Minimum DC link Voltages for the Generator Bridge Converter of a SCIG Based Variable Speed Wind Turbine with Fully Rated Converters

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Abstract. Squirrel Cage Induction Generator (SCIG) based variable speed wind turbine with Fully Rated Converters (FRC) is a popular choice in the industry for the modern multi mega-watt wind turbines. Typical FRC system uses a fixed DC link voltage that allows operation in all steady state and dynamic operating conditions while allowing the modulation index of the PWM scheme to vary. However, the analysis made in this paper shows that at steady state, in the maximum power point tracking region where the turbine is operated at variable speeds with generator controlled using Rotor Flux Oriented Control (R-FOC), it is possible to operate the Generator Bridge (GB) converter with significantly lower DC link voltages than the fixed value used, by maintaining maximum modulation index in the PWM scheme. This paper presents a methodology of determining the minimum DC link voltages for such a system supported by simulation results showing the successful operation of a GB converter with minimum DC link voltages in the maximum power point tracking region.

Key words

DC link voltage, Modulation Index, IGBT, Generator Bridge Converter, SCIG

1. Introduction

Variable speed wind turbines with Squirrel Cage Induction Generators (SCIG) and Fully Rated Converters (FRC) are used by some leading manufacturers in the industry for modern large wind turbines of multi-megawatt capacity. Power converter manufacturers strive for continuous improvement of products and systems, and achieving higher inherent reliability is one of the areas of research.

Typically, the FRC consists of back to back pulse width modulated voltage source converters based on Insulated Gate Bipolar Transistor (IGBT) modules, interconnected through DC link capacitors [1]-[5]. Authors' previous work [1] presented minimum DC link voltage operation of the network bridge converter that covered first part of the overall objective of operating the FRC system with variable DC link voltages optimised at minimum values. This paper presents the theoretical and quantitative analysis on determining the minimum DC link voltages required for the Generator Bridge (GB) converter of an FRC system with SCIG controlled with Rotor-Flux Oriented Control (R-FOC). The quantitative analysis is based on data of a commercial multi-megawatt FRC system. Supporting simulation results are presented based on MatLab/Simulink simulation model.

2. Minimum DC Link Voltages for Generator Bridge Converter

The schematic diagram of the GB side used for the analysis is shown in Fig. 1. The GB converter is controlled with R-FOC in synchronous d-q reference frame with rotor flux linkage aligned with d axis having rated rotor flux linkage. The controller feeds the magnitude of the space vector $V_{s,gen}*$ of the voltages to be generated at GB converter terminals and its angle θ_{gen} to the PWM reference signal generator.

The methodology of determining the minimum DC link voltage for the above GB converter system is as follows.
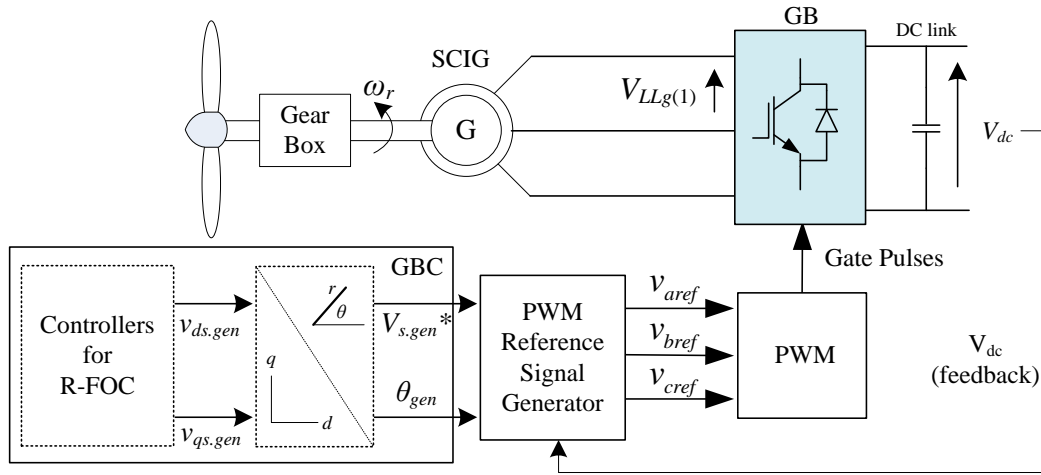
Fig. 1. Generator bridge side of the wind energy system

A. Methodology

The notation of parameters and variables used in this section are listed in Table 1 below.

Table I. – Nomenclature

Parameter/Variable	Notation	Unit
Stator d axis voltage	$v_{ds,gen}$	V
Stator q axis voltage	$v_{qs,gen}$	V
Stator d axis current	i_{ds}	A
Stator q axis current	i_{qs}	A
Generator rotor speed (Mechanical)	ω_r	rad/s
Generator rotor speed (Electrical)	ω_{re}	rad/s
Synchronous speed (Electrical)	ω	rad/s
Electromagnetic Torque of SCIG	T_e	Nm
Pair of poles	p	-
Stator resistance	R_s	Ω
Rotor resistance	R_r	Ω
Stator inductance	L_s	H
Rotor inductance	L_r	H
Magnetization inductance	L_m	H
Rated rotor flux linkage	λ_r	Vs
DC link voltage	V_{dc}	V
Modulation Index	m	-
Maximum Modulation Index	m_{max}	-
Fundamental frequency line to line voltage at GB converter terminals	$V_{LLg(1)}$	V

Space Vector Modulation (SVM) PWM is used in this analysis where the anticipated $V_{LLg(1)}$ at steady state is related to the V_{dc} by equation (1).

$$V_{LLg(1)} = m \times \frac{V_{dc}}{\sqrt{2}}; 0 \leq m \leq 1 \qquad (1)$$

$V_{LL(g)1}$ required depend on the power level to be exported by the GB converter under prevailing wind conditions and, the control algorithm employed. Normally V_{dc} is kept at a constant while allowing m to vary to develop different $V_{LL(g)1}$.

However if m can be maintained at its maximum m_{max}, the GB can be operated with respective minimum DC link voltage $V_{dc,min}$ given by equation (2) when delivering a given power level determined by the prevailing wind condition.

$$V_{dc,min} = \frac{V_{LLg(1)}}{\sqrt{2}m_{max}} \qquad (2)$$

Theoretically m_{max} is 1 without over modulation, however in practice m_{max} is slightly lower due to practical limitations such as minimum pulse width and dead times [1].

Derivation of $V_{LLg(1)}$ to determine $V_{dc,min}$ is as follows. The generator speed is controlled to meet maximum power point tracking where the power (P) vs. ω_r is available for a given wind turbine generator. Assuming no losses, corresponding T_e vs. ω_r characteristics can be derived using the expression P = $T_e\omega_r$. With the use of these characteristics and assuming that rated rotor flux linkage is maintained, i_{ds} and i_{qs} can be calculated using equations (3) and (4) respectively [2],[10].

$$i_{ds} = \frac{\lambda_r}{L_m} \qquad (3)$$

$$i_{qs} = \frac{T_e}{(3/2)p(L_m/L_r)\lambda_r} \qquad (4)$$

Synchronous speed ω at each power and speed combination can be calculated using equation (5) obtained by rearranging a standard expression for T_e [2],[10].

$$\omega = \frac{2}{3}\frac{T_e}{pR_r\lambda_r^2} + \omega_{re} \qquad (5)$$

Using i_{ds}, i_{qs} and ω derived from equations (3) to (5) above, $v_{ds,gen}$ and $v_{qs,gen}$ can be calculated using equations (6) and (7) where $\sigma = 1 - L_m^2/(L_s + L_r)$ [2],[9],[10].

$$v_{ds.gen} = R_s i_{ds} - \omega \sigma L_s i_{qs} \qquad (6)$$

$$v_{qs.gen} = R_s i_{qs} - \omega \frac{L_m}{L_r} \lambda_r + \omega \sigma L_s i_{ds} \qquad (7)$$

These $v_{ds,gen}$ and $v_{qs,gen}$ are used in equations (8) to derive $V_{s,gen}*$.

$$V_{s,gen}* = \sqrt{\frac{3}{2}\left(v_{d.gen}^2 + v_{q.gen}^2\right)} \qquad (8)$$

Under balanced conditions at steady state, $V_{s,gen}*$ is equal to $V_{LLg(1)}$. Therefore, $V_{dc,min}$ can be calculated using equation (2).

Above methodology is used to calculate the $V_{dc,min}$ for a GB converter of a commercial wind turbine system in the following section.

B. Calculation of $V_{dc,min}$ for a commercial multi-megawatt wind turbine

A quantitative analysis was carried out using the data of a commercial multi-megawatt wind turbine system. Due to the commercial sensitivity of data, results are presented in per unit (pu). Fig. 2 (a) shows the power vs. generator rotor speed characteristics of the wind turbine from 0 to 1pu speed range.
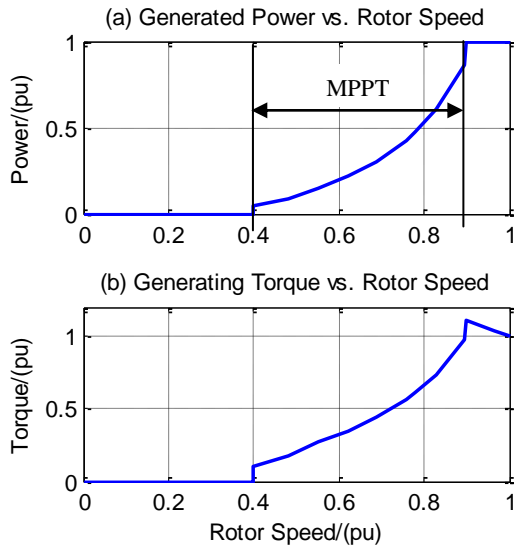

Fig. 2. (a) Power vs. ω_r and (b) T_e vs. ω_r characteristics of the wind turbine under consideration

The rated rotor speed here is when the SCIG is operating at generating mode while delivering rated power. The speed range 0.4pu to 0.897pu corresponds to maximum power point tracking (MPPT) and above that constant

power operation. The resulting torque vs. speed curve is shown in Fig. 2 (b).

The m_{max} specified for the GB converter under consideration is 0.9775. The calculated $V_{LLg(1)}$, $V_{dc,min}$ and stator electrical frequency f ($= \omega/2\pi$Hz) for each speed and power combinations of Fig. 2 (a) are given in Table II. $V_{dc,min}$ is normalized with respect to the rated DC link of 1100V.

Table II. – Calculated $V_{LLg(1)}$ $V_{dc,min}$ and f for the GB Converter

Speed (pu)	Power (pu)	$V_{LLg(1)}$ (pu)	$V_{dc,min}$ (pu)	f (Hz)
0.400	0.043	0.469	0.447	19.3
0.483	0.087	0.547	0.539	23.3
0.552	0.148	0.624	0.616	26.6
0.621	0.217	0.701	0.693	29.9
0.690	0.304	0.780	0.754	33.2
0.759	0.426	0.857	0.830	36.5
0.779	0.478	0.881	0.853	37.5
0.828	0.609	0.936	0.906	39.8
0.897	0.870	1.017	1.004	43.1
0.897	1.000	1.019	1.006	43.1
0.966	1.000	1.097	1.083	46.4
1.000	1.000	1.136	1.099	48.1

Table II shows that the GB converter terminal voltage increases with the speed of the wind turbine. In the MPPT region below 0.897pu speed, $V_{dc,min}$ is below the rated value. For example, at a speed of 0.690pu, $V_{dc,min}$ is 0.754pu which is about 25% below the rated value. Maximum reduction of DC link voltage of approximately 45% can be achieved when running at the lowest speed delivering the lowest power. When run at the highest speed delivering the highest power, a reduction of approximty10% can be achieved. At speeds above 0.897pu , $V_{LLg(1)}$ exceeds the rated value which demands a $V_{dc,min}$ higher than 1pu. In this region with flux weakening is adopted in order to clamp the required $V_{LLg(1)}$ to the rated value.

Simulations were carried out to demonstrate the operation with the $V_{dc,min}$. Description of the simulation model and the simulation results are presented in the following section.

3. Simulation of GB converter with $V_{dc,min}$

A. Simulation Model

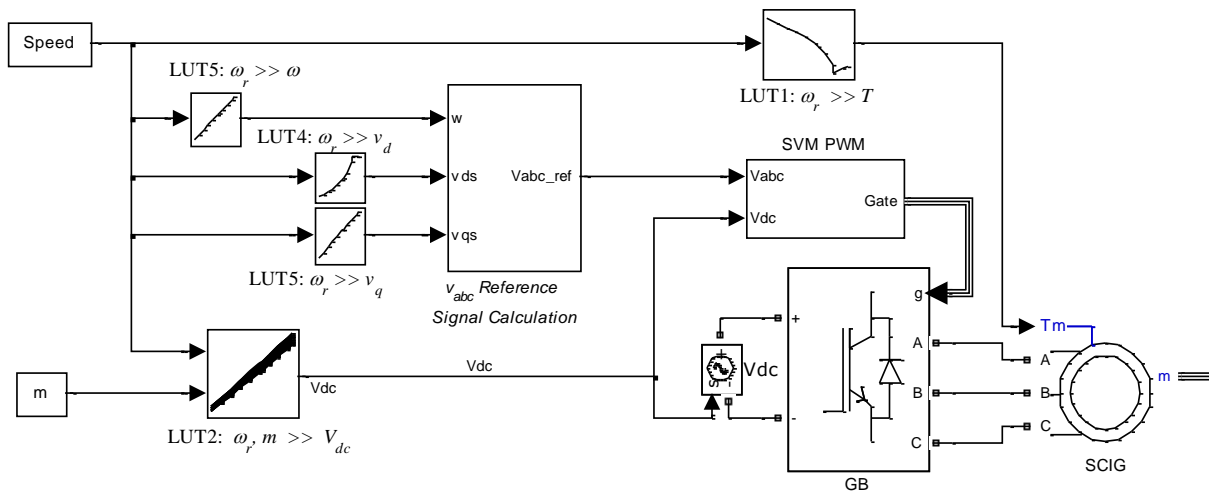The GB side system shown in Fig.1 was modelled using MatLab/Simulink. The model is shown in Fig. 3.

Fig. 3. Simulink Model Layout

The SCIG is modelled using the inbuilt asynchronous machine model available in Simulink SimPowerSystems block set. The inertia of the turbine shaft and the drive train was referred to the generator shaft. The torque input to the SCIG is fed by LUT1 which models the MPPT characteristics shown in Fig. 2. (a). The GB converter is modelled as an IGBT based two level converter fed with an ideal controlled DC voltage source. The control input given to the DC source is the output of two dimensional look up table LUT2 which contains V_{dc} Vs ω_r characteristics with m as a parameter. Inputs to LUT2 are speed of and m. In this case, m is set to $m_{max} = 0.9775$ which gives $V_{dc,min}$ at any given operational speed. With speed as the input, LUT3, LUT4 and LUT5 feeds synchronous speed, $v_{ds,gen}$ and $v_{qs,gen}$ respectively to the V_{abc} reference signal generator which consists of blocks for the dq-to-abc transformation and the calculation of the angle θ_{gen} needed for the generation of the reference signals required for the SVM PWM block. The PWM technique used is basic SVM with a switching frequency of 1.75 kHz. It also uses the DC link voltage from LUT2 as an input for derivation of the gate pulses that is fed to the GB converter. The three modulation signals for each phase inside this block have peaks equal to the modulation index m. Modulation signals are compared with the triangular carrier waveform bound between ±1. Details of this implementation can be found in [9]. The parameters of the model are based on the system used in the quantitative analysis. All look up tables are loaded at the start of a simulation.

B. Simulation Results

Fig.4 shows key steady state waveforms for two fundamental frequency cycles when the speed input is 0.690pu and the modulation index set to the maximum value of 0.9775.
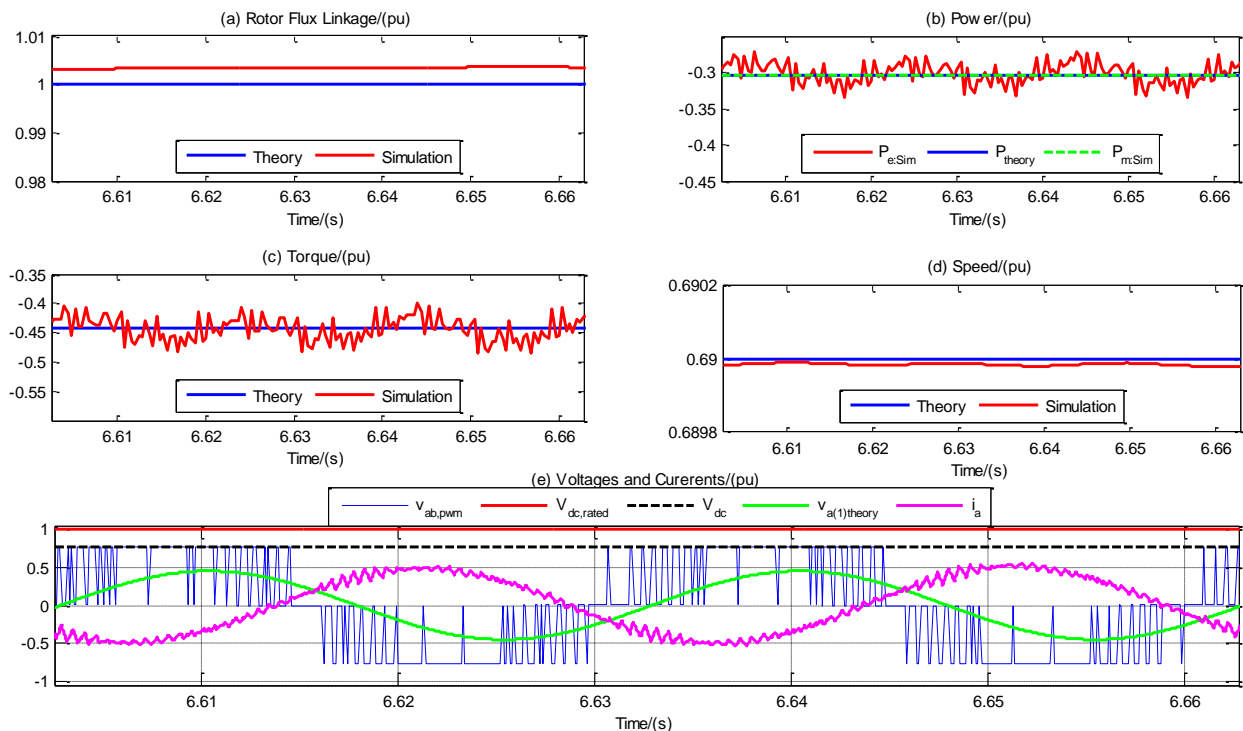

Fig. 4. Waveforms when running the SCIG at speed of 0.690pu and $m = 0.9775$ over 0.06s time span

The fundamental frequency of the generated stator voltages is 33.2Hz. The DC link voltage is 0.754pu. Fig 4. (a) shows that the rotor flux linkage in the simulation is 0.5% above the rated value which is insignificant. Fig 4. (b) shows instantaneous electrical power fed through the GB converter ($P_{e:Sim}$), and mechanical power fed to the generator shaft ($P_{m:Sim}$). $P_{e:Sim}$ fluctuates about the theoretically expected power (P_{theory}) of -0.304pu. By a moving average technique the average value was calculated and was found to be -0.302. Similarly torque variation shown in Fig 4. (c) fluctuates about the expected value of -0.45pu. The negative power and torque indicates that SCIG is operating in the generating mode. Fig 4. (d) shows that the rotor speed is accurately maintained at the expected value of 0.690pu. The rated DC link voltage $V_{dc,rated} = 1$pu and the minimum DC link of 0.754pu are also shown in Fig 4 (e) along with phase *a-b* line voltage at GB converter terminals $v_{ab,pwm}$.

Additional waveforms of theoretically expected fundamental frequency phase *a* voltage $v_{a(1)theory}$ and phase *a* current i_a are also given.

Fig. 5. shows the triangular waveform (V_{tri}) and phase 'a' modulation signals generated within the SVM PWM block resulted in simulation at different operating speeds. The control signals are arranged in a way to be horizontally symmetric about the signal at the lowest speed of 0.400pu for comparison. This clearly shows that peak of the modulation signal is maintained at the same value at each case. This value is equal to the maximum *m* = 0.9775.

Plots (a) to (i) in Fig. (6) shows the simulation waveforms of $v_{ab,pwm}$ for each of the operating speeds in MPPT region along with the operating DC link voltages over a 0.6s time span.
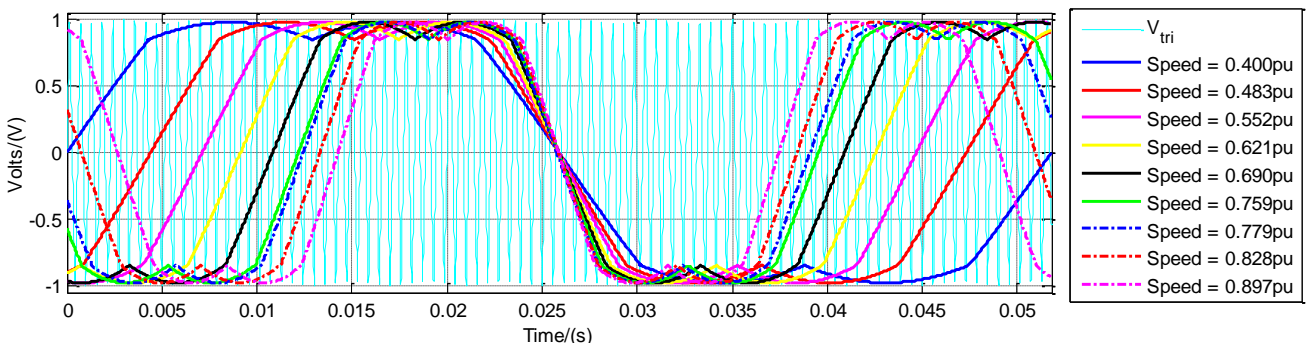

Fig. 5. Triangular waveform V_{tri} and Phase 'a' control signals generated in SVM block at different operating speeds with *m* = 0.9775
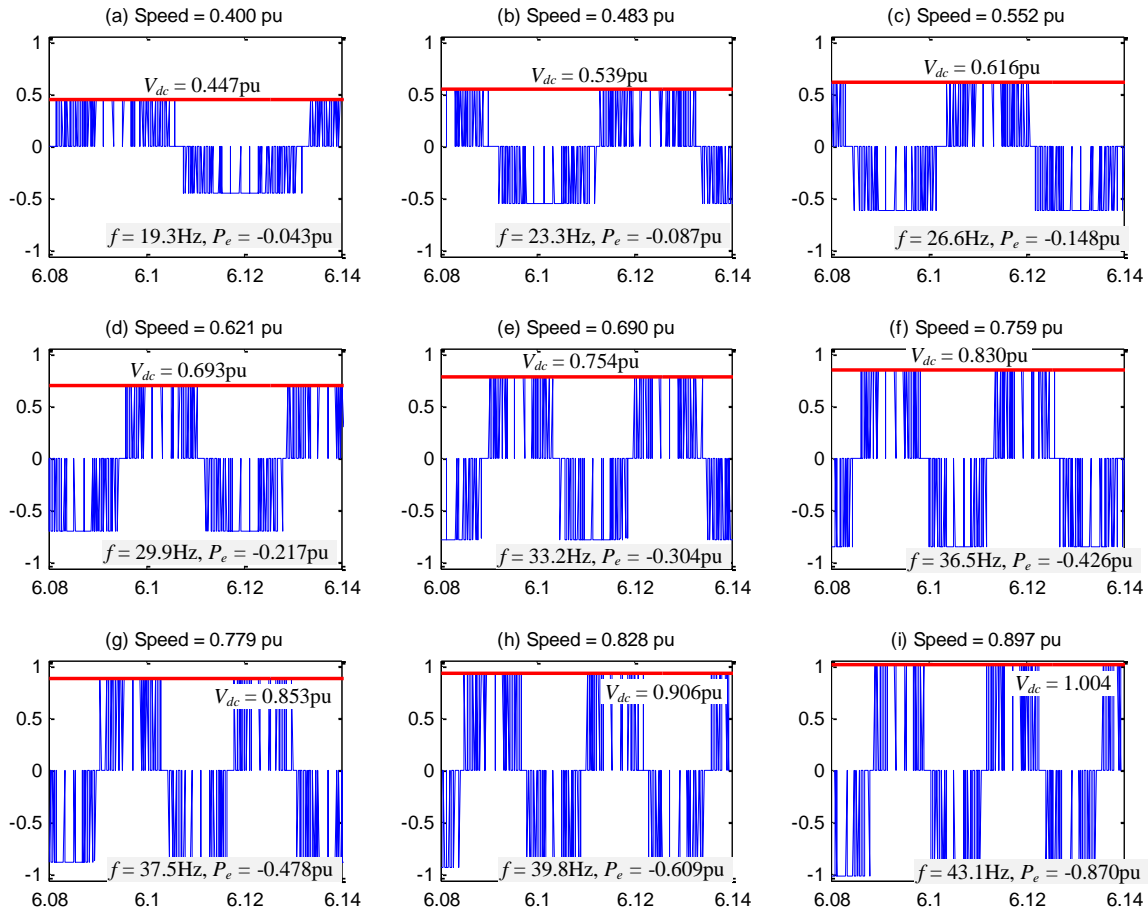

Fig. 6. $v_{ab,pwm}$ waveforms at steady state over the MPPT range with *m* = 0.9775 at different operating speeds over 0.6s time span

Stator fundamental frequency and, the average power delivered through the GB converter (P_e) are stated in each plot. For each speed, $v_{ab,pwm}$ is different in fundamental frequency set by the frequency of the modulating signals, and its maximum value set by V_{dc}. The similarity in the composition over a cycle is an indication of having maintaining m at 0.9775 in each case. When the average power levels delivered are concerned, it is exactly the same in magnitude to the theoretically expected values.

Fig. 7. shows the operating chart of the SCIG in the wind turbine in its torque vs. speed. The blue curve shows the inverted curve of Fig. 2 (a). The average T_e obtained from simulation for different speeds are given by the red points. Green vertical lines are the torque speed characteristics set by the R-FOC. Each curve corresponds to the specific f and $V_{llg(1)}$ written on the curve as shown in the figure. The operating points from the simulations coincide with the intersection points of the blue curve and the corresponding green curve as expected. Respective constant power curves given by magenta lines going through the operating points indicates accurate power flow from the SCIG to the DC link through GB converter.
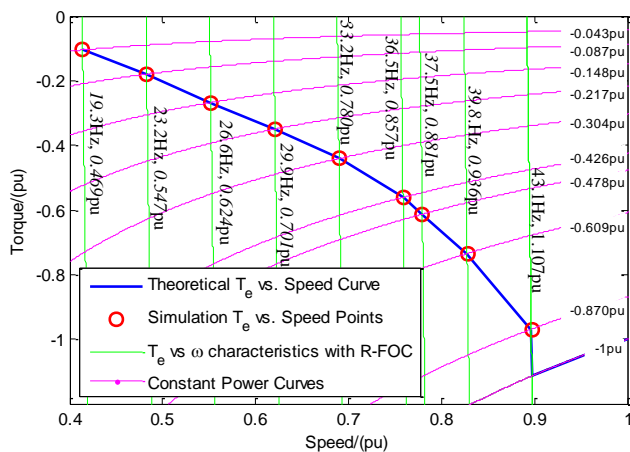

Fig. 7. Torque vs. Speed Characteristics and Constant power Curves

4. Discussion

The forgoing analysis and simulation shows that in the MPPT region, the GB can operate satisfactorily in the steady state with minimum DC link voltages with R-FOC set to rated flux linkage. Because of the intermittent nature of wind resources, wind turbines will run in this range over long time intervals during normal operation. Therefore, the reduction of electrical and thermal stresses achievable with reduced DC link voltages is off significant benefit. Cosmic ray induced failure rates could also be lowered. IGBT modules used in the existing FRCs are rated at 1700V. The 60% margin above which failure rates increase exponentially [6]-[8] in this case is 1020V or 0.927pu. According to above results, operation of the GB converter with DC link voltages well below this margin is possible in MPPT range. However the integration of this to the overall control schemes needs coordination with minimum DC link voltage requirement of the network bridge converter. This work is on-going and the combined operation will be presented in future publications.

5. Conclusions

The GB converter of a SCIG based variable speed wind turbine with FRCs controlled with R-FOC maintaining rated flux could employ significantly lower DC link voltages than the predetermined fixed voltage normally used, when operating in the MPPT range. The minimum DC link voltages can be achieved by maintaining the maximum modulation index in the PWM algorithm. Integration of the use of minimum DC link voltages to control algorithms could be highly beneficial in reducing the operating stresses on the IGBT modules in the power converters to realize higher inherent reliability. However integration of this into the control algorithms needs coordination with minimum DC link voltage requirement of the network bridge converter.

Acknowledgement

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