

A Supervisory Predictive Control using Indirect Matrix Converter for a Variable Speed Wind Energy Conversion System

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Abstract:- In this paper, a predictive control of Wind Energy generation system for a Stand-Alone application is presented. The proposed scheme is implied using a wind driven Permanent Magnet Synchronous Generator (PMSG) connected to an Indirect Matrix Converter (IMC). The IMC is controlled using Space Vector Pulse Width Modulation (SVPWM) technique. The IMC consisting of bi-directional rectifier connected to a Voltage Source Inverter. The four quadrant rectification is performed in the generation side and the two-level inversion in the load side. A Soft-Switching technique is followed for the input side converter. The Stand-Alone application of driving an induction motor is performed at its rated speed through a constant frequency operation. The PMSG, SVM and the Induction Motor are mathematically modeled and the results are simulated using MATLAB/SIMULINK 7.14 (R2012b). The feasibility of the proposed system is validated from the results for a variable speed energy system.

Keywords:- Indirect Matrix Converter (IMC), Permanent Magnet Synchronous Generator (PMSG), Space Vector Pulse Width Modulation (SVPWM), Stand-Alone Application, Wind Energy Conversion System (WECS)

I. INTRODUCTION

The renewable energy is now considered to the most desired way of generating energy though non-renewable energy is under practice. The recent research and development has proved that the energy generation through a non-polluting sources change the world from the environment pollution crisis. The development on renewable resource is recently practiced in the rural electrification. The renewable sources like wind, solar, hydro and geothermal have many advantages over others. Among this, the most desirable and fast research and development is concentrated in the wind because of its predominant characteristics. Among the Wind Energy Conversion Schemes the recent and most desired method of implementation is the Variable Speed Wind Energy Conversion System [8]. The variable speed turbines are dynamic when considered to fixed speed wind turbines. In the proposed system the Permanent Magnet Synchronous Generator [4] is used as the Variable Speed Wind Turbine [8]. The rural electrification is one of the recent developments where the Stand-Alone systems for the irrigation and other domestic application are concentrated more. The proposed work is to drive an induction motor at maximum power output with the efficient control of the power electronic circuits [9]. The direct AC-AC converters are the recent implementation better efficiency over the application in industrial drive systems. The Indirect Matrix Converter (IMC) [1]-[2] is one of the classifications of the Direct AC-AC Converter which is more efficient and simple to implement in drive applications. In this power generation system, the PMSG Wind turbine is connected to the Indirect Matrix Converter which forms the bridge between the generating system and the load. The IMC is controlled using the SVM technique for low harmonic, lossless applications. The circuit model is shown in the Fig 1.

The PMSG [5] – [6] is a variable speed wind turbine requires no gear box setup which adds the advantage over other types. The PMSG produces a three phase sinusoidal output which may vary in magnitude depending on the wind velocity. The drive to be driven for a stand-alone application requires a constant voltage irrespective of the load variations and the wind velocity. The IMC is supervisory controlled using the SVM technique to produce the three phase constant output for the stand-alone drive system. The SVM of the IMC individually modulated for the rectification and inversion stages.

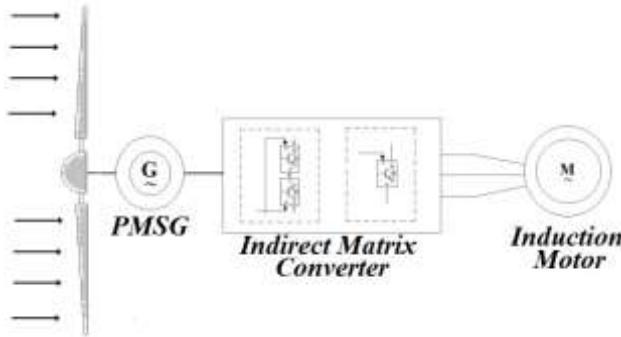


Fig. 1. Proposed Circuit Model

II. PHASE CO-ORDINATE MODELING OF PMSG

The PMSG is modeled using the phase voltage equations of the stator co-ordinates. They are represented as,

$$V_a = i_a R_s + p\varphi_a$$

$$V_b = i_b R_s + p\varphi_b$$

$$V_c = i_c R_s + p\varphi_c$$

Where, $p = \frac{d}{dt}$, i_a, i_b and i_c are the phase currents, φ_a, φ_b and φ_c are the flux developed by the phase currents and R_s is the stator resistance.

$$\begin{vmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{vmatrix} = \begin{vmatrix} L_{sl} + L_{aa}(\theta_{er}) & L_{ab}(\theta_{er}) & L_{ca}(\theta_{er}) \\ L_{ab}(\theta_{er}) & L_{sl} + L_{aa}(\theta_{er}) & L_{bc}(\theta_{er}) \\ L_{ca}(\theta_{er}) & L_{bc}(\theta_{er}) & L_{sl} + L_{cc}(\theta_{er}) \end{vmatrix} \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} + \begin{vmatrix} \varphi_{PMa}(\theta_{er}) \\ \varphi_{PMb}(\theta_{er}) \\ \varphi_{PMc}(\theta_{er}) \end{vmatrix}$$

Where, θ_{er} is the rotor PM axis angle to a axis / electrical angle.

For the distributed windings of IPM rotor machines, θ_{er} is more efficiently considered as the self-inductance and mutual inductance mainly depend on it. But the stator inductance is invariant for the surface PM Pole rotors. The additional factor depending on the stator inductance on $N_s \theta_{er}$ is due to the existence of slot openings. In consideration with the rotor pole configurations, the stator self and mutual inductance are similar characterized for the concentrated windings. Contradictorily, the distributed windings are larger in values. However, the concentrated windings have smaller end-turn leakage inductance. The space harmonics are also one of the factors to be considered in the fluxes of the permanent magnet machines.

Therefore, with this fact the modeling of the machine takes the assumption that, self and the mutual inductance are either constant or vary sinusoidally with the rotor position ($2\theta_{er}$). In general, the flux linkages $\varphi_{PMa,b,c}(\theta_{er})$ variation in the stator phases are sinusoidal but with θ_{er} . Eventually the time pulsation in the torque and current are observed due to harmonics in the d-q model for the $\omega_1=\omega_2$:

$$|L_{abc} \theta_{er}| = \begin{vmatrix} L_{ls} + L_0 + L_2 \cos 2\theta_{er} & M_0 + L_2 \cos(2\theta_{er} + \frac{2\pi}{3}) & M_0 + L_2 \cos(2\theta_{er} - \frac{2\pi}{3}) \\ M_0 + L_2 \cos(2\theta_{er} + \frac{2\pi}{3}) & L_{sl} + L_0 + L_2 \cos(2\theta_{er} - \frac{2\pi}{3}) & M_0 + L_2 \cos 2\theta_{er} \\ M_0 + L_2 \cos(2\theta_{er} - \frac{2\pi}{3}) & M_0 + L_2 \cos 2\theta_{er} & L_{sl} + L_0 + L_2 \cos(2\theta_{er} + \frac{2\pi}{3}) \end{vmatrix}$$

$$M = -\frac{L_0}{2} \text{ for distributed windings}$$

Thus the matrix form of the phasor coordinates are given as,

$$|i_{a,b,c}| |R_s| - |V_{a,b,c}| = -\frac{d|\varphi_{a,b,c}|}{dt}$$

$$\varphi_{a,b,c} = |L_{a,b,c} \theta_{er}| |i_{a,b,c}| + \varphi_{PMa,b,c}(\theta_{er})$$

The Park's transformation from stator to rotor coordinates are given as in the Figure 2 are expressed as,

$$\begin{vmatrix} i_d \\ i_q \\ i_0 \end{vmatrix} = |P(\theta_{er})| \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix}$$

$$P(\theta_{er}) = \frac{2}{3} \begin{vmatrix} \cos(-\theta_{er}) & \cos(-\theta_{er} + \frac{2\pi}{3}) & \cos(-\theta_{er} - \frac{2\pi}{3}) \\ \sin(-\theta_{er}) & \sin(-\theta_{er} + \frac{2\pi}{3}) & \sin(-\theta_{er} - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix}$$

The same transformations are valid for φ_{dq0} , V_{dq0} .

Finally, for sinusoidal $\varphi_{PMa,b,c}(\theta_{er})$ distributions,

$$i_d R_s - V_d = L_d \frac{di_d}{dt} + \omega_r L_q i_q$$

$$i_q R_s - V_q = -L_q \frac{di_q}{dt} - \omega_r (L_d i_d + \varphi_{PM1})$$

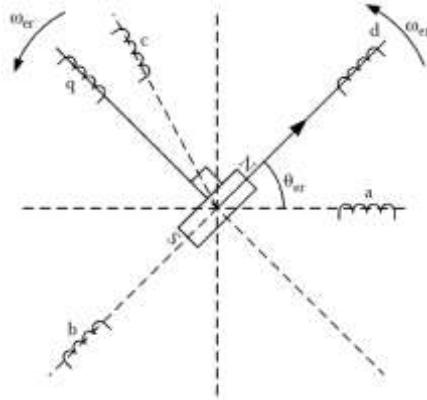


Fig. 2. Three Phase d-q transformation

With

$$\bar{\varphi}_s = \varphi_d + j\varphi_q; \varphi_d = \varphi_{PM1} + L_q i_d; \varphi_q = L_q i_q$$

$$\bar{V}_s = V_d + jV_q; \bar{i}_s = i_d + j i_q$$

From the above equations the space-vector model of the PMSG is obtained as,

$$\bar{i}_s - \bar{V}_s = -\frac{d\bar{\varphi}_s}{dt} - j\omega_r \bar{\varphi}_s$$

The torque is obtained as,

$$T_e = p_1 \frac{P_e}{\omega_r} = \frac{3}{2} p_1 (\varphi_{PM1} + (L_d - L_q) i_d) i_q$$

$$L_d = L_{st} + \frac{3}{2} (L_0 - |L_2|); L_q = L_{st} + \frac{3}{2} (L_0 + |L_2|)$$

From the derived expressions the d-q equivalent circuit of the PMSG is given as in the Fig 3.

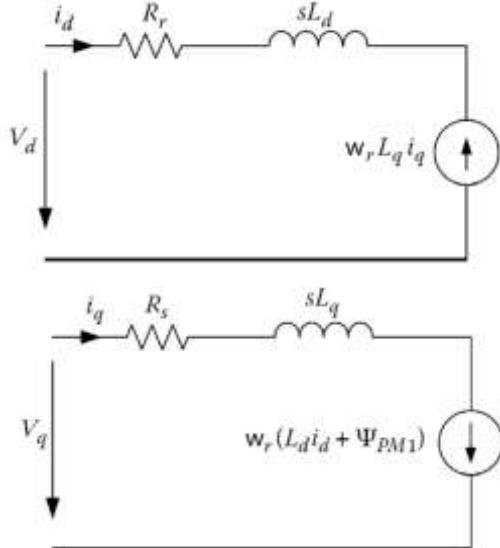


Fig. 3. d-q equivalent circuit of PMSG

The Fig 4 shows the vector representation of the PMSG. The torque value is in negative because of the current i_q which is negative. Under steady state condition, the phase voltages are given as,

$$V_{abc} = V_1 \sqrt{2} \cos \left(\omega_r t - (i-1) \frac{2\pi}{3} \right)$$

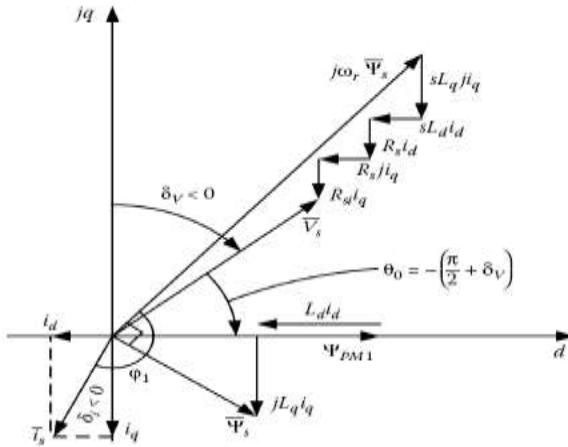


Fig. 4: Vector Representation of PMSG

III. PREDECTIVE CONTROL METHOD OF IMC

The Indirect Matrix Converter [15] switches are controlled using the Space Vector Pulse Width Modulation Technique (SVPWM) [10] [16]. The IMC as discussed in II consists of the rectification and the inversion stage controlled by the bidirectional and unidirectional switches respectively. These two stages in a switching control should be always balanced. To obtain the balanced state the control for the rectification and the inversion is done separately. Therefore, the SVPWM is used to modulate both the stages individually. The SVPWM produces the combination of the vectors to synthesis a reference vector. The switching state is thus determined through the modulation pattern obtained from the reference vector and the duty cycle. The uniformity of the modulation in both the rectification and the inversion stage gives the balanced input current and the output voltages during each switching period. To implement this modulation strategy, the output voltages and the currents generated by each switching combination of the matrix converter are represented as space vectors using the transformation,

$$\bar{x} = \frac{2}{3}(x_1 + x_2 e^{j\frac{2}{3}\pi} + x_3 e^{-j\frac{2}{3}\pi})$$

The IMC generates the instantaneous phase voltages generated by the switching combinations which is given as in the form of instantaneous transfer matrix,

$$V_{oPh} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{ap} & S_{an} \\ S_{bp} & S_{bn} \\ S_{cp} & S_{cn} \end{bmatrix} * \begin{bmatrix} S_{pA} & S_{pB} & S_{pC} \\ S_{nA} & S_{nB} & S_{nC} \end{bmatrix} * \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

$$= T_{INV} * T_{REC} * V_i$$

Where, T_{INV} & T_{REC} are the instantaneous transfer matrix of the inversion and the rectification stage respectively.

1.1. Rectification Stage

The input lines are always observed such that they are never been shorted. This can be achieved by considering the switching summation is always equal to one given as,

$$S_{aq} + S_{bq} + S_{cq} = 1, q \in \{p, n\}$$

The above equation shows the bidirectional switching pattern which is valid for the generated voltage and the currents. The similarity should contain that of a direct matrix converter such that the rectifier generating the DC link voltage takes the responsibility of maintain the set of sinusoidal and balanced input current with displacement angle.

From the equation (8) the SVPWM, the distinctive input currents space vectors are generated by the first six switching combinations with the fixed directions as shown in the Fig.5.

A synchronised input current and the input voltages are required to form the balanced set of input voltages. Using the space vector transformation the reference input current space vector is given as,

$$\bar{I}_{in} = I_{im} e^{j(\omega_i y - \varphi_i)} = I_{im} \angle \theta_i$$

Where I_{im} and $\angle \theta_i$ are the magnitude and phase shift of the reference voltage.

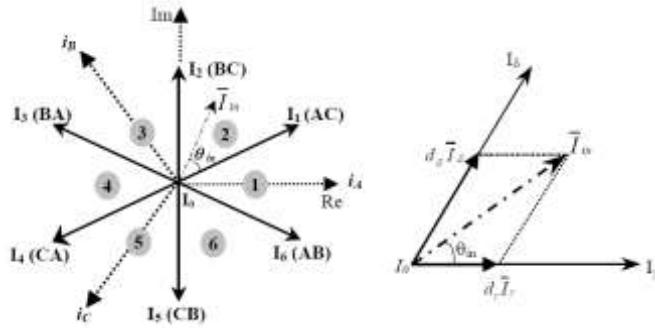


Fig. 5: Input Current Space Vector in rectification stage.

The valid switching combinations for the current source rectifier and the respective voltage and current values are tabulated in Table 1

TABLE I. OUTPUT VOLTAGE AND INPUT CURRENT OF SWITCHING STATES (1=ON 0=OFF)

Switching State						Output Voltages			Input Currents		
S_{pA}	S_{pB}	S_{pC}	S_{nA}	S_{nB}	S_{nC}	V_{pZ}	V_{nZ}	V_{pn}	i_A	i_B	i_C
1	0	0	0	0	1	V_a	V_c	V_{ac}	i_p	0	i_p
0	1	0	0	0	1	V_b	V_c	V_{bc}	0	i_p	i_p
0	1	0	1	0	0	V_b	V_a	V_{ba}	i_p	i_p	0
0	0	1	1	0	0	V_c	V_a	V_{ca}	i_p	0	i_p
0	0	1	0	1	0	V_c	V_b	V_{cb}	0	i_p	i_p
1	0	0	0	1	0	V_a	V_b	V_{ab}	i_p	i_p	0
1	0	0	1	0	0	V_a	V_a	0	0	0	0
0	1	0	0	1	0	V_b	V_b	0	0	0	0
0	0	1	0	0	1	V_c	V_c	0	0	0	0

1.2. Inversion Stage

The inversion stage is similar to the rectification stage except the initial stage is considered as a stand-alone, three-phase, two level voltage sources inverter that supplied with the DC sources, $2*V_{DC}$. The shoot-through problem which is the simultaneous conduction of the top or bottom switches are been turned ON by modulating the expression which reduces the use of Impedance Sources. The equation is given as,

$$S_{jp} + S_{jn} = 1, \quad j \in \{a, b, c\}$$

Where S_{jp} and S_{jn} are the switching functions of the top and bottom unidirectional switches respectively. The output phase voltages are obtained as,

$$V_{as} = V_{pn} \left(\frac{2}{3} S_{ap} - \frac{1}{3} S_{bp} - \frac{1}{3} S_{cp} \right)$$

$$V_{bs} = V_{pn} \left(\frac{2}{3} S_{bp} - \frac{1}{3} S_{ap} - \frac{1}{3} S_{cp} \right)$$

$$V_{cs} = V_{pn} \left(\frac{2}{3} S_{cp} - \frac{1}{3} S_{ap} - \frac{1}{3} S_{bp} \right)$$

Using the Space vector transformation from the equation (8), the output first six switching combinations are transferred into six distinctive output voltage space vectors with fixed directions as in the figure 6.

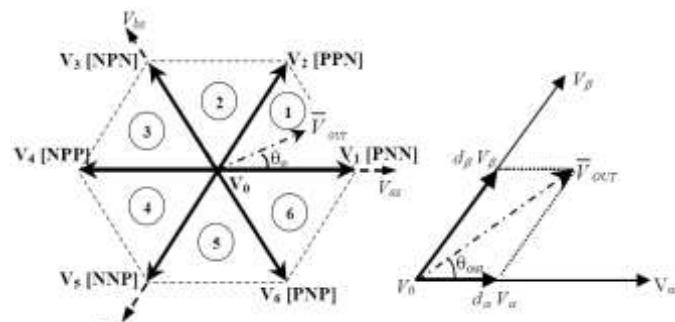


Figure 6: Output voltage vector in inversion stage

The valid switching combinations for the inversion stage are tabulated in the Table 2.

TABLE II. SWITCHING STATES OF THE INVERSION STAGE (1=ON 0=OFF)

Switching State						Output Phase Voltages		
S_{pA}	S_{pB}	S_{pC}	S_{nA}	S_{nB}	S_{nC}	V_{pZ}	V_{nZ}	V_{pn}
1	0	0	0	1	1	$\frac{2}{3}V_{pn}$	$-\frac{1}{3}V_{pn}$	$-\frac{1}{3}V_{pn}$
1	1	0	0	0	1	$\frac{1}{3}V_{pn}$	$\frac{1}{3}V_{pn}$	$-\frac{2}{3}V_{pn}$
0	1	0	1	0	1	$-\frac{1}{3}V_{pn}$	$\frac{2}{3}V_{pn}$	$-\frac{1}{3}V_{pn}$
0	1	1	1	0	0	$-\frac{2}{3}V_{pn}$	$\frac{1}{3}V_{pn}$	$\frac{1}{3}V_{pn}$
0	0	1	1	1	0	$-\frac{1}{3}V_{pn}$	$-\frac{1}{3}V_{pn}$	$\frac{2}{3}V_{pn}$
1	0	1	0	1	0	$\frac{1}{3}V_{pn}$	$-\frac{2}{3}V_{pn}$	$\frac{1}{3}V_{pn}$

For a three phase voltage source inverter, a set of sinusoidal balanced output is desired and can be expressed in the form of

$$\overline{V_{out}} = V_{om} e^{j(\omega_0 t - \theta_0)} = V_{om} \angle \theta_0$$

Where V_{om} is the magnitude and $\angle \theta_0$ is the direction of the phase voltages.

IV. SIMULATION AND RESULTS

The simulation is done using the Matlab Coding for the PMSG and the Induction Motor in MATLAB 7.14. The Modeling of the PMSG, Induction Motor is shown in the Fig 7.

The PMSG is modeled in Matlab function. The input parameters are set in the Matlab coding. The three phase output voltage, current, power, speed are derived using the machine equations. The PMSG is modeled for 4kW power.

The Induction Motor is designed for a mechanical power of 5HP. The Induction motor is modeled in such an assumption that the rated speed is attained in the closed loop system. The load torque is derived from the machine variables and it is given as a closed loop to the input. The modeled machines are connected to the IMC which is controlled by the SVPWM. The SVPWM is also modeled to perform efficiently.

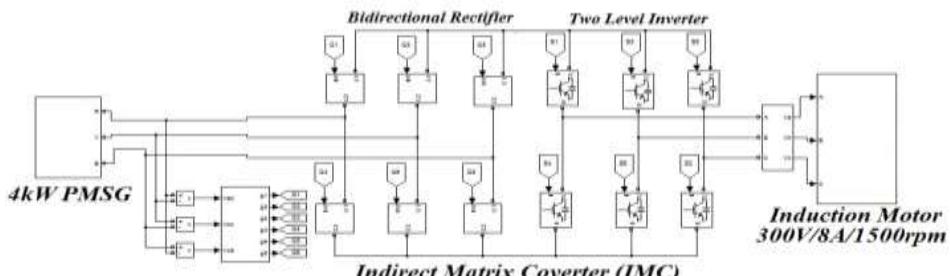
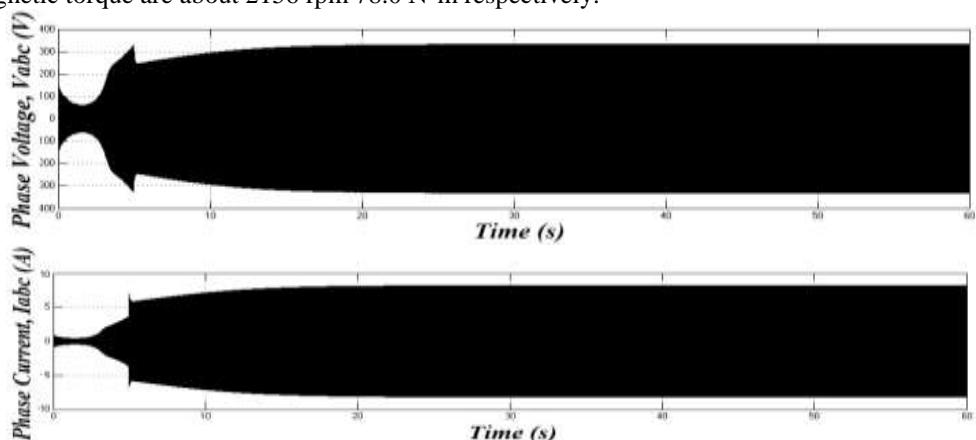


Figure 7: Simulink Model of the Proposed PMSG & IMC

The outputs of the wind driven PMSG are shown in the Fig 8. The phase voltage is obtained to be 320V and the PMSG output current is 8A. The output power obtained is 4060W. The rotor speed and the electromagnetic torque are about 2156 rpm 78.0 N-m respectively.



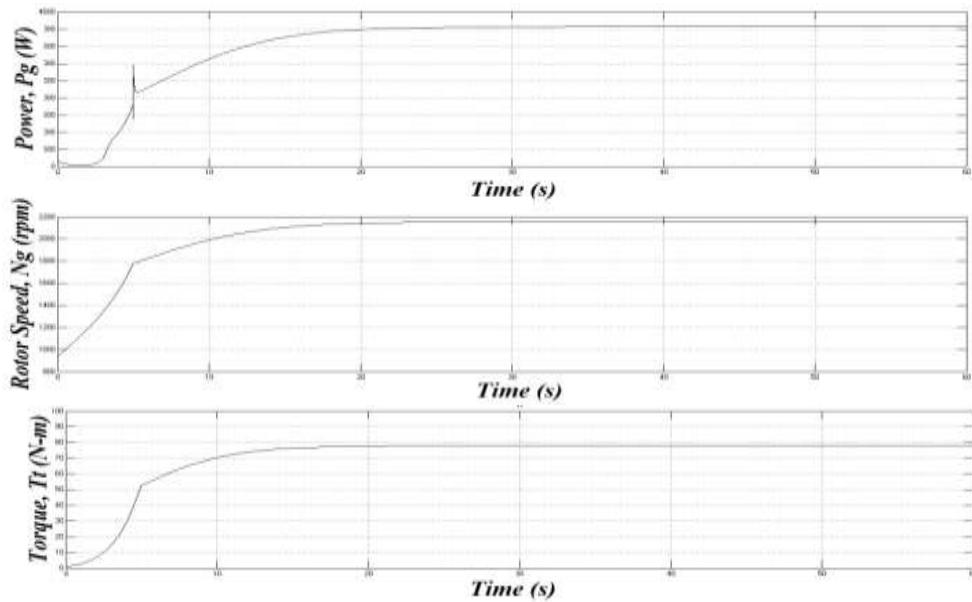


Fig 8: Output of PMSG Wind Turbine

The simulated output is then supplied to the IMC for the rectification and the inversion to drive the Induction Motor. The Rectified DC current and voltage are 20A and 400V respectively as shown in the Fig.9.

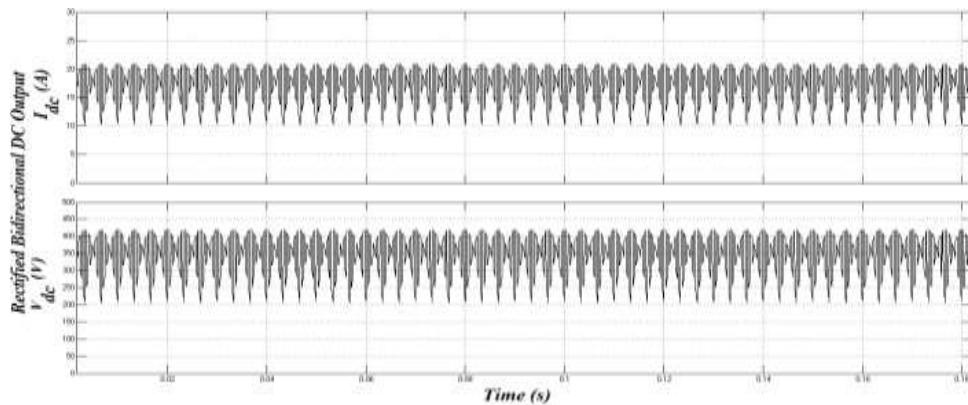
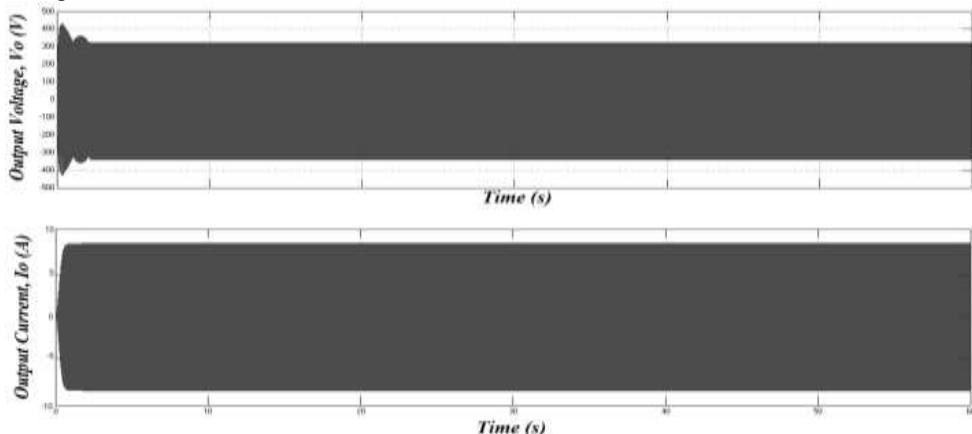


Fig. 9: Rectified DC Outputs from Bi-directional Rectifier

The bi-directional rectified DC is the source for the two level inverter which is inverted and then supplied to the induction motor drive system. The Induction Motor is modeled for 4 pole, 50Hz, 1500rpm. The inverted output voltage and current are 300V and 8A respectively. The motor is driven at its rated speed of 1500rpm with the electromagnetic torque of 5N-m. The output power is obtained to be 3780 W. The output is shown in the Fig.10.



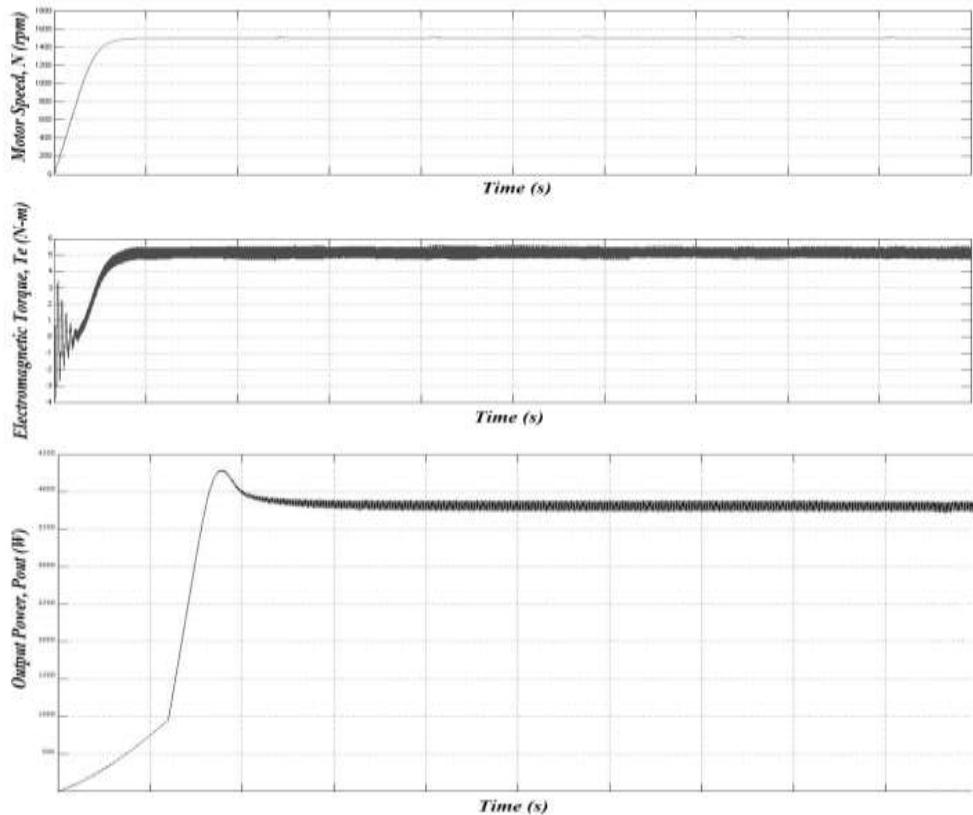


Figure 10: Output of IMC and Induction Motor

The results are tabulate in the table 3.

TABLE III. TABLE 3: OUTPUT RESULTS

Wind Velocity	Input Power	Output Power	Efficiency
10 m/s	4060W	3780	93.10%

V. CONCLUSION

The Supervisory predictive control using the Indirect Matrix Converter (IMC) for a Stand-Alone application through a Wind driven PMSG is presented efficiently. The proposed work is mathematically modeled for the PMSG, Induction Motor and SVM are mathematically to provide the efficient system. The induction motor is designed for a mechanical power of 5HP. The losses in the drive system are significantly reduced and obtaining the maximum efficiency for the designed machine parameters. The SVM controlled IMC is more predominant for the drive characteristics as the current harmonics is less whose value as THD is observed to be 3.43%. The induction motor is driven at a constant rated speed of 1500rpm. The output power is obtained as 3780W and the output efficiency is 93.10%. Thus the predicated control using IMC for Stand-Alone application is efficient.

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