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Maximum Power-Point Tracking of Wind Turbine using Doubly Fed Induction Generator in Wind Power System

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ABSTRACT –

Now a day, application of Doubly Fed Induction Generator has become famous in large Wind Power System due to Variable Speed operation and Partial Scale Power Electronics converters. The Voltage Oriented Vector Control Strategy has been employed for RSC & GSC for satisfying requirement likes Real & Reactive Power Control and Grid Synchronization. In this paper, main focus is to performance operation of DFIG under different operating condition for generating maximum possible power from Wind Turbine. Simulation of DFIG connected with Grid and its associated Power Electronic converter has been carried in MATLAB using Standard PI Controller.

KEYWORDS - Doubly Fed Induction Generator (DFIG), Grid Voltage Oriented Vector Control (GVOVC) Technique, Stator Voltage Oriented Vector Control (SVOVC) Technique Syncronously Rotating Reference Frame (SRRF)

NOMELCLATURE

$v_s,\ v_r$	Stator & Rotor voltage respectively
$i_s,\ \ i_r$	Stator & Rotor current respectively
$\lambda_s,\ \ \lambda_r$	Stator & Rotor flux respectively
$R_s, \& \ R_r$	Stator & Rotor resistance respectively
$L_s, \& \ L_r$	Stator & Rotor self inductance respectively
L_m	Magnetizing inductance
v_g	Grid voltage
i_g	Grid Converter current
$p_g \& \ Q_g$	Exchange of Real & Reactive power between Grid and GSC respectively
$P_s \ \& \ P_r$	Stator & Rotor Real power respectively
P_t	Total Real power fed to Grid

Q_s & Q_r Stator & Rotor reactive power respectively

T_e Electromagnetic torque

ω_e Synchronous angular frequency

ω_r Rotor electrical angular frequency

ω_s Slip angular frequency

s Slip

d Subscript indicates direct axis componet of varaible

q Subscript indicates quadrature axis compent of vaiable

$*$ Subscript indicates reference value

v_{dc} Voltage across DC-Link

I. INTRODUCTION

The DFIG is a Slip Ring Induction M/C whose Stator winding connected with Grid directly, where as Rotor winding connected with Grid via Back-to-Back PE Converter as shown in fig (1). It permits Variable Speed Constant Frequency (VSCF) - operation by adjusting Frequency & Phase-Sequence of injected rotor current to compensate any deviation of rotor speed from the synchronous speed. With help of Back to Back Converter PE in Rotor Circuit, DFIG can be operate for generating electrical energy from Sub-Synchronous to Super-Synchronous Speed range [2]. Vector Control Technique (VCT) are employed for both RSC & GSC for achieving decouple control of Real & Reactive Power.[3] As the wind is highly variable nature, Total Energy Out-put of Wind Turbines using DFIG is more as compared to other types of Wind Turbines [4]

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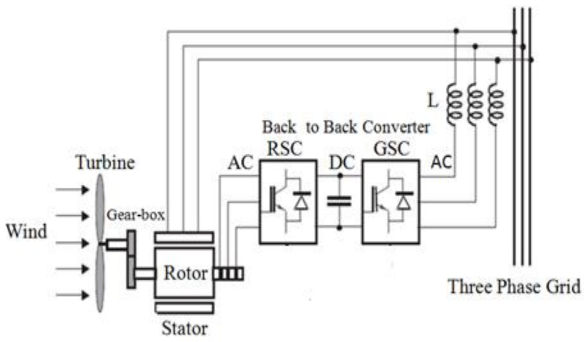

Fig.1 Basic Electrical Configuration for DFIG

Section 2 shows control system for GSC. Section 3 shows control system for RSC. Section IV shows simulation circuit along with set-up. Section 4 gives simulation results. Finally section 5 gives conclusion of analysis.

II. COTROL SYSTEM OF GRID SIDE CONVERTER

The purpose of GSC is to keep dc-link voltage at fix reference value without considering power flow between Rotor & Grid and controls exchange of Reactive Power between Grid & GSC. The GVOVC technique is used to solve these issues.

A. Dynamic Model For GSC system

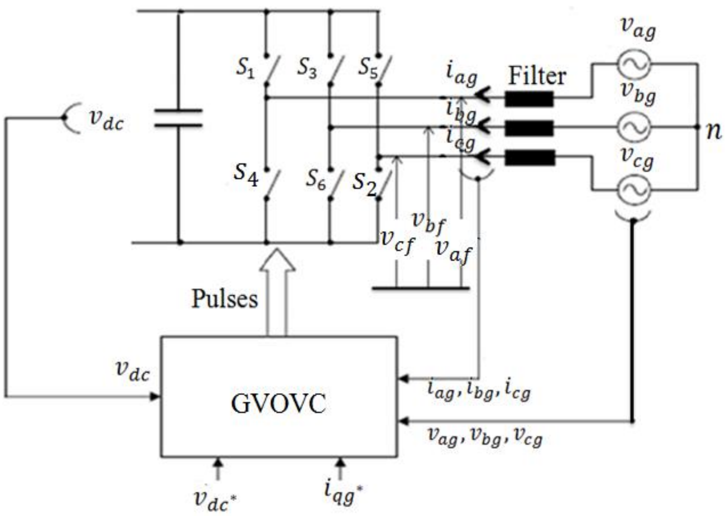

Fig 2: Schematic Diagram for GSC System

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Voltage balanced equation of GSC System is as under;

$$\begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix} = R_f \begin{bmatrix} i_{ag} \\ i_{bg} \\ i_{cg} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{ag} \\ i_{bg} \\ i_{cg} \end{bmatrix} + \begin{bmatrix} v_{af} \\ v_{bf} \\ v_{cf} \end{bmatrix} \qquad (1)$$

Transformation of equation (1) into synchronously rotating reference frame yield:

$$v_{dg} = R_f i_{dg} + L_f\, p i_{dg} - \omega_e L_f i_{qg} + v_{df} \qquad (2)$$

$$v_{qg} = R_f i_{qg} + L_f\, p i_{qg} + \omega_e L_f i_{dg} + v_{qf} \qquad (3)$$

Where terms $\omega_e L_f i_{qg}$ and $\omega_e L_f i_{dg}$ are due to the rotation effect of reference frame.

Continuing with the model, the exchange of Real and Reactive Power between Grid and GSC is given by the equation:

$$P_g = \frac{3}{2}(v_{dg} i_{dg} + v_{qg} i_{qg}) \qquad (4)$$

$$Q_g = \frac{3}{2}(v_{qg} i_{dg} - v_{dg} i_{qg}) \qquad (5)$$

B. Alignment of Synchronously Rotating Reference Frame :

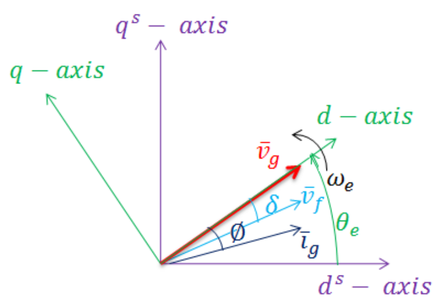

Fig 3. Alignment of SRRF along position of Grid Voltage

From vector diagram as shown in fig (3), it is clear that $v_{qg} = 0$ and$v_{ds} = |v_g|$. The substitution of these values into equations (4-5) yield:

$$P_g = \frac{3}{2} v_g i_{dg} \qquad (6)$$

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$$Q_g = -\frac{3}{2} v_g i_{qg} \qquad (7)$$

From above equations (6-7), Real & Reactive power will be proportional d *and* $q -$ axes grid converter current respectively. Thus an alignment of the $d -$ axis of SRRF along with Grid Voltage $\bar{v}_g$ yield simple and decouple control of Real & Reactive Power.

C. Control Algorithm of Rotor Side Converter

Grid Voltage Orientated Vector Control Technique employs two current loops: one for $d -$ axis current component i_{dg} and other for $q -$ axis current component i_{qg}.

The $d -$ axis reference grid converter current i_{dg^*} is get from dc-link voltage error $(v_{dc}^* - v_{dc})$ processed through proportional-integral (PI) controller as shown in figure 4.

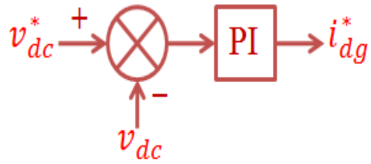

Figure 4: Determination of d-Axis Reference Grid Converter Current

The i_{qg^*} will determines the power factor of Grid Side Supply (i.e. Reactive power at the Grid Terminal) and so generally it may set to zero value for keeping exchange of Reactive power between Grid & GSC equal to zero.

The d & $q -$ axes reference and actual grid converter current are compared with each other respectively in order to get v'_{dg} *and* v'_{qg} as shown in fig (5).

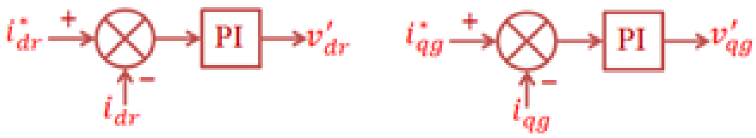

Figure.5: Determination of Control Signals for GSC

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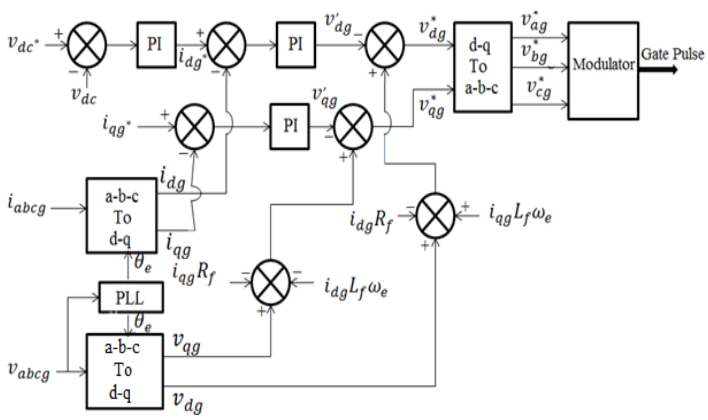

Fig 6: B.D. of Grid Voltage Oriented Vector Control Tech. for GSC

From fig 6, it is clear that from v_{dc}^{*} and i_{qg}^{*}, it generates gate pulses for $s_1\ to\ s_6$. The modulator generates pulses from $a-b-c$ reference voltages: v_{ag}^{*}, v_{bg}^{*} and v_{cg}^{*} which are first generated in the d-q form i.e. v_{dg}^{*} and v_{qg}^{*}. These $d-q$ reference voltages v_{dg}^{*} and v_{qg}^{*} are controlled separately from $d-q$ current controller. Thus by changing v_{dg}, i_{dg} is mainly changed whereas by changing v_{qg}, i_{qg} is mainly changed. Finally, the voltage compensating term are adding at the output of each current controller to achieve good dynamic response. Thus the reference voltage becomes as given below:

$$v_{dg^*} = -v_{dg'} + (v_{dg} - R_f i_{dg} + L_f \omega_e i_{qg}) \qquad (7)$$

$$v_{qg^*} = -v_{qg'} + (v_{qg} - R_f i_{\ qg} - L_f \omega_e i_{dg}) \qquad (8)$$

III. COTROL SYSTEM OF ROTOR (RSC) SIDE CONVERTER

The RSC provides excitation for the rotor winding. The purpose of RSC is to control torque, speed and PF of stator terminals. It provides a variable frequency excitation as per available wind speed for generating maximum possible out- put power. The SVOVC technique is used to solve these issues.

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A. DFIG Model

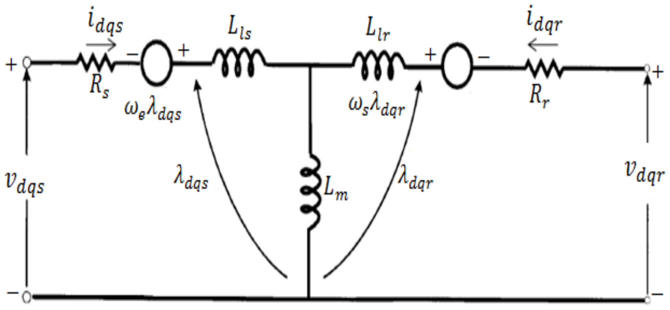

Figure.7: Equivalent Circuit of DFIG into SRRF

The equations of stator and rotor voltages as per fig (7) are as under:

$$v_{ds} = R_s i_{ds} + p\lambda_{ds} - \omega_e\lambda_{qs} \qquad (10)$$

$$v_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_e\lambda_{ds} \qquad (11)$$

$$v_{dr} = R_r i_{dr} + p\lambda_{dr} - \omega_s\lambda_{qr} \qquad (12)$$

$$v_{qr} = R_r i_{qr} + p\lambda_{qr} + \omega_s\lambda_{dr} \qquad (13)$$

Where, $\omega_s = \omega_e - \omega_r$

From figure 7, the flux linkages in terms of inductance and current are given by

$$\lambda_{ds} = L_s i_{ds} + l_m i_{dr} \qquad (14)$$

$$\lambda_{dr} = L_r i_{dr} + l_m i_{ds} \qquad (15)$$

$$\lambda_{qs} = L_s i_{qs} + l_m i_{qr} \qquad (16)$$

$$\lambda_{qr} = L_r i_{qr} + l_m i_{qs} \qquad (17)$$

Where, $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$

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The Electrical Powers of the Stator & Rotor are given by

$$P_s = \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \qquad (18)$$

$$P_r = \frac{3}{2}(v_{dr}i_{dr} + v_{qr}i_{qr}) \qquad (19)$$

$$Q_s = \frac{3}{2}(v_{qs}i_{ds} - v_{ds}i_{qs}) \qquad (20)$$

$$Q_r = \frac{3}{2}(v_{qr}i_{dr} - v_{dr}i_{qr}) \qquad (21)$$

And Electromagnetic Torque is calculated as below:

$$T_e = \frac{3}{2}\frac{L_m}{L_s}(\lambda_{ds}i_{qr} - \lambda_{qr}i_{dr}) \qquad (22)$$

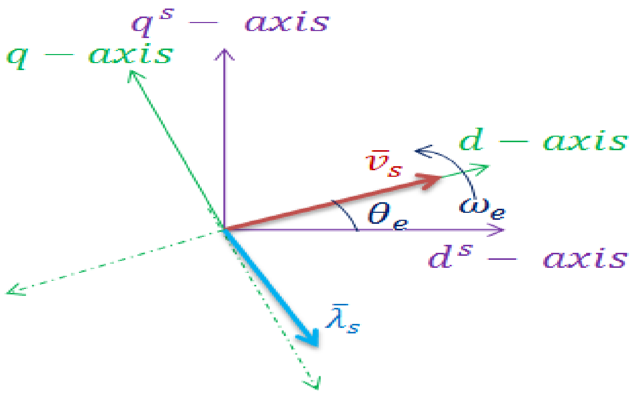

Figure 8: Alignment of SRRF along position of stator voltage

From vector diagram as shown in fig (8), it is clear that $v_{qs} = 0$ and $v_{ds} = |v_g|$. The substitution of these values into equations (18-20) yield:

$$P_s = \frac{3}{2}v_g i_{ds} \qquad (23)$$

$$Q_s = -\frac{3}{2}v_g i_{qs} \qquad (24)$$

The alignment of $d - axis$ along the position of stator voltage aligns the stator flux along the q-axis approximately i.e. $\lambda_{qs} = |\lambda_s|$ and $\lambda_{ds} = 0$. The substitution of these values into equations (14-16) yield:

$$L_s i_{ds} + L_m i_{dr} = 0 \qquad (25)$$

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$$L_s i_{qs} + L_m i_{qr} = -\lambda_s \qquad (26)$$

The substitution of values i_{ds} and i_{qs} from equations (25-26) into equations (23-24) yield:

$$P_s = -\frac{3}{2} v_g \frac{L_m}{L_s} i_{dr} \qquad (27)$$

$$Q_s = \frac{3}{2} v_g \left(\frac{\lambda_s}{L_s} + \frac{L_m}{L_s} i_{qr}\right) \qquad (28)$$

From equations (27-28) it is clear that Stator Real & Reactive power will be depends upon $d-$ axis and $q-$axis rotor current i.e. i_{dr} & i_{qr} respectively. Thus an alignment of $d-$ axis of SRRF along with Stator Voltage yield simple and decouple control of Real & Reactive power.

B. Control Algorithm of Rotor Side Converter

SVOVC Technique utilized two current loops: one for $d - axis$ current component i_{dr} and other for $q - axis$ current component i_{qr}.

The $d-$ axis rotor reference current i^*_{dr} is being determined from the equation (29).

$$T^*_e = 1.5 \frac{L_m}{L_s} \lambda_s i^*_{dr} \qquad (29)$$

Where, the reference torque T^*_e is being derived from the rotor speed error $(\omega^*_r - \omega_r)$ processed through the proportional-integral (PI) controller as shown in figure 9.

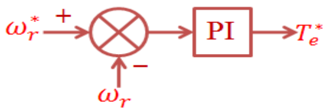

Figure 9: Determination of Reference Torque

Reference rotor - speed ω^*_r may be set as per available wind velocity for generating maximum possible power. This operation is obtained by using the look-up table [4].

The $q-$ axis reference rotor current i^*_{qr} will determines PF of the stator terminal. It may be set to zero value by considering all of Reactive power required for operation of DFIG is being supplied from Stator Side [8]. So ultimately, it can be set to any desired value that delivers Stator Power at unity PF

The $d\ \&\ q-$ axes reference and actual rotor current are compared with each other respectively in order to get v'_{dr} *and* v'_{qr} as shown in figure 10.

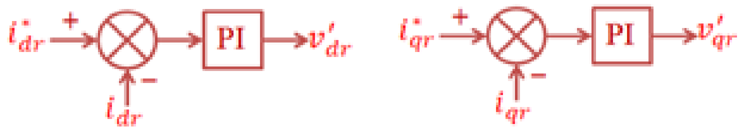

Figure 10: Determination of Control Signals for RSC

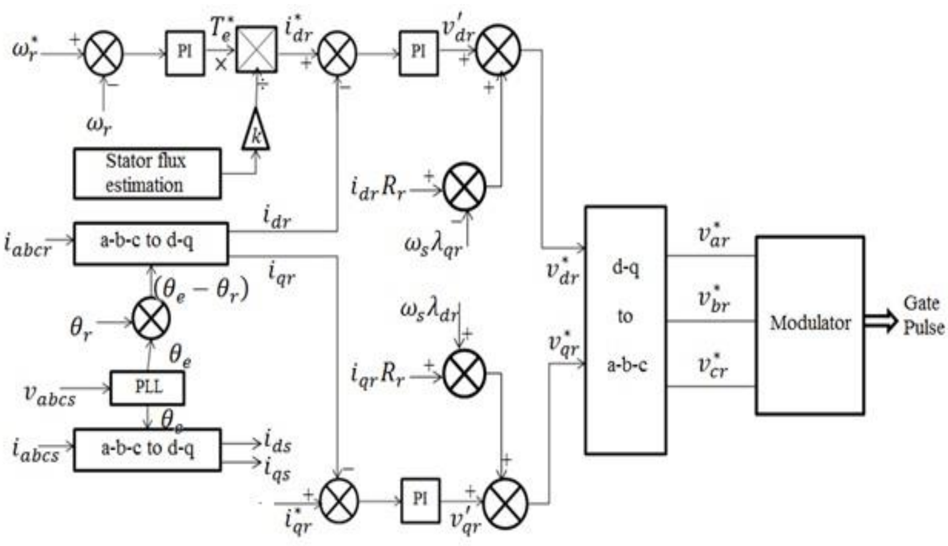

Figure 11: B.D. of Stator Voltage Oriented Vector Control Tech. for RSC

Here, it is clear that from the reference rotor speed ω_r^* and $q-$ axis reference rotor current i_{qr}^*, it generates gate pulses for s_1 *to* s_6. The modulator generates pulses from $a-b-c$ reference voltages: v_{ar}^*, v_{gr}^* and v_{cr}^* which are first generated in the $d-q$ form i.e. v_{dr}^* and v_{qr}^*. These $d-q$ reference voltages v_{dr}^* and v_{qr}^* are controlled separately from the $d-q$ current controller. Thus by changing v_{dr}, i_{dr} is mainly changed whereas by changing v_{qr}, i_{qr} is mainly changed. Finally, the voltage compensating term are adding at the output of each current controller to achieve good dynamic response. Thus the reference voltages becomes as given below:

$$v_{dr}^* = v'_{dr} + i_{dr}R_r - \omega_s\lambda_{qr} \qquad (30)$$

$$v_{qr}^* = v'_{qr} + i_{qr}R_r + \omega_s\lambda_{dr} \qquad (31)$$

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IV. SIMULATION CIRCUIT

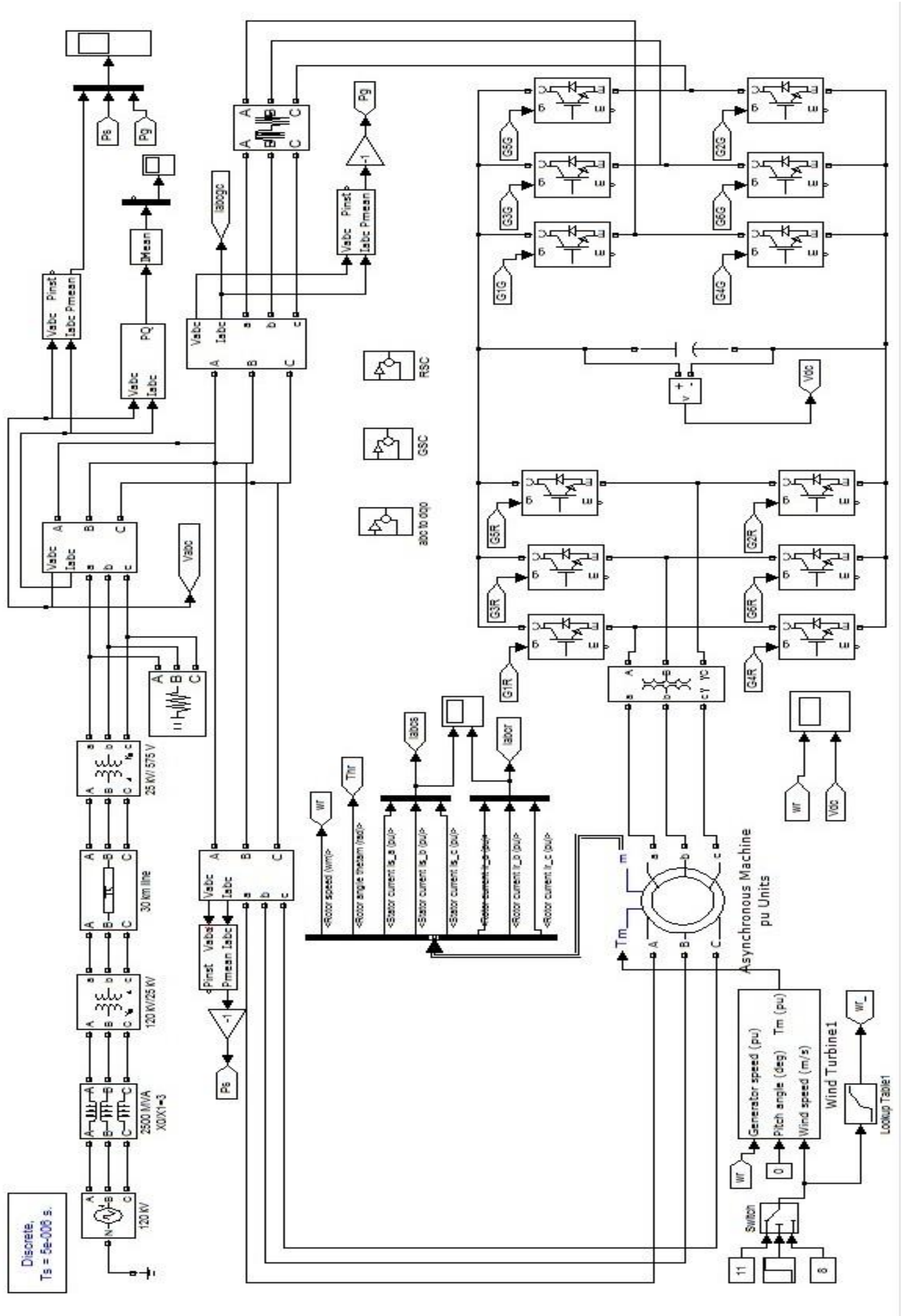

Figure12: Simulation circuit of grid connected DFIG

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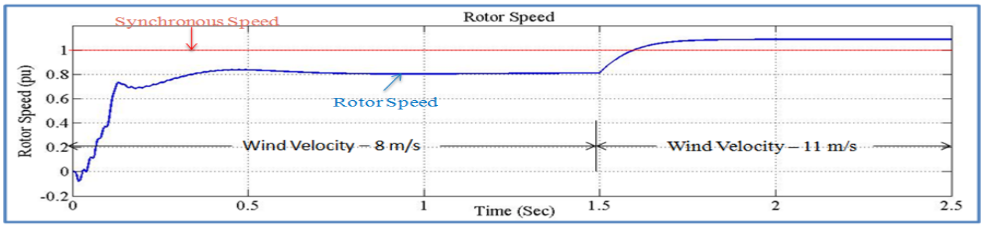
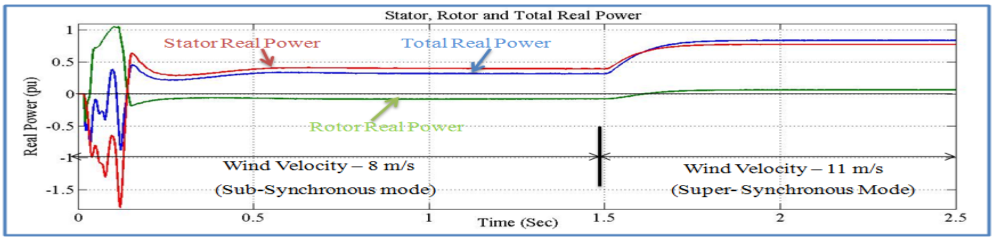
V. SIMULATION RESULT AND DISCUSSION

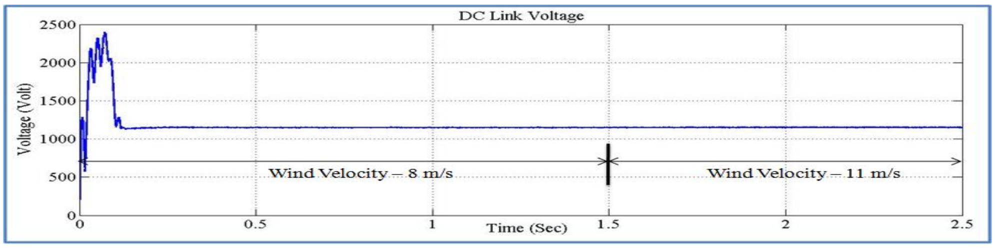
The 1.5 MW wind turbine based on DFIG connected to the grid whose parameters shown in Appendix-I is simulated in MATLAB using standard PI controller. Performance of DFIG is analysed under different operating conditions by considering effect of wind speed variation.



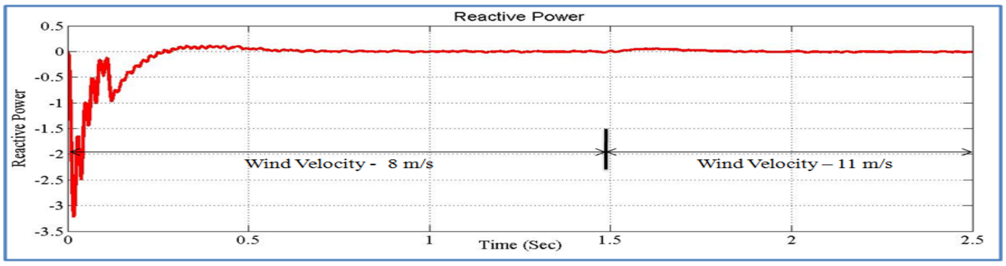
(a) Rotor Speed Variation With Wind Speed



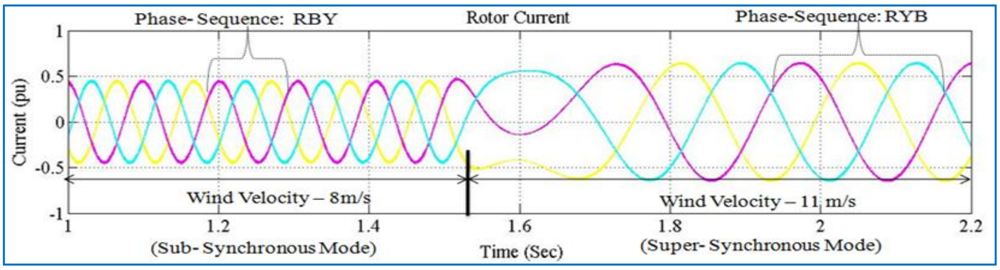
(b) Stator & Rotor Real Power Variation With Wind Speed



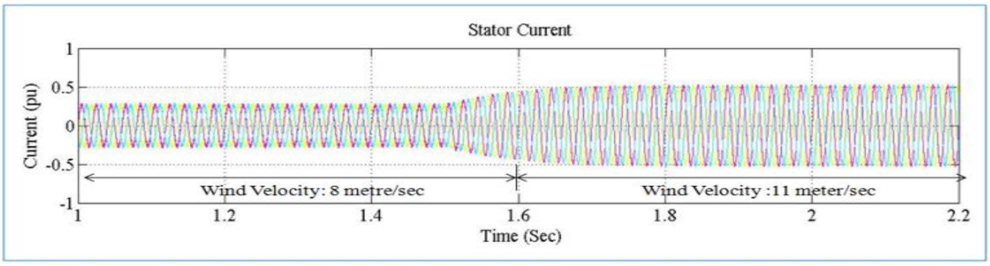
(c) Voltage Across DC-Link



(d) Exchange of Reactive Power At Stator Terminal



(e)Three Phase Rotor Current Variation With Wind Speed



(f) Three Phase Rotor Current Variation With Wind Speed

Figure 13: Performances of 1.5 MW - DFIG with variation in Wind Speed from 8m/s to 11 m/s

Table: 1.

Comparison of Real Power (in term of per unit) fed by DFIG to Grid at different wind speed

Wind speed (m/s)	Rotor speed (rad/s)	Operating Mode	Stator Real Power (KW)	Rotor Real Power (KW)	Total Real Power (KW)
8.0	0.803	Sub-Syn. Mode	0.400	-0.082	0.319
8.5	0.844		0.457	-0.074	0.383
9.0	0.887		0.518	-0.060	0.458
9.5	0.932		0.580	-0.042	0.538
10.0	0.977		0.646	-0.016	0.629
10.5	1.024	Super Syn. mode	0.714	0.014	0.728
11.0	1.073		0.784	0.055	0.838

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Table: 2.

Comparison of Real Power (in term of SI unit) fed by DFIG to Grid at different wind speed

wind speed (m/s)	rotor speed (rad/s)	Operating Mode	Stator Real Power (KW)	Rotor Real Power (KW)	Total Real Power (KW)
8.0	84.11	Sub- Syn. Mode	600	-122	478
8.5	88.43		686	-111	574
9.0	92.91		776	-89	687
9.5	97.55		871	-63	807
10.0	102.33		968	-24	944
10.5	107.28	Super Syn. mode	1071	21	1092
11.0	112.38		1176	82	1258

Note: synchronous speed =104.72 radian /sec

The graphical representation of Real Power Generation as per table-2 is shown in figure 14.

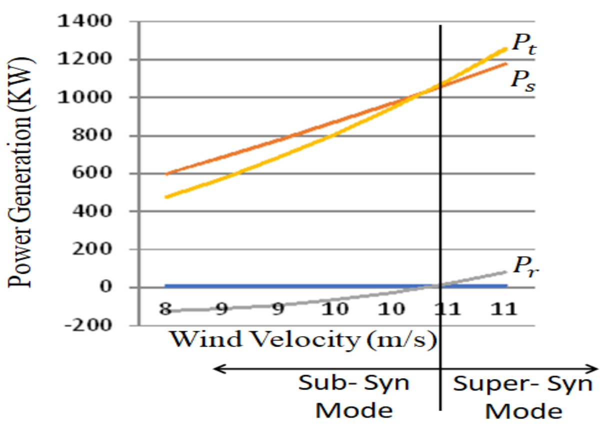

Fig. 14 Graphical representation of Real Power Generation

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IV. CONCLUSION

The modeling and controlling of DFIG has been carried out for large wind energy application. From above discussion it is clear that The DFIG can be operated over the large range of rotor speed above and below synchronous speed and also able to generate maximum power from wind turbine as per available wind speed and so there is an improvement in capacity utilization factor as well as the efficiency of overall system.

APPENDIX

Table 3:

Parameter of DFIG

Parameter	**Value**	**Unit**
Rated Power	1.5	Mega Watt
Stator Voltage	575	Volt
Stator Current Frequency	50	Hertz
Stator / Rotor turns ratio	0.30	-
Stator resistance R_s	0.007	P. U.
Rotor resistance R_r'	0.005	P. U.
Stator leakage Inductance $L_{\sigma s}$	3.071	P. U.
Rotor leakage Inductance $L'_{\sigma r}$	3.056	P. U.
Magnetizing Inductance	2.9	P. U.
Number of Pole Pair	3	-

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