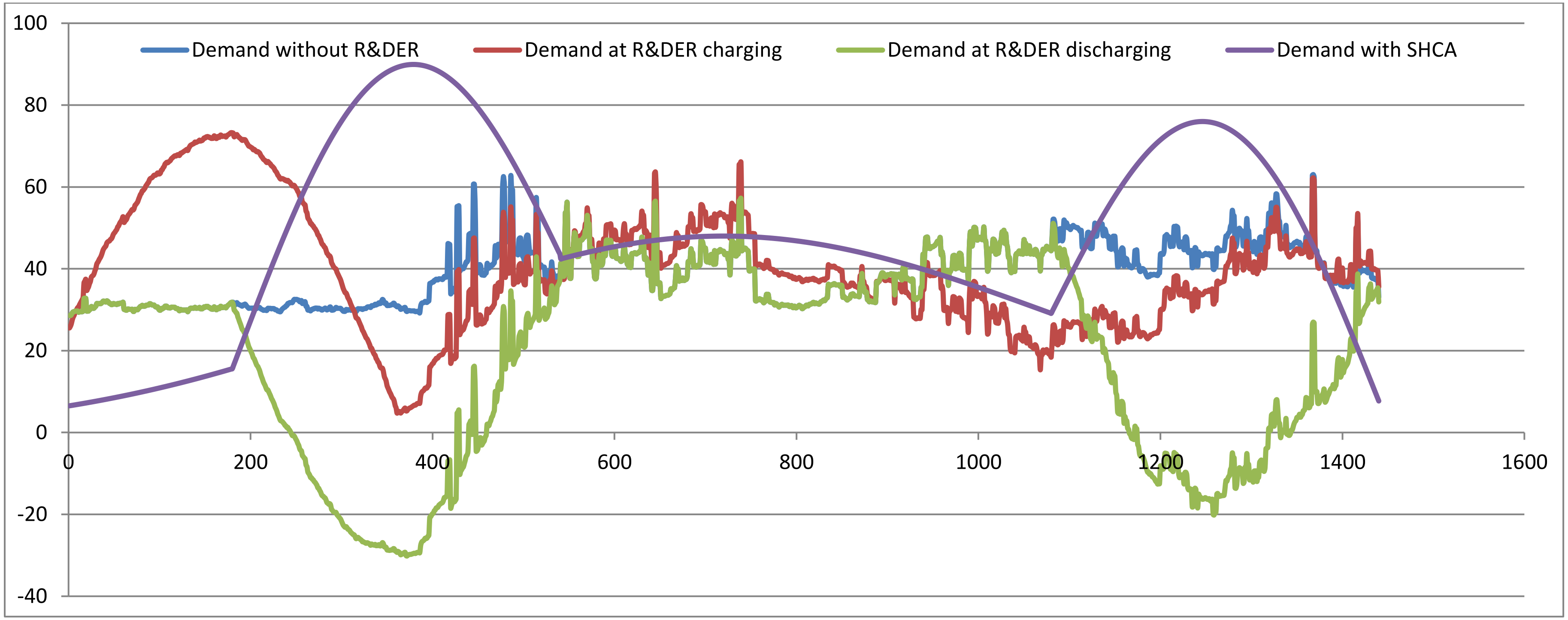

Figure 5.19: Implementation of SHCA on node N52

$$\text{Load factor} = \frac{159.975\text{kVA}}{197.5\text{kVA}} = 0.81 \text{ Diversity factor} = \frac{839.375\text{kVA}}{197.5\text{kVA}} = 4.25 \text{ Demand factor} = \frac{197.5\text{kVA}}{224.43\text{kVA}} = 0.88$$

Result analysis

- Demand increased up to 72kVA (600%) at node N52 when EV charged as shown in red line
- PV generation was zero between 6:00 pm to 6:00 am and EV charging caused under voltage at node N52
- Demand decreased up to -25kVA at node N52 when EV discharged as shown in green line
- Reverse power flow, islanding and over voltage occurred
- SHCA optimised amount of EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.81), demand factor (4.25) and diversity factor (0.88) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Node 53 with SHCA

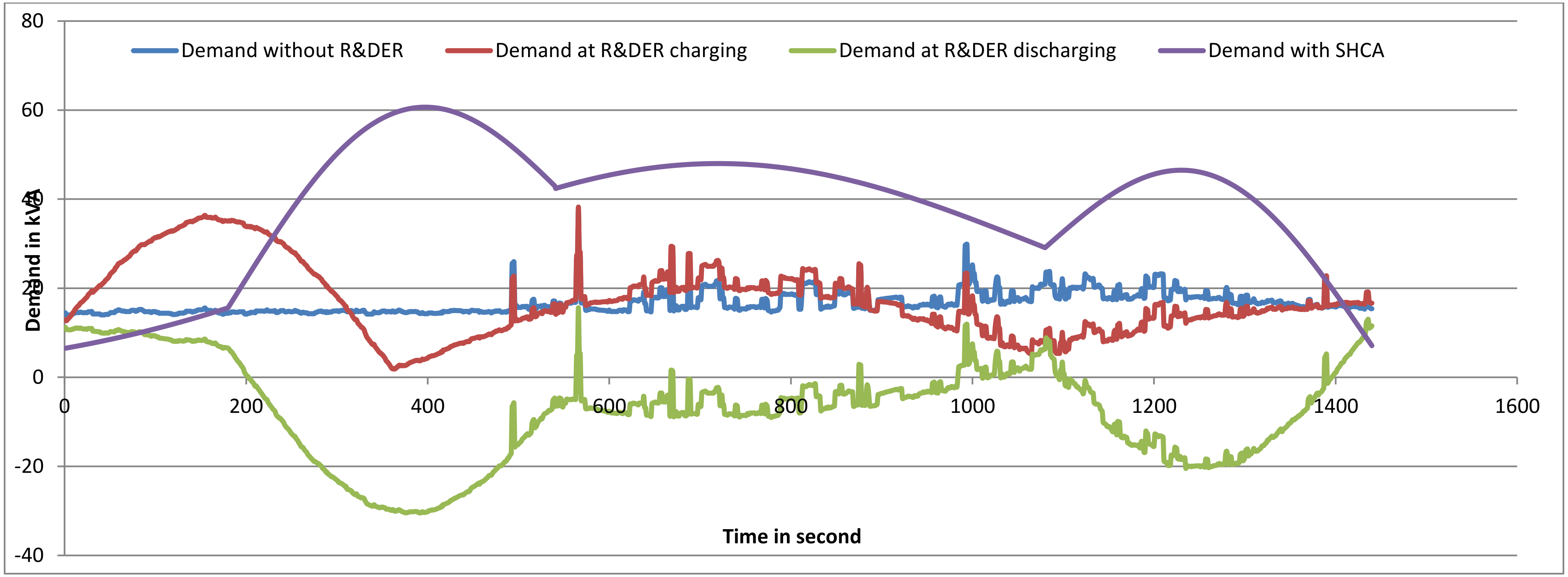

Figure 5.20: Implementation of SHCA on node N53

$$\text{Load factor} = \frac{165.9\text{kVA}}{197.5\text{A}} = 0.84 \;\; \text{Diversity factor} = \frac{827.525\text{kVA}}{197.5\text{kVA}} = 4.19 \quad \text{Demand factor} = \frac{197.5\text{kVA}}{243.83\text{kVA}} = 0.81$$

Result analysis

- Demand increased up to 40kVA (250%) at node N53 when EV charged as shown in red line
- PV generation was zero between 6:00 pm to 6:00 am and EV charging caused under voltage at node N53
- Demand decreased up to -30kVA at node N53 when EV discharged as shown in green line
- Node N53 stayed islanded when EV discharged, hence unbalanced at SGDS feeder impact primary feeder
- Reverse power flow, islanding and over voltage occurred
- SHCA optimised amount of EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.84), demand factor (4.19) and diversity factor (0.81) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Node 54 with SHCA

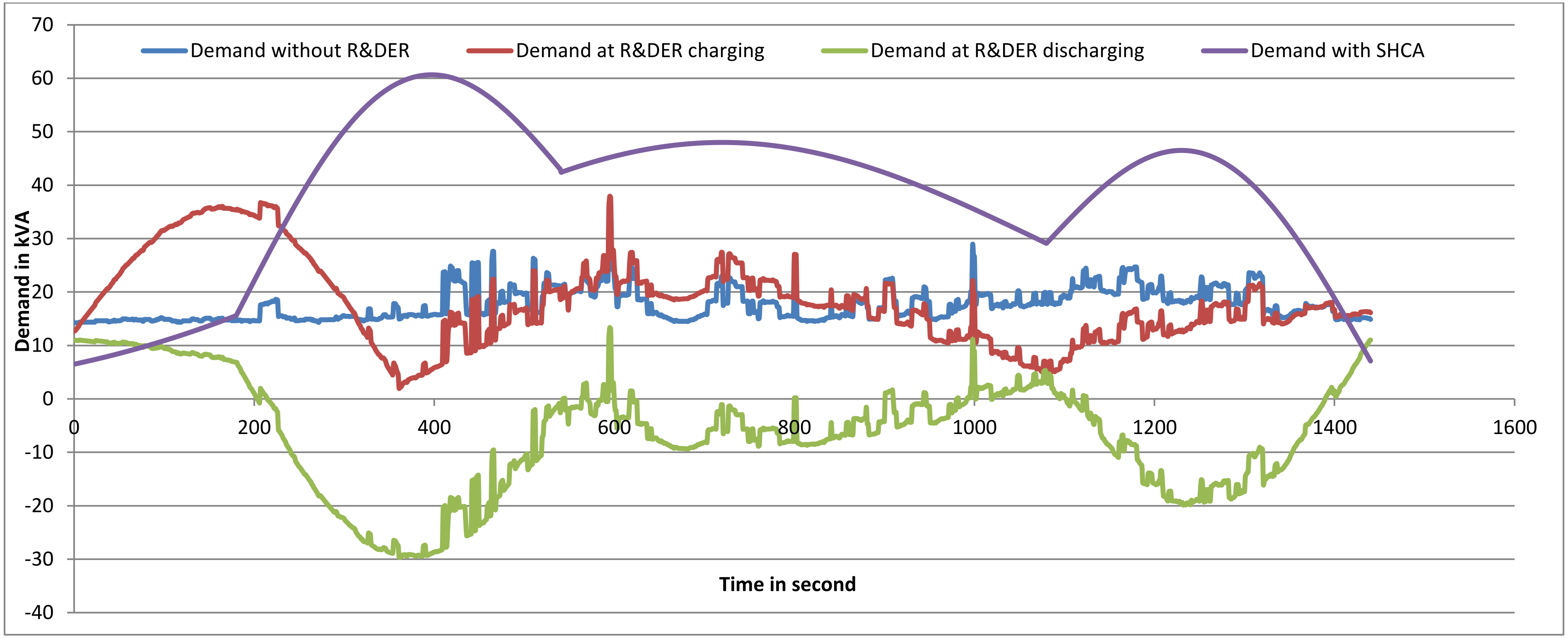

Figure 5.21: Implementation of SHCA on node N54

$$\text{Load factor} = \frac{161.95\text{kVA}}{197.5\text{kVA}} = 0.82 \quad \text{Diversity factor} = \frac{833.45\text{kVA}}{197.5\text{kVA}} = 4.22 \ \text{Demand factor} = \frac{197.5\text{kVA}}{253.21\text{kVA}} = 0.78$$

Result analysis

- Demand increased up to 38kVA (250%) at node N54 when EV charged as shown in red line
- Switching surge occurred during peak demand time
- PV generation was zero between 6:00 pm to 6:00 am and EV charging caused under voltage at node N54
- Demand decreased up to -30kVA at node N54 when EV discharged as shown in green line
- Node N53 stayed islanded when EV discharged, hence unbalanced at SGDS feeder impact primary feeder
- Reverse power flow, islanding and over voltage occurred
- SHCA optimised amount of EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.82), demand factor (4.22) and diversity factor (0.78) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Node 55 with SHCA

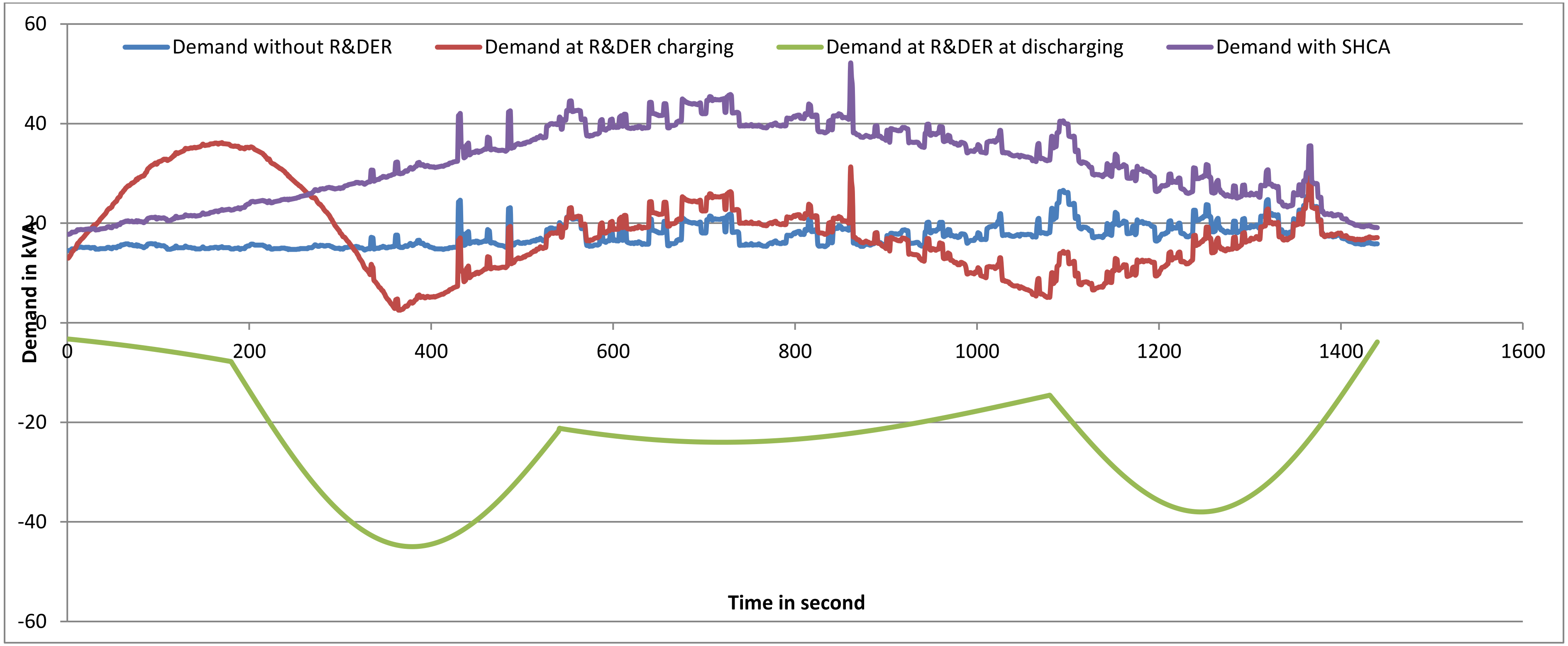

Figure 5.22: Implementation of SHCA on node N55

$$\text{Load factor} = \frac{163.925\text{kVA}}{197.5\text{kVA}} = 0.83 \;\; \text{Diversity factor} = \frac{811.725\text{kVA}}{197.5\text{kVA}} = 4.11 \;\text{Demand factor} = \frac{197.5\text{kVA}}{256.49\text{kVA}} = 0.77$$

Result analysis

- Demand increased up to 36kVA (250%) at node N55 when EV charged as shown in red line
- PV generation was zero between 6:00 pm to 6:00 am and EV charging caused under voltage at node N55
- Demand decreased up to 5kVA at node N55 when EV discharged as shown in green line
- Node N55 stayed islanded when EV discharged, hence unbalanced at SGDS feeder impact primary feeder
- Reverse power flow, islanding and over voltage occurred
- SHCA optimised amount of EV to discharge and charge
- SHCA optimised controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit for proposed SGDS
- The optimised load curve by implementing SHCA is shown in smooth blue line (i.e. demand with SHCA)
- SHCA was implemented to ensure optimum control by means of charging of EV and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor (0.83), demand factor (4.11) and diversity factor (0.77) as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

Proposed SGDS

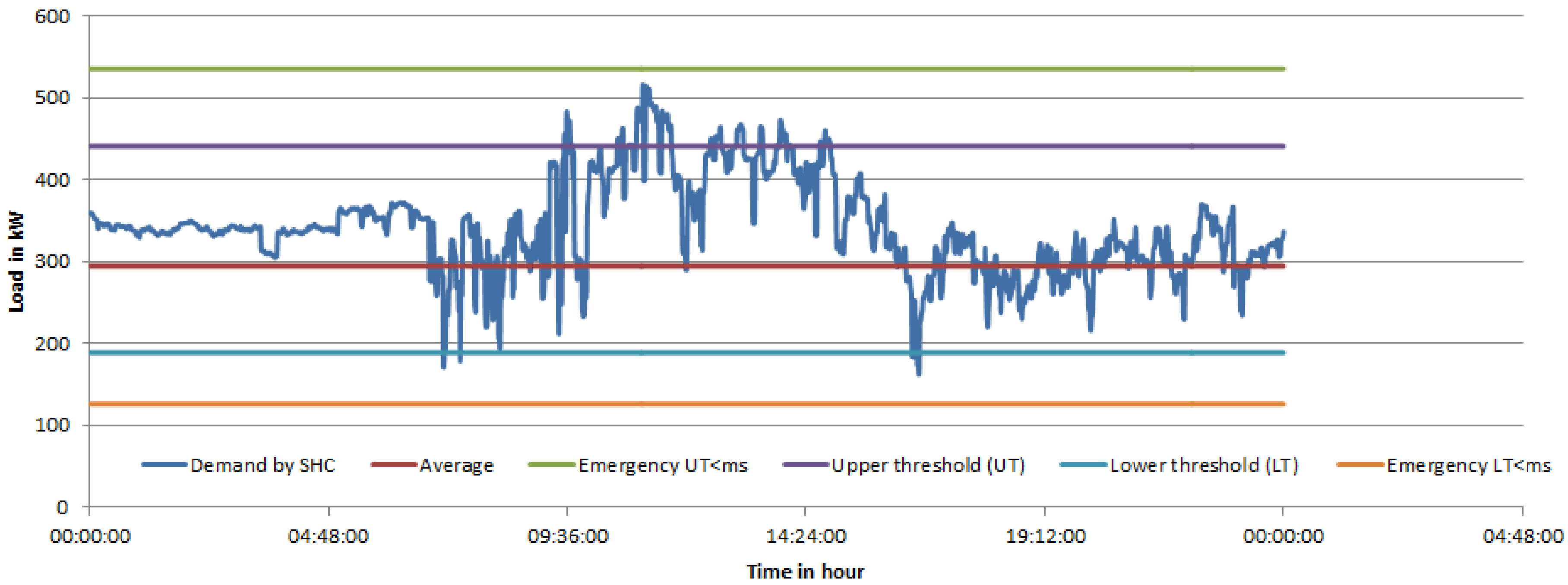

Figure 5.23: Optimised load curve with Self-Healing Control Algorithm

$$\text{Load factor} = \frac{165.9\text{kVA}}{197.5\text{kVA}} = 0.84 \;\text{Diversity factor} = \frac{835.425\text{kVA}}{197.5\text{kVA}} = 4.23 \quad \text{Demand factor} = \frac{197.5\text{kVA}}{240.85\text{kVA}} = 0.82$$

Result analysis

- Demand increased up to 530kVA for a long time in proposed SGDS when EV and EES charged which is above 90% of full-load capacity of distribution transformer as shown load curve (blue line).
- According to equipment safety, if distribution transformer run in over load conditions, overheat causes, basic insulation level of transformer core damages, eddy current loss increases
- Hence, the system becomes inefficient, equipment failure occurs and power outage occurs, thus overall reliability decreases
- Reverse power flow, islanding, under voltage and over voltage occurred
- SHCA implemented self-learning and self-diagnosis (i.e.: state-variable approach) to understand state of the system
- SHCA implemented Bayesian Probability to identify the best loop to power flow and best node to optimise power
- SHCA implemented Genetic Algorithm to learn the best node voltage while optimised EES, EV and Controlled load operations
- SHCA responded demand in such a way that load curve optimised to the best fit by identifying upper threshold, lower threshold, average demand, and the critical/emergency current rating
- SHCA was implemented to ensure optimum control by means of charging of EV and EES and function controlled load while PV generation is at MPPT and main grid is in steady state
- SHCA was implemented to ensure efficient operations of grid nodes by achieving load factor, demand factor and diversity factor as calculated above
- The reliability by means of enhanced optimum control and efficient operations by implementing SHCA was achieved

It can see from the figure that the system neither exceeds emergency upper threshold demands nor lower threshold demand. This means that Self-Healing Control method seeks for alternative energy resources to maintain emergency upper and lower threshold demand. This is achieved by using interactions of smart sensors, and real time data about sources and loads. There is high demand between 9:15 am and 16:00 pm. This is due to charging of EES and HEV as well as PV generation. However, there is some low demand time available near about at 8:30 am and 17:15 pm. This is due to declining of EES and HEV on-site charging demand. Self-Healing Control method decreases their duration less than 5 minutes by optimising demand response. Therefore, a consistent demand response is achieved.

5.3.1 Summary of experiment-2

A comparison among conventional electric distribution system, Smart Grid Distribution System without Self-Healing Control and Smart Grid Distribution System with Self-Healing Control is shown in table 5-1.

Table 5-1: Summary of load curves and factors

Nodes	Conventional DS	SGDS without SHC	Variations	SGDS Nodes with SHCA	Load factor	Diversity factor	Demand factor
Load factor	67%	49%	18% (decreased)	N49	0.86	4.27	0.79
Demand factor	4.14	0.97	316% (decreased)	N50	0.83	4.31	0.82
Diversity factor	0.25	1.05	80% (increased)	N51	0.88	4.26	0.85
				N52	0.81	4.25	0.88
				N53	0.84	4.19	0.81
				N54	0.82	4.22	0.78
				N55	0.83	4.11	0.77
				Proposed SGDS	0.84	4.23	0.82

In conventional electric distribution system, the diversity factor is generally low as shown in figure 5-16-5 to 23. The load factor and demand factor is unpredictable due to uncertain consumption behaviour of customer loads. This situation got worst due to wide-scale integration of R&DRER as discussed in chapter 3. The future impact in fact is out of imagination as most of the equipment is designed for conventional electric distribution system with pre-determined voltage, current, frequency and stability magnitudes. Therefore, an optimal control model in terms of Self-Healing Control in this thesis was found effective for the future electric distribution system named as SGDS.

The SHC mitigate wide-scale R&DER integration as shown in figure 5-16 to 5-23. The load factor, diversity factor and demand factor were optimised in such a way that customer can usages their appliances during R&DER at its maximum generation and dispatch mode. This in turns motivates customers to use more sustainable green energy at a convenient time. Optimised load factor, diversity factor and demand factor also provide optimum (i.e. maximum) lifespan of network equipment including fuses, circuit breakers, cables, transformers and customer appliances. Hence, it can be summarised that the overall reliability of the system improves.

However, optimising load factor, demand factor and diversity factor mean that centralised SHCA set up switching sequences or time delay to optimise voltage profile and power flow. This time delay or frequent switching emerges switching surges that may severely impact sensitive and non-critical loads operations. Therefore, another experiment carried out for validating SHCA to mitigate switching surges/transient.

However, source-load model for traditional electric distributed system cannot be same as Smart Grid Distribution System. It rather appropriate for location based analogy. This is due to existence of sources within the load distribution. Additionally, threshold setting on load curve means more distributed control across the loads. This in turn introduces switching surges at each load terminals which require more investigation. As discussed earlier frequent switching and its power magnitudes reduce equipment lifespan, it is significant to consider amount of transient overvoltage as well bus voltages. Consequently, another experiment carried out to investigate switching surges on nodes voltages with SHCA and presented in the following section.

5.4: Experiment-3: SHCA for mitigating voltage instability due to switching surges

5.4.1 Experiment setup

In practice, DSO uses surge protective devices to protect distribution equipment such as in-line surge arresters for circuits exposed to lightning according to industry standard, surge arrester with RC snubber or ZORC (Zinc oxide voltage suppressor with parallel resistor) for transformers, surge arresters in parallel with RC snubber for arc-furnace transformers, surge arrester in parallel with RC snubber for variable frequency drive motors. These surge arresters are designed for specified voltage ratings for example, 6000V surge protector for 230V line single phase distribution line and home appliances. During a disturbance, if the line voltage increases to 6000V and R&DER turns on in order to responds demand, surge voltage can increases greater than 6000V. In this case, almost all surge protective devices in the line and customer appliances those are switched-on whether in use or not will certainly damage. The impact may not be noted instantly as customer may not turn on to use all devices together like as a washing machine, an electric kettle, a microwave oven and power supplies. However, such equipment failure drastically reduces the reliability though DSO never considers such events in SAIFI, MAIFI and SAIDI indices.

Additionally, distribution as well as substation transformer has completely different electrical characteristics than a synchronous or asynchronous generator. In principle, the automatic voltage regulator and the generator excitation system interact during small and large disturbances in a power system while transformer doesn't have such system or equipment. Additionally, transformers are constant flux machines while generators are constant voltage sources. Therefore, it is impractical to compare a distribution transformer with an EES or HEV or a PV. In fact, EES or HEV rely on charging or discharging state to behave as sources. PV relies on time and weather to behave as a source. These diverse natures of sources including non-linear loads were learned by SHCA. Hence, transient phenomena and bidirectional power flow can be modelled using distribution transformer-Motor-R&DER model. Consequently, a distribution transformer-Motor-R&DER model as shown in figure 5-24 is used in experiment 3 to demonstrate how SHCA incorporates with distribution system control and monitoring equipment and mitigate transient surges.

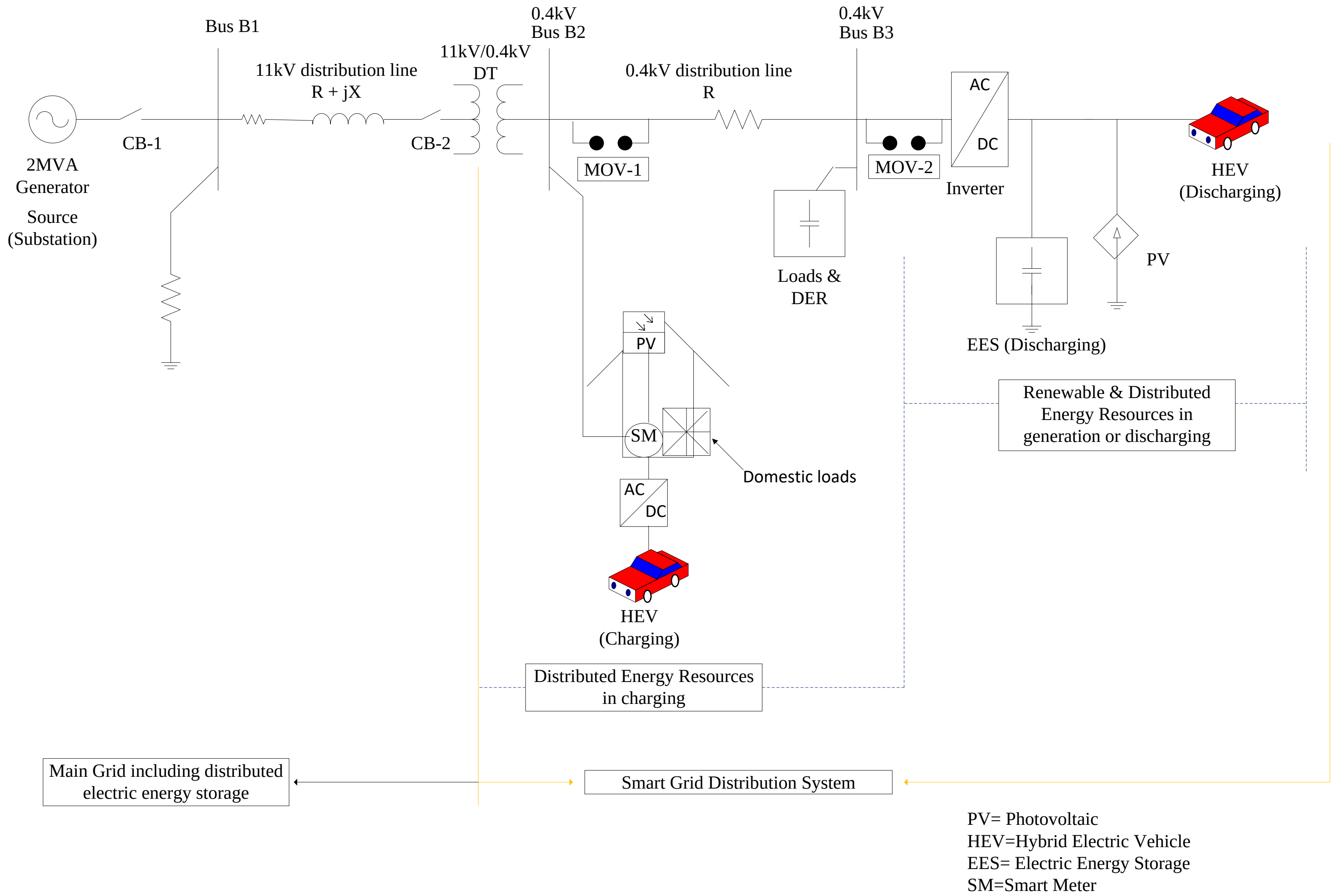

Figure 5.24: Modified generator-Motor-R&DER model for proposed Smart Grid Distribution System.

The single-line SGDS diagram represents three-phase 0.4kV, 50Hz power source delivering power from an 800kVA transformer with constant magnetic flux and a 450kW R&DER with time-dependent state-variable to an equivalent system through a 20 mile and a 10 mile distribution line respectively. Each line is series-compensated by capacitor to increase the power dispatching capacity. Each series-compensator is protected by two metal-oxide varistors, MOV-1 and MOV-2. The circuit breakers CB-1 and CB-2 are used in line as shown in figure 5-24. The 0.4kV system is modelled by a simple constant flux source driving by a constant 11kV voltage source, R&DER and controlled and uncontrolled loads. The 11kV source is assumed to be a synchronous machine and considered as a constant voltage source beyond the distribution transformer. Initially, renewable and distributed energy resources are in standby mode. It is assumed that EES and HEV are fully charged and PV is in generation while solar energy is available but delivering active power only. The synchronous machine is therefore generating real and reactive power required to regulate the 0.4kV bus B2 voltage at 1.0 p.u.

The MATLAB diagram is modelled followed by the schematic diagram and presented in figure 5-25. The main grid power is modelled by using a synchronous machine delivering power through a two-winding three-phase transformer. The R&DER source is delivering power through an interconnected controller (in practice, inverter, converter and controller are in use). Its SoC and DoD are time-variant and are set to respond within 100ms.

The B1, B2 and B3 blocks are the three-phase Voltage-Current (V-I) measurement blocks that measure the line-to-ground voltages and the line currents. The voltages and currents are measured in per unit (p.u) and displayed in oscilloscope as presented in the following figures. The base kVA was assumed to be 100kVA for the entire working. The SHCA signals/data are picked up by a Supervisory Control and Data Acquisition (SCADA) block.

The transformer flux-characteristics are approximated by two-segment of a typical transformer. The knee point of saturation is 1.2 pu. The first segment related to magnetising characteristic in linear region. The inductive magnetising current at 1 pu is 0.001pu, analogous to 0.1% reactive power losses. The active power losses or iron losses of transformer are clearly identified by magnetisation resistances R_m = 1000pu, related to 0.1% losses at nominal value of bus B2 voltage. The desired load and steady-state of the system were tested in powergui block.

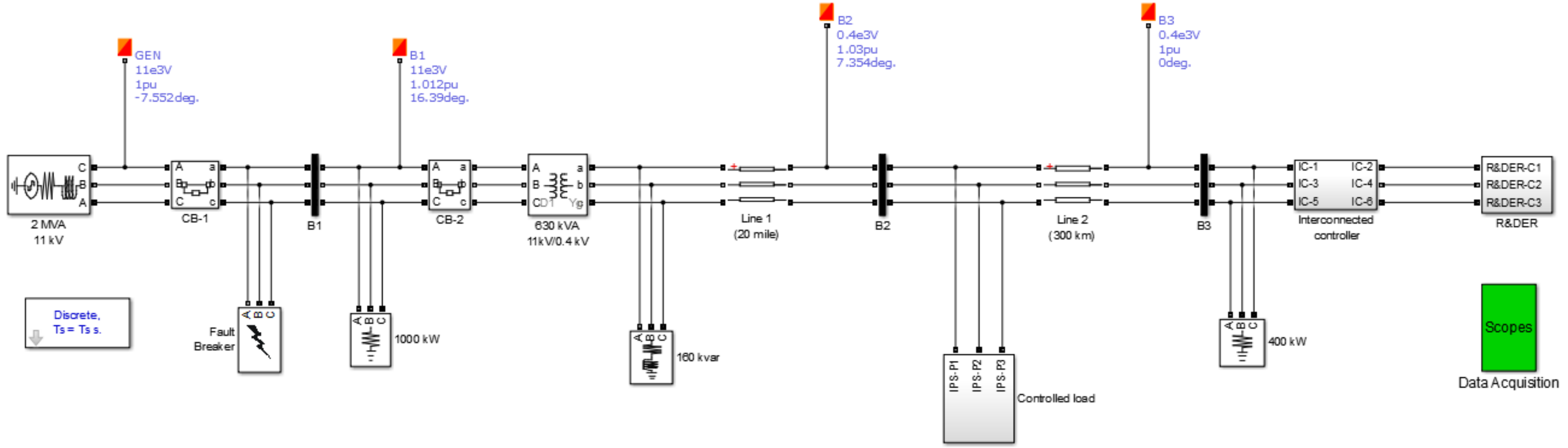

Figure 5.25: MATLAB Simcape Model of proposed SGDS for transient analysis

A single-line to ground fault is applied in bus B1 for 20ms and 120ms considered as a small disturbance. It was assumed that system has resilience to the small disturbances for up to 50ms. This tolerance was set by using self-diagnostic method of SHCA. It is noted that the fault was set for more than 50ms later in this section where system were analysed in worst-case scenario. During small disturbances such as single-line to ground fault, recloser in 11kVfeeder performs reclosing operation to clear the fault, incorporates with SCADA and reclose the automatic circuit breaker to retain the power. SHCA incorporates with SCADA and turns of IPS controlled loads for the duration of small disturbance. Figure 5-27 shows how system retains power during the small disturbance such as single-line to ground fault. The simulation uses fixed step discretised models. The simulation was run for 200ms. The following results were found for steady-state condition of the system as shown in figure 5-26.

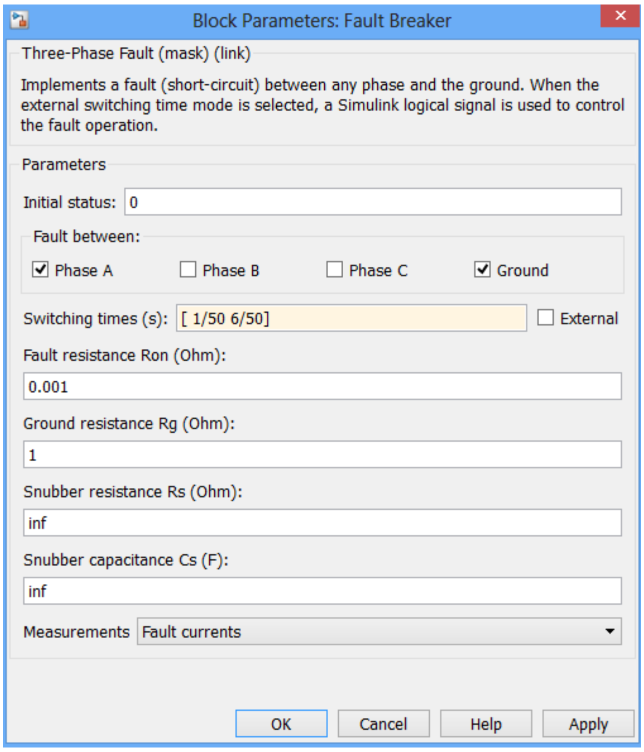

Figure 5.26: Fault setting

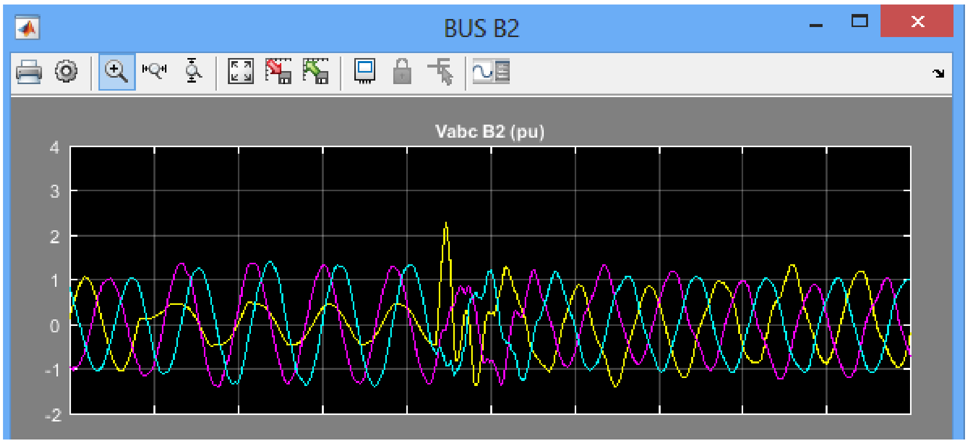

Figure 5.27: Transient responds for small disturbance on bus B2 [Y axis= Voltage pu, X-axis, time = ms]

The single-line to ground fault duration was increased in order to demonstrate the worst-case scenario of the system and presented in the following section. The single-line to ground fault duration was set for 200ms for this occasion. The system was run for 200ms as well. In principle, currents through the line increases as fault stays in the system. Therefore, circuit breaker, CB-2 trips and isolates 0.4kV system in order to protection proposed SGDS as shown in figure 5-28.

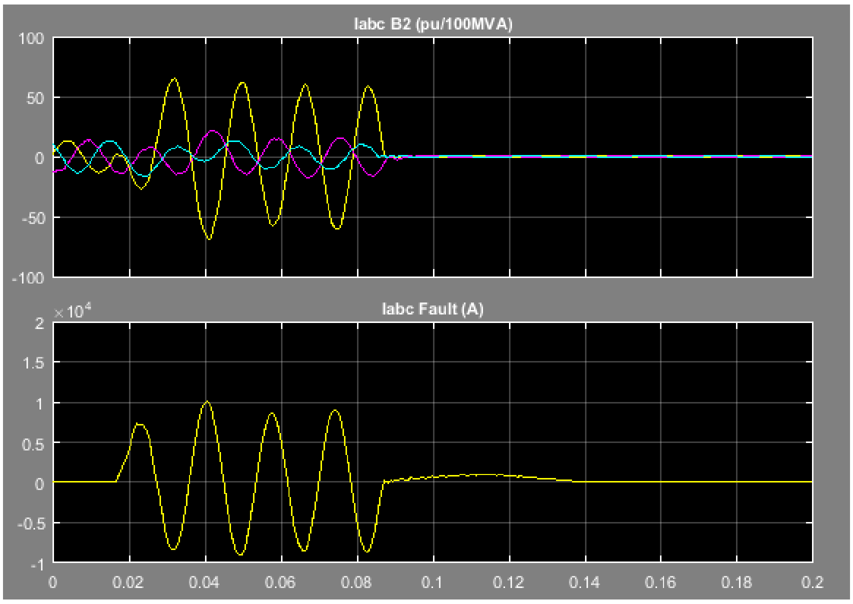

Figure 5.28: SGDS in worst-case scenario [Y-axis= fault current (MVA), X-axis=Time (ms)]

However, load connected at bus B1 can retain power supply as shown in figure 5-28.

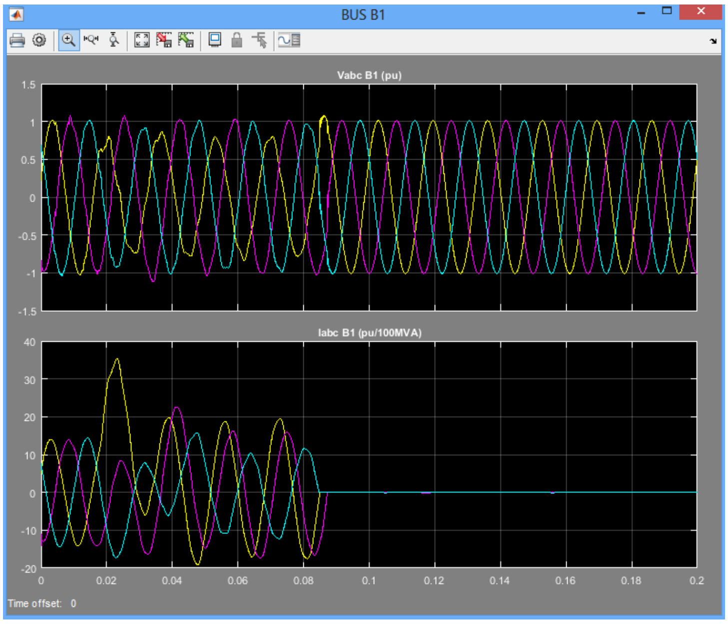

Figure 5.29: Voltage and current at bus B1 for a single-line to ground fault.

5.4.2: Summary of experiment-3

The model has simulated in three phase mode both for small and large disturbance. It was found that SHCA provided resilience to the SGDS. Hence, the CB-2 did not trip off for small disturbance even though voltage instability occurred for a specified time. During a large disturbance, CB-2 tripped off to isolate SGDS to protect its network assets from brown-out. It was found that SHCA provided maximum tolerance level to the SGDS which is not a real case at conventional electric distribution system. However, the system could run in a microgrid mode as if R&DER acts as a source. The challenge in there is to responds with demand, especially in reactive power demand. This is due to the availability of real power through inverter of PV and complexity of reactive power dispatch of EES and HEV. Therefore, SGDS was unable to operate in microgrid with the existence of R&DER due to incapability of satisfying of supply-demand balance. The risk is that the voltage at different nodes could fall down below 0.9 pu during high or unpredicted demand or during motor start effect.

Additionally, Basic Insulation Level, Voltage withstand, surge protector, UPS for medical equipment (sensitive loads). In conventional electric distribution system, switching surges were negligible with respect to large interconnected multi-terminal power systems. In the contrary, switching surges for modern goods such as ipad, smart phones, laptops, macbooks, computer power supplies are severe not only in magnitude but also for duration. If the surges don't clear by a specified time provided by the manufacturer, equipment may brown-out. Prolonged surges may develop the heat throughout the network that may damages the invaluable insulation of the distribution cables.

Chapter 6: Conclusion and Future work

6.1 Conclusion

A centralised Self-Healing Control Algorithm was formulated and implemented on a proposed Smart Grid Distribution system. The aim was to develop the SHCA algorithm to enhance reliability for a proposed SGDS which was achieved by formulating SHCA in chapter-4. Enhanced reliability was achieved by implementing SHCA which was presented in chapter-5, experiment-1 and experiment-1. The reliability indices SAIFI, SAIDI and MAIFI was found zero, hence no calculation was shown.

Additionally, SHCA for sustainable and reliable green energy for future electricity network (i.e.: SG and SGDS) was presented in this thesis by means of optimum renewable and distributed energy resources integration, optimal control and efficient operation, optimal demand response (i.e.: supply-demand balance), adaptive voltage stability and real time pricing for the proposed SGDS. The PV, EES and HEV within the existing electric distribution system have been managed by SHCA in such a way that consumptions of green energy are at its maximum level with little or no interruptions. The load factors, demand factors and diversity factors have been evaluated after SHC implementation and found improved results as presented in table 5-3. Improving load factor means customer can get cheap green energy seeking by a Smart Meter within an AMI network. Improving demand factor means an intelligent demand response procedure that responds with customer demand to control sources and loads such as discharging of EES and HEV or turning on controlled loads while PV is at MPPT as demonstrated in experiment-1. The diversity factor optimisation means that various peak-demand responds optimally with or no system interruptions. The system interruptions such as momentary or sustainable were only found in experiment-3 during a line-to-ground fault. There were no MAIFI and SAIFI events detected in experiment-1 and experiment-2 while EESs and HEVs switched back and forth from SoC to DoD stages. This was a great achievement that enhanced operations of distributed and multiple sources within a 0.4kV feeder line. The SHCA incorporated with SCADA and distributed power network assets that provided a smooth transition for the proposed SGDS. Although the bus B_2 voltage in experiment-1 and experiment-3 was unstable during sudden demand raised and single-line-to-ground fault respectively, however, the self-learning and self-diagnosis capability of SHCA enhanced tolerance to the system to restore without any major interruption.

Additionally, the reliability benchmarks of power system are SAIFI, SAIDI and MAIFI, however, the proposed SGDS is shown that it requires a new benchmark based on customer index rather than overall substation system or power system. As discussed, the power availability at different nodes varies according to their location, and R&DER availability. Therefore, Node N49 to Node N55 can survive with their R&DER during a momentary interruption and could minimise MAIFI of the system as presented in experiment 1-3. However, SGDS islanded during sustained interruption and increased SAIFI and SAIDI even though adequate energy was available across the feeder. This is identified a potential future work and discussed section 6.2.

Moreover, it has been presented that Self-Healing Control Algorithm closely monitored controlled, uncontrolled and sensitive loads and cut-off controlled load at bus 2 as appropriated. For example, a washing machine that was in operation with spinning mode, was stopped within a specified time in order to respond to disturbance while making sure that it does not affect the washing quality. A fridge-freezer was switched off for few seconds to few minutes that did not affect the food quality. A central heating can be switched off while that does not affect the house temperature instantly. All in all, standby and non-sensitive loads can be shut down in order to mitigate overload or large disturbances and aim to restore within millisecond to 5 minutes to retain SAIFI and SAIDI desired.

In addition to these factors, the significant improvement made by SHCA was to identify the requirements of hybrid R&DER operation to the proposed SGDS. For example, grid-tied PV isolates for overvoltage and overload events, EES SoC and DoD have protection issue and HEV SoC and DoD is location as well as time-dependent. These make the proposed SGDS operation impossible to operate in the microgrid mode due to lack of dispatch ability. In these circumstances, SHCA identified that not only an Intelligent Power Switch with a centralised control algorithm (i.e.: SHCA) for the proposed SGDS is required but also an Intelligent Digital Controller (IDC) is required for enhancing the hybrid operation of the proposed SGDS. This means an IDC could operate the proposed SGDS both in grid-tied as well as autonomous mode. In such case, IDC acts as a local controller incorporating with a centralised controller (known as master control of the microgrid) to implement such an operation for the greatest of the Smart Grid vision. Each microgrid is connected to the main grid via an IDC while SHCA is embedded into a centralised controller located in the substation. The controlled load can turn on during the peak generation or dispatch ability condition of R&DER such as high capacity, high-voltage wind farm, PV and EES. This can also implement net-zero building concepts for the Smart Grid. For example, a building or a smart home returns same amount of green energy to the main grid as it uses from the main grid while demanded. Since the ultimate aim of the Smart Grid is to ensure sustainable, reliable and secure green energy for the future electric power system, hence, SHCA is one of the optimistic technologies to achieve such sustainable Smart Green Energy.

It is of course the significant achievement of SHCA where it switched on-off controlled loads through an IPS automatically during small and large disturbances and restore SGDS by optimising voltage threshold of the radial feeder. The feeder voltage never exceeded the voltage withstand level so that equipment never experienced any failure in experiment-1 and experiment-3. These means the equipment can survive for their lifespan set by the manufacturer. In other words, reducing equipment failure means reducing power outage frequency as well as the duration. Thus, it can be summarised that the reliability is increased. Moreover, the IPS operations were negligible in terms of customer satisfaction point. This was due to development of a priority-tree implemented by SHCA. In priority-tree SHCA categorised sensitive and feasible equipment. Such as lift and fridge-freezer are the sensitive equipment, since their service involve with customer safety and food quality. On the other hand, equipment such as washing machine, dryer and air conditioner operations were controlled by SHCA to ensure that these equipment compromise their operation with sustainability of electrical energy, grid stability and eventually customer satisfaction. For example, a washing machine was run 10 times for hand wash which takes generally one-hour to complete its operation by using conventional electrical energy. SHCA implementation prolonged its operational cycle 30s to 5 minutes for 6 times by using more renewable and distributed energy resources while it completes the washing cycle in its specified times for four times. The key achievement was its usage of more renewable and distributed energy resources. Thus IPS installation, as mention in section 2.5, for various equipment designer were justified as demonstrated in experiment 1 and 2 in chapter 5.

However, the drawback of this thesis is its incapability of the islanding operation of the proposed SGDS in order to ensure Smart Energy Management for the future electricity network. This has been set as the future work as discussed in the following section.

6.2: Future work

The proposed SGDS can be modelled in any lateral of the figure 3.1 like as lateral F10. This widens the SGDS network and provides flexibility in control and operation of the entire substation service zone. An Intelligent Digital Control can be proposed for future work that would act as local controller for each lateral (i.e.: each SGDS). IDC will be enabling to operate each SGDS both in grid-tied and islanded mode that is at this moment not a possible grid operation mode. It can act as a master controller during an islanding operation while acting as a local controller in the grid-tied mode. In this circumstance, centralised substation controller can be called as a master controller for the Smart Microgrid which is a fabulous research topic in many years.

Additionally, the R&DER integration and its optimisation should take annual load growth, ageing network and equipment, geographical location, customer behaviour into account in order to optimise the wide-scale integration. This requires extensive survey on different standards of DPN equipment, wiring regulations, voltage, frequency and power quality level. This is due to the customer behaviour and geographical location that may increase or decrease R&DER integration rationally. Therefore, R&DER integration require optimisation.

However, both in grid-tied and islanding operation of the proposed SGDS are identified as one of the key future works due to its economic viability and future demand as the global warming causing natural disaster to increase across the world. In such cases, SHCA can enable radial feeder to segment into multiple nodes for example 12 primary (11kV) nodes in figure 3.1 (section 3.1) and 7-node in figure 3.2. Each node will be able to operate independently in major event day (major event day for sustained interruption or during large disturbances, storms, flood and so on). The power in each controlled and uncontrolled load terminals can be optimised so as to secure necessary supply until system restore back to normal operation. Minimum impacts or even no service interruption will be experienced at the customer premises during small and large disturbances unless the entire power outage occur in the main power system for a long time where R&DER will not be available. Each node in each microgrid can also operate both in grid-tied as well as autonomous mode called as nanogrid. A configuration where each node is equipped with IPS, Smart Meter and AMI those communicate and control by primarily the local IDC and eventually by the master controller. It shows that the loads are distributed in their own node rather that concentrates on one bus. Industrial load, commercial load, municipal load and residential loads have their own nature of demand in terms of real and reactive power. However, SHCA enables, node to node load shedding as well as individual loads by an Intelligence Power Switch which protect entire plant from the failure. It rather fails optimised controlled loads only. Additionally, SHCA can be implemented on location based for each nanogrid, nodes and smart home or smart building. .

References

[1] James A. Momoh ‘’ Computation Techniques for Distribution System’’, Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 2: Sec.-2.12, pp-41.
[2] William Kirstering ‘’ Introduction to Distribution System’’, ‘’Distribution System Design and Analysis’’, Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 1: Sec.-1.3, pp5.
[3] T. Strasser et al., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," in IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2424-2438, April 2015.
[4] James A. Momoh ‘’ Distribution System Reliability and Maintenance’’, Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 5: Sec.-5.1-5.6, pp-115-129.
[5] T. Strasser et al., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," in IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2424-2438, April 2015.
[6] ‘’Jan Machowski, James R Bumby‘’ Electromechanical Dynamics – Large Disturbances’’, ‘’Power system Dynamics: stability and Control’’, Second Edition, ISBN 978-0-470-72558-0 (cloth), The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom, John Wiley & Sons Ltd, 2008, Ch. 8: Sec.-8.5, pp 354-360.
[7] ‘’Jan Machowski, James R Bumby‘’ Electromechanical Dynamics – Large Disturbances’’, ‘’Power system Dynamics: stability and Control’’, Second Edition, ISBN 978-0-470-72558-0 (cloth), The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom, John Wiley & Sons Ltd, 2008, Ch. 8: Sec.-8.5, pp 354-360.

[8] http://www2.nationalgrid.com/UK/Industry-information/Electricity-system-operator incentives/transmission-losses/
[9] C. A. Hill, M. C. Such, D. Chen, J. Gonzalez and W. M. Grady, "Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation," in IEEE Transactions on Smart Grid, vol. 3, no. 2, pp. 850-857, June 2012.
[10] Gopakumar, P.; Reddy, M.J.B.; Mohanta, D.K., "Adaptive fault identification and classification methodology for smart power grids using synchronous phasor angle measurements," Generation, Transmission & Distribution, IET , vol.9, no.2, pp.133,145, 1 29 2015 doi: 10.1049/iet-gtd.2014.0024
[11] Jia DongLi; Meng Xiaoli; Song Xiaohui, "Study on technology system of self-healing control in smart distribution grid," Advanced Power System Automation and Protection (APAP), 2011 International Conference on , vol.1, no., pp.26,30, 16-20 Oct. 2011

[12] Galli, S.; Scaglione, A.; Zhifang Wang, "For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid," Proceedings of the IEEE , vol.99, no.6, pp.998,1027, June 2011

[13] Yong Zhang; Yikang Gu; Vlatkovic, V.; Xiaojuan Wang, "Progress of smart sensor and smart sensor networks," Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on , vol.4, no., pp.3600,3606 Vol.4, 15-19 June 2004

[14] I. Colak, "Introduction to smart grid," 2016 International Smart Grid Workshop and Certificate Program (ISGWCP), Istanbul, Turkey, 2016, pp. 1-5.

[15] James A. Momoh ‘’ Distribution Automation and Control Functions’’, Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 5: Sec.-5.1-5.3, pp-41.
[16] R. E. Brown, "Impact of Smart Grid on distribution system design," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, Pittsburgh, PA, 2008, pp. 1-4.

[17] M. Vadari, "Dynamic microgrids - A potential solution for enhanced resiliency in distribution systems," 2014 International Test Conference, Seattle, WA, USA, 2014, pp. 1-1.

[18] M. Kefayati and C. Caramanis, "Efficient Energy Delivery Management for PHEVs," Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on, Gaithersburg, MD, 2010, pp. 525-530.

[19] Z. Lin, F. Wen and Y. Xue, "A Restorative Self-Healing Algorithm for Transmission Systems Based on Complex Network Theory," in IEEE Transactions on Smart Grid, vol. 7, no. 4, pp. 2154-2162, July 2016.

[20] Y. Wei-Wei, L. Hua-Qiang, H. Qiang and W. Xing, "Multi-factor decision-making of cascading outages in power system based on electric network dissection," Power System Technology (POWERCON), 2014 International Conference on, Chengdu, 2014, pp. 176-180.

[21] William Kirstering '' Distribution System Design'', ''Distribution System Design and Analysis'', Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 2: Sec.-2.5, pp76.

[22] William Kirstering '' Introduction to Distribution'', ''Distribution System Design and Analysis'', Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 1: Sec.-1.5, pp21.

[23] Vlad, V.; Popa, C.D.; Graur, A.; Pentiuc, R.D., "Concepts and models for design and simulation of distributed control systems for future power grid," Harmonics and Quality of Power (ICHQP), 2014 IEEE 16th International Conference on , vol., no., pp.444,447, 25-28 May 2014

[24] Lampropoulos, I.; Vanalme, G.M.A.; Kling, W.L., "A methodology for modeling the behavior of electricity prosumers within the smart grid," Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES , vol., no., pp.1,8, 11-13 Oct. 2010

[25] Turan Gonen; ''Protection and Control in distribution system; ''Electric Power Distribution Systems and Engineering''; Second Edition; Washington DC, USA; CRC Press; 2013; Ch. 8; sec. 8.1-8.14; pp. 471-493.

[26] James A. Momoh '' Distribution Automation and Control Functions'', Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 2: Sec.-2.1, pp41.

[27] T A Short '' Distribution System Protection and Control'', Electric power distribution, Handbook, First Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2004, Ch. 8: Sec.-8.1, pp471-475.

[28] William Kirstering '' Distribution System Design'', ''Distribution System Design and Analysis'', Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 3: Sec.-3.1, pp61-75.

[29] Turan Gonen; ''Protection and Control in distribution system; ''Electric Power Distribution Systems and Engineering''; Second Edition; Washington DC, USA; CRC Press; 2013; Ch. 8; sec. 8.1-8.14; pp. 471-493.

[30] James A. Momoh '' Distribution Automation and Control Functions'', Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 2: Sec.-2.1, pp41.

[31] T A Short '' Distribution System Protection and Control'', Electric power distribution, Handbook, First Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2004, Ch. 8: Sec.-8.1, pp471-475.

[32] William Kirstering '' Distribution System Design'', ''Distribution System Design and Analysis'', Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 3: Sec.-3.1, pp61-75.

[33] Turan Gonen; ''Protection and Control in distribution system; ''Electric Power Distribution Systems and Engineering''; Second Edition; Washington DC, USA; CRC Press; 2013; Ch. 8; sec. 8.1-8.14; pp. 471-493.
[34] James A. Momoh '' Distribution Automation and Control Functions'', Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 2: Sec.-2.1, pp41.
[35] T A Short '' Distribution System Protection and Control'', Electric power distribution, Handbook, First Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2004, Ch. 8: Sec.-8.1, pp471-475.
[36] William Kirstering '' Distribution System Design'', ''Distribution System Design and Analysis'', Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 3: Sec.-3.1, pp61-75.
[37] D. Haughton and G. T. Heydt, "Smart distribution system design: Automatic reconfiguration for improved reliability," IEEE PES General Meeting, Minneapolis, MN, 2010, pp. 1-8.

[38] X. Dong, Z. Wu, Z. Liu, H. Ji, Z. Wang and P. Li, "Research and application on operation and control technologies of smart distribution network," 2016 China International Conference on Electricity Distribution (CICED), Xi'an, 2016, pp. 1-5.

[39] X. Zhou et al., "An overview on distribution automation system," 2016 Chinese Control and Decision Conference (CCDC), Yinchuan, 2016, pp. 3667-3671.

[40] R. M. J. Rathnayaka and K. Hemapala, "Developing of scalable SCADA in view of acquiring multi-protocol smart grid devices," 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai, 2016, pp. 182-187.

[41] A. I. Nousdilis, A. I. Chrysochos, G. K. Papagiannis and G. C. Christoforidis, "The impact of Photovoltaic Self-Consumption Rate on voltage levels in LV distribution grids," 2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Cadiz, 2017, pp. 650-655.

[42] Yong Zhang; YikangGu; Vlatkovic, V.; Xiaojuan Wang, "Progress of smart sensor and smart sensor networks," Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on , vol.4, no., pp.3600,3606 Vol.4, 15-19 June 2004 doi: 10.1109/WCICA.2004.1343265

[43] Moghe, R.; Lambert, F.C.; Divan, D., "Smart "Stick-on" Sensors for the Smart Grid," Smart Grid, IEEE Transactions on , vol.3, no.1, pp.241,252, March 2012 doi: 10.1109/TSG.2011.2166280

[44] Technology Roadmap Smart Grids, IEA, Paris, France, Tech. Rep., 2011. [Online]. Available: http://www.iea.org

[45] H. Farhangi, "The path of the smart grid," IEEE Power Energy Mag., vol. 8, no. 1, pp. 18–28, Jan./Feb. 2010.

[46] V. C. Gungoret al., "A survey on smart grid potential applications and communication requirements," IEEE Trans. Ind. Informat., vol. 9, no. 1, pp. 28–42, Feb. 2013.

[47] M. Sechilariu, W. Baochao, and F. Locment, "Building integrated photovoltaic system with energy storage and smart grid communication," IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 1607–1618, Apr. 2013.

[48] V. Gungoret al., “Smart grid technologies: Communication technologies and standards,” IEEE Trans. Ind. Informat., vol. 7, no. 4, pp. 529–539, Nov. 2011.

[49] M. Specht, S. Rohjans, J. Trefke, M. Uslar, and J. M. Gonzalez, “International smart grid roadmaps and their assessment,” ICST EAI Endorsed Trans. Energy Web, vol. 13, no. 1, pp. 1–18, 2013.

[50] NIST Framework and Roadmap for Smart Grid Interoperability Standards Release 2.0, NIST, US Dept. Commerce, Gaithersburg, MD, USA, Tech. Rep. NIST Publication 1108R2, 2012. [Online]. Available: http:// www.nist.gov

[51] IEC Smart Grid Standardization Roadmap, IEC, Geneva, Switzerland, Tech. Rep., Ed. 1.0, 2010. [Online]. Available: http://www.iec.ch

[52] IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads, USA, IEEE Std. 2030-2011, Sep. 10, 2011.

[53] The German Roadmap e-Energy/Smart Grids 2.0—Smart Grids Standardization Status, Trends and Prospects, German Commission for Electrical, Electronic and Information Technologies of DIN and VDE, Frankfurt, Germany, Tech. Rep., 2013. [Online]. Available: http://www. vde.com

[54] W. Tushar, J. A. Zhang, C. Yuen, D. B. Smith and N. Ul Hassan, "Management of Renewable Energy for a Shared Facility Controller in Smart Grid," in IEEE Access, vol. 4, no. , pp. 4269-4281, 2016.

[55] V. Calderaro, V. Galdi, A. Piccolo and P. Siano, "Improving reliability system by optimal sectionaliser placement in smart distribution grid," 2010 IEEE International Symposium on Industrial Electronics, Bari, 2010, pp. 2530-2536.

[56] D. Jia, X. Meng and X. Song, "Study on technology system of self-healing control in smart distribution grid," Advanced Power System Automation and Protection (APAP), 2011 International Conference on, Beijing, 2011, pp. 26-30

[57] Su Sheng, K. K. Li, W. L. Chan, Zeng Xiangjun and Duan Xianzhong, "Agent-based self-healing protection system," in IEEE Transactions on Power Delivery, vol. 21, no. 2, pp. 610-618, April 2006.

[58] X. Qiang, G. Haibin, F. Xugang and C. Zhenzhi, "Research on self-healing strategy of smart distribution grid based on improved ant colony algorithm," 2016 Chinese Control and Decision Conference (CCDC), Yinchuan, 2016, pp. 390-395.

[59] A. Zidan and E. F. El-Saadany, "A Cooperative Multiagent Framework for Self-Healing Mechanisms in Distribution Systems," in IEEE Transactions on Smart Grid, vol. 3, no. 3, pp. 1525-1539, Sept. 2012.

[60] L. Deng, J. Fei, C. Ban, C. Cai and X. Zhang, "The simulation of self-healing restoration control for smart distribution network," Software Engineering and Service Science (ICSESS), 2015 6th IEEE International Conference on, Beijing, 2015, pp. 482-485.

[61] Kang Taifeng et al., "An alarm management framework for self-healing smart distribution system," 2014 China International Conference on Electricity Distribution (CICED), Shenzhen, 2014, pp. 293-296.

[62] Wen Dan，Liu Min ‘’A Survey on Self-Healing Control of Smart Distribution Grid’’, 2012 International Conference on Future Electrical Power and Energy Systems, Lecture Notes in Information Technology, Vol.9

[63] J. W. Shim, T. Nam, J. Y. Jang, T. K. Ko, M. C. Ahn and K. Hur, "Towards a Self-Healing Electric Grid With Superconducting Fault Current Controllers," in IEEE Transactions on Applied Superconductivity, vol. 22, no. 3, pp. 5600904-5600904, June 2012.

[64] Z. Jiao, K. Men and J. Zhong, "A control strategy to fast relieve overload in a self-healing smart grid," 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, 2012, pp. 1-7.

[64] Z. Jiao, X. Wang and H. Gong, "Wide area measurement/wide area information-based control strategy to fast relieve overloads in a self-healing power grid," in IET Generation, Transmission & Distribution, vol. 8, no. 6, pp. 1168-1176, June 2014.

[65] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[66] V. Calderaro, V. Galdi, A. Piccolo and P. Siano, "Improving reliability system by optimal sectionaliser placement in smart distribution grid," 2010 IEEE International Symposium on Industrial Electronics, Bari, 2010, pp. 2530-2536.

[67] D. Haughton and G. T. Heydt, "Smart distribution system design: Automatic reconfiguration for improved reliability," IEEE PES General Meeting, Minneapolis, MN, 2010, pp. 1-8.

[68] L. Deng, J. Fei, C. Ban, C. Cai and X. Zhang, "The simulation of self-healing restoration control for smart distribution network," Software Engineering and Service Science (ICSESS), 2015 6th IEEE International Conference on, Beijing, 2015, pp. 482-485.

[69] E. K. Ismail and T. K. Sindhu, "Self-healing practice for an LT 11 kV overhead radial distribution network feeder," Power, Energy and Control (ICPEC), 2013 International Conference on, Sri Rangalatchum Dindigul, 2013, pp. 170-173.

[70] A. Bahmanyar et al., "Fast fault location for fast restoration of smart electrical distribution grids," 2016 IEEE International Smart Cities Conference (ISC2), Trento, Italy, 2016, pp. 1-6.

[71] A. Narimani, G. Nourbakhsh, G. F. Ledwich and G. R. Walker, "Impact of electric energy storage scheduling on reliability of distribution system," 2015 IEEE 11th International Conference on Power Electronics and Drive Systems, Sydney, NSW, 2015, pp. 405-408

[72] A. Zidan; M. Khairalla; A. M. Abdrabou; T. Khalifa; K. Shaban; A. Abdrabou; R. El Shatshat; A. M. Gaouda, "Fault Detection, Isolation, and Service Restoration in Distribution Systems: State-of-the-Art and Future Trends," in IEEE Transactions on Smart Grid , vol.PP, no.99, pp.1-16

[73]Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[74] James A. Momoh ‘’ Distribution Automation and Control Functions’’, Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 5: Sec.-5.1-5.3, pp-41.

[75] William HY. Kirstering ‘’ Introduction to Distribution System ’’, ‘’Distribution System Design and Analysis’’, Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch. 1: Sec.-1.3, pp-5.

[76] ‘’Jan Machowski, James R Bumby‘’ Electromechanical Dynamics – Large Disturbances’’, ‘’Power system Dynamics: stability and Control’’, Second Edition, ISBN 978-0-470-72558-0 (cloth), The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom, John Wiley & Sons Ltd, 2008, Ch. 8: Sec.-8.5, pp 354-360.

[77] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[78] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[79] Yong Zhang; Yikang Gu; Vlatkovic, V.; Xiaojuan Wang, "Progress of smart sensor and smart sensor networks," Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on , vol.4, no., pp.3600,3606 Vol.4, 15-19 June 2004

[80] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[81] Grid, N. (2017). [online] Available at: http://www2.nationalgrid.com/UK/Industry-information/Electricity-system-operator incentives/transmission-losses/ [Accessed 28 Oct. 2017].

[82] I. Colak, "Introduction to smart grid," 2016 International Smart Grid Workshop and Certificate Program (ISGWCP), Istanbul, Turkey, 2016, pp. 1-5.

[83] R. E. Brown, "Impact of Smart Grid on distribution system design," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, Pittsburgh, PA, 2008, pp. 1-4.

[84] ’Jan Machowski, James R Bumby‘’ Electromechanical Dynamics – Large Disturbances’’, ‘’Power system Dynamics: stability and Control’’, Second Edition, ISBN 978-0-470-72558-0 (cloth), The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom, John Wiley & Sons Ltd, 2008, Ch. 8: Sec.-8.5, pp 354-360.

[85] R. E. Brown, "Impact of Smart Grid on distribution system design," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, Pittsburgh, PA, 2008, pp. 1-4.

[86] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[87] James A. Momoh ‘’ Distribution Automation and Control Functions’’, Electric power distribution, automation, protection, and control, First Edition, ISBN-10: 0849368359, Washington DC, USA, CRC Press, September 2008, Ch. 5: Sec.-5.1-5.3, pp-41.

[88] M. Vadari, "Dynamic microgrids - A potential solution for enhanced resiliency in distribution systems," 2014 International Test Conference, Seattle, WA, USA, 2014, pp. 1-1

[89] Vlad, V.; Popa, C.D.; Graur, A.; Pentiuc, R.D., "Concepts and models for design and simulation of distributed control systems for future power grid," Harmonics and Quality of Power (ICHQP), 2014 IEEE 16th International Conference on , vol., no., pp.444,447, 25-28 May 2014

[90] Lampropoulos, I.; Vanalme, G.M.A.; Kling, W.L., "A methodology for modelling the behavior of electricity prosumers within the smart grid," Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES , vol., no., pp.1,8, 11-13 Oct. 2010

[91] Turan Gonen; ‘’Protection and Control in distribution system; ‘’Electric Power Distribution Systems and Engineering’’; Second Edition; Washington DC, USA; CRC Press; 2013; Ch. 8; sec. 8.1-8.14; pp. 471-493

[92] William HY. Kirstering ‘’ Introduction to Distribution System ’’, ‘’Distribution System Design and Analysis’’, Third Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2011, Ch.7 : Sec.-7.1-1.15, pp-145-190

[93] T A Short ‘’ Distribution System Protection and Control’’, Electric power distribution, Handbook, First Edition, ISBN- 0-8493-1791-6, Washington DC, USA, CRC Press LLC, September 2004, Ch. 8: Sec.-8.1, pp471-475.

[94] E. Serban, M. Ordonez, C. Pondiche, K. Feng, M. Anun and P. Servati, "Power management control strategy in photovoltaic and energy storage for off-grid power systems," 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Vancouver, BC, 2016, pp. 1-8.

[95] Su Sheng, K. K. Li, W. L. Chan, Zeng Xiangjun and Duan Xianzhong, "Agent-based self-healing protection system," in IEEE Transactions on Power Delivery, vol. 21, no. 2, pp. 610-618, April 2006.

[96] X. Qiang, G. Haibin, F. Xugang and C. Zhenzhi, "Research on self-healing strategy of smart distribution grid based on improved ant colony algorithm," 2016 Chinese Control and Decision Conference (CCDC), Yinchuan, 2016, pp. 390-395.

[97] A. Zidan and E. F. El-Saadany, "A Cooperative Multiagent Framework for Self-Healing Mechanisms in Distribution Systems," in IEEE Transactions on Smart Grid, vol. 3, no. 3, pp. 1525-1539, Sept. 2012.

[98] L. Deng, J. Fei, C. Ban, C. Cai and X. Zhang, "The simulation of self-healing restoration control for smart distribution network," Software Engineering and Service Science (ICSESS), 2015 6th IEEE International Conference on, Beijing, 2015, pp. 482-485.

[99] Kang Taifeng et al., "An alarm management framework for self-healing smart distribution system," 2014 China International Conference on Electricity Distribution (CICED), Shenzhen, 2014, pp. 293-296.

[100] Wen Dan，Liu Min ''A Survey on Self-Healing Control of Smart Distribution Grid'', 2012 International Conference on Future Electrical Power and Energy Systems, Lecture Notes in Information Technology, Vol.9

[101] J. W. Shim, T. Nam, J. Y. Jang, T. K. Ko, M. C. Ahn and K. Hur, "Towards a Self-Healing Electric Grid With Superconducting Fault Current Controllers," in IEEE Transactions on Applied Superconductivity, vol. 22, no. 3, pp. 5600904-5600904, June 2012.

[102] Z. Jiao, K. Men and J. Zhong, "A control strategy to fast relieve overload in a self-healing smart grid," 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, 2012, pp. 1-7.

[103] Z. Jiao, X. Wang and H. Gong, "Wide area measurement/wide area information-based control strategy to fast relieve overloads in a self-healing power grid," in IET Generation, Transmission & Distribution, vol. 8, no. 6, pp. 1168-1176, June 2014.

[104] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[105] V. Calderaro, V. Galdi, A. Piccolo and P. Siano, "Improving reliability system by optimal sectionaliser placement in smart distribution grid," 2010 IEEE International Symposium on Industrial Electronics, Bari, 2010, pp. 2530-2536.

[106] D. Haughton and G. T. Heydt, "Smart distribution system design: Automatic reconfiguration for improved reliability," IEEE PES General Meeting, Minneapolis, MN, 2010, pp. 1-8.

[107] L. Deng, J. Fei, C. Ban, C. Cai and X. Zhang, "The simulation of self-healing restoration control for smart distribution network," Software Engineering and Service Science (ICSESS), 2015 6th IEEE International Conference on, Beijing, 2015, pp. 482-485.

[108] A. Kulkarni and M. Amlekar, "Intelligent Power Monitoring Switch using MSP430," 2015 International Conference on Pervasive Computing (ICPC), Pune, 2015, pp. 1-4

[109] L. F. R. Vásquez, J. G. B. Pérez and C. Duarte, "Residential electric distribution system based on Intelligent Power Switch," 2016 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), Ixtapa, 2016, pp. 1-5

[110] M. Nour, H. Ramadan, A. Ali and C. Farkas, "Impacts of plug-in electric vehicles charging on low voltage distribution network," 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), Aswan, 2018, pp. 357-362.

[111] Strasser, T.; Andren, F.; Kathan, J.; Cecati, C.; Buccella, C.; Siano, P.; Leitao, P.; Zhabelova, G.; Vyatkin, V.; Vrba, P.; Marik, V., "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," Industrial Electronics, IEEE Transactions on, vol.62, no.4, pp.2424,2438, April 2015

[112] A. Zidan; M. Khairalla; A. M. Abdrabou; T. Khalifa; K. Shaban; A. Abdrabou; R. El Shatshat; A. M. Gaouda, "Fault Detection, Isolation, and Service Restoration in Distribution Systems: State-of-the-Art and Future Trends," in IEEE Transactions on Smart Grid , vol.PP, no.99, pp.1-16

[113] I. Dusparic, A. Taylor, A. Marinescu, V. Cahill and S. Clarke, "Maximizing renewable energy use with decentralized residential demand response," 2015 IEEE First International Smart Cities Conference (ISC2), Guadalajara, 2015, pp. 1-6.

[114] C. Alcaraz and J. Lopez, "A Cyber-Physical Systems-Based Checkpoint Model for Structural Controllability," in IEEE Systems Journal, vol. PP, no. 99, pp. 1-12.

[115] S. Otoum, B. Kantarci and H. T. Mouftah, "Hierarchical trust-based black-hole detection in WSN-based smart grid monitoring," 2017 IEEE International Conference on Communications (ICC), Paris, 2017, pp. 1-6.

[116] A. A. S. Emhemed and G. M. Burt, "An Advanced Protection Scheme for Enabling an LVDC Last Mile Distribution Network," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2602-2609, Sept. 2014.

[117] A. K. Srivastava, A. L. Hahn, O. O. Adesope, C. H. Hauser and D. E. Bakken, "Experience With a Multidisciplinary, Team-Taught Smart Grid Cyber Infrastructure Course," in IEEE Transactions on Power Systems, vol. 32, no. 3, pp. 2267-2275, May 2017.

[118] M. Sănduleac, L. Alacreu, L. Pons, A. Solar, R. Alemany and C. Stănescu, "Medium/low voltage Smart Grid observability and PQ assessment with Unbundled Smart Meters," 2016 IEEE International Energy Conference (ENERGYCON), Leuven, 2016, pp. 1-6.