Abstract—this paper presents the vector control of six phase permanent magnet synchronous generator which is directly connected to a six leg converter. A mathematical model of the machine has been developed using the generalized two phase real component transformation. Dual synchronous d-q current control is employed so as to eliminate current imbalances. The six legs the converter are controlled to extract the maximum power from the wind turbine with reduced torque pulsation, reduced harmonics and minimum stator losses using vector space decomposition space vector modulation. Matlab® Simulink is used for simulation.

Index Terms— orthogonal subspace transformation, multi leg converter, six phase permanent magnet machines, space vector pulse width modulation, vector control, vector space decomposition.

I. INTRODUCTION

MULTI Phase machines provides several advantages such as: reduction of amplitude of pulsating torque and increased pulsating frequency; reduction of current per phase for the same rated voltage; lowering the dc-link current harmonics; reducing the stator copper loss; improving reliability and give additional degree of freedom[1]-[3]. Permanent magnet synchronous generators known to have higher power density, higher efficiency, more stable and secure during normal operation. Off shore wind energy system needs to be more reliable and lighter than on shore wind energy system. Therefore, Multiphase PMSGs have become attractive for large off shore wind farm.

Multiphase machines drives, motors, has been used as in Electric Vehicles(EV), hybrid EV, aerospace, ship propulsion, and high-power applications in which the requirements are not cost oppressive when compared to the overall system[1]-[4]. Reference [2] gives thorough survey related to Multiphase drives in various subcategories, and including the application of Multiphase machines for electric generation.

In [5] parallel connection of converters in modular way is investigated to allow the use of classical converters. The application of multiphase PMSG for wind is also shown in [6] that the two three phase windings are controlled independently.

In this paper the six-phase PMSG has two groups of three phase windings which are separated by 30 degrees. The arrangement of the six phases and definition of reference frames is shown in Fig. 1.

II. SYSTEM DESCRIPTION

The proposed wind energy conversion system along with the control scheme is shown in Fig. 2. It is assumed that the average DC link voltage is kept constant by the grid side converter which is modeled by constant dc ideal voltage source.

A. Wind turbine

The power extracted from wind by turbine is given by
\[ P_t = \frac{1}{2} C_p \rho A v_w^3 \]  

(1)

Where \( \rho \) is the air density, \( A \) is the area swept out by the turbine blades, \( v_w \) is the wind velocity, and \( C_p \) is the power coefficient. \( C_p \) is a function of the pitch angle \( \beta \) and of the tip speed ratio \( \lambda \), shown in Fig. 3. Tip speed ratio is the ratio of turbine speed at the tip of a blade to wind velocity.

\[ \lambda = \frac{\omega R}{v_w} \]

(2)

where \( R \) is the turbine radius, and \( \omega \) is the turbine angular speed.

For a given wind turbine, the maximum power extracted can be tracked by adjusting the speed of the generator either using maximum power tracking or the optimal tip speed ratio.

\[ \text{B. Six Phase PMSG Modeling} \]

By neglecting the magnetic saturation and core losses, and assuming a sinusoidal air gap flux, the voltage equations of generator in phase quantities are

\[ [V_s] = [R_s][i_s] + p \cdot ([L_s][i_s]) + p \cdot ([\lambda_{SM}]) \]

(2)

\[ [\lambda_{SM}] = \lambda_M \left[ \cos \theta_r \cos \left( \theta_r - \frac{2\pi}{3} \right) \cos \left( \theta_r + \frac{2\pi}{3} \right) \cos \left( \theta_r - \pi_6 \cos \theta_r - 5\pi_6 \cos \theta_r - 3\pi_6 \right) \right] \]

(3)

where the voltage and current are defined as

\[ V_s = [V_{s1} V_{s2} V_{s3} V_{s4} V_{s5} V_{s6}]^T \]

\[ t_s = [l_{s1} l_{s2} l_{s3} l_{s4} l_{s5} l_{s6}]^T \]

\( \lambda_M \) is the permanent magnet flux linkage, \( \theta_r \) is the angle between magnetic axis of phase 'a' and rotating magnetic field, as shown in Fig. 1., and \( p \cdot ( ) = \frac{d}{dt} ( ) \).

The resistance term and the inductance terms of (2) are given by (4); for Surface Mounted PMSG the pulsatory components of the magnetizing inductance of stator windings are zero. Mutual leakage inductance is ignored and has little effect on torque pulsation and voltage harmonic distortion since the separation angle between the two sets of three phase windings is 30°, [8].

\[ [R_s] = \begin{bmatrix} r_s & 0 & 0 & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & 0 & 0 & r_s & 0 & 0 \\ 0 & 0 & 0 & 0 & r_s & 0 \\ 0 & 0 & 0 & 0 & 0 & r_s \end{bmatrix} \]

(4a)

\[ [L_s] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \]

(4b)

Where \( r_s \), \( L_q \) and \( L_l \) are resistance, leakage reactance and magnetizing reactance of a stator winding respectively.

Using generalized two phase real component transformation or vector space decomposition theory, the original six dimensional space representation of the machine is mapped to three orthogonal two dimensional subspaces, [16]. The power invariant transformation matrix is used to map phase quantities to orthogonal subspace quantities, which is

\[ [T_{6}] = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & \cos \theta & \cos \theta & \cos \theta & \cos \theta & \cos \theta \\ 0 & \sin \theta & \sin \theta & \sin \theta & \sin \theta & \sin \theta \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \]

(5)

where \( \theta = \frac{\pi}{6} \).

Applying transformation \([T_{6}] \) to (2) and (3), the vector space decomposition variable can be written as

\[ [V_{vsd}] = [R_s][i_{vsd}] + [L_{vsd}] p \cdot ([l_{vsd}]) + \omega_r [\lambda_{vsd}] \]

(6)

\[ [\lambda_{vsd}] = \sqrt{3} \lambda_M \omega_r [-\sin \theta, \cos \theta, 0 \ 0 \ 0 \ 0]^T \]

(7)

where \( \omega_r = \frac{d\theta_r}{dt} \).

\[ [V_{vsd}] = [V_a V_b V_x V_y V_z1 V_z2]^T [l_{vsd}] = [l_a l_b l_x l_y l_z1 l_z2]^T \]

And

\[ [L_{vsd}] = \begin{bmatrix} L_a & 0 & 0 & 0 & 0 & 0 \\ 0 & L_a & 0 & 0 & 0 & 0 \\ 0 & 0 & L_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & L_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & L_1 \end{bmatrix} \]

(8a)

\[ L_a = 3L_1 + L_l \]

(8b)

As seen above the voltage and flux equations are as a function of rotor position. This can be eliminated by using...
shows the generic scheme of six leg converter which helps for optimal operation of the generator. Fig. 4, converters give more freedom to choose switching states compared with a three-phase converter. Besides six leg so that the current stress of each switch can be reduced

C. Six Leg Converter

Using more legs means, power is shared by the many legs so that the current stress of each switch can be reduced compared with a three-phase converter. Besides six leg converters give more freedom to choose switching states which helps for optimal operation of the generator. Fig. 4, shows the generic scheme of six leg converter.

Only one of the power switches of the same leg can operate in the “ON” state to avoid the short circuit of the DC-link. The switching function can be represented in terms of the upper switch of each leg as \( f(S_{a1}, S_{b1}, S_{a2}, S_{b2}, S_{c1}, S_{c2}) \).

Applying the transformation matrix \( \mathbf{T}_a \) on the phase voltages of the converter, the converter voltages with respect to the stationary reference frame given by

\[
\begin{align*}
V_{\alpha} & = v_{a1} + \frac{1}{2} v_{\beta} + \frac{1}{2} v_x, \\
V_{\beta} & = -v_{a1} + v_{\beta} - v_x, \\
V_x & = -v_{a1} - v_{\beta} + v_x, \\
V_{z1} & = v_{z1} + v_{z2}, \\
V_{z2} & = -v_{z1} + v_{z2},
\end{align*}
\]

and

\[
\begin{bmatrix}
S_{a1} \\
S_{b1} \\
S_{a2} \\
S_{b2} \\
S_{c1} \\
S_{c2}
\end{bmatrix} = \mathbf{V}_{ab} \begin{bmatrix}
1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & 1/2 & -1 \\
0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

As seen from (11) and (12), the current components in \((x, y)\) and \((z_1, z_2)\) are limited to stator resistor and stator leakage inductance. These currents do not contribute to electromechanical energy conversion but losses. Thereby the electromechanical energy conversion variables are mapped in the only \((d,q)\) subspace. This makes the modeling of the machine and torque calculation simpler. The electro-magnetic torque expression can be calculated from the air gap power. The air gap power is the part of input power which does not contribute to resistive loss or rate of change of stored energy in the inductances.

\[
P_{ag} = P_{el} - P_{loss} - P_{rateChangeStoredMagnetic}
\]

And if there are \( P \) poles, the electrical torque \( T_e \) is

\[
T_e = \frac{P_{ag}}{2} = \frac{P}{2} \lambda M q = K i_q
\]
Fig. 5. Converter voltage on (α,β) subspace; 0, 7, 56, 63 are zero states

Fig. 6. Converter voltage on (x, y) subspace; 0, 7, 56, 63 zero states

D. Space Vector PWM

The vector space decomposition technique is of priority. As shown in Fig. 5 and Fig. 6, the largest voltages (outer most) on (α,β) become smallest (inner most) voltages on (x, y) subspace. The medium voltages have the same magnitude on both (α,β) and (x, y) subspaces. Hence, the largest voltages are chosen as active voltage thereby the switching control is simplified to 12 sectors. To minimize losses in the (x, y) subspaces four active vector and one zero vector are chosen to build the space vector in (α,β) subspace. The red vectors in Fig. 5 and Fig. 6 shows the four active voltages when the resultant vector lies on the first sector (−π/12 ≤ θ ≤ π/12).

Imposing on the converter that average zero volt-seconds of the switching vectors on (x, y) subspace and at same time equalizing the average volt-seconds of switching vectors on (α,β) to that of the reference voltages at the output of the inner current controller, further reduction in losses can be achieved. The time duration of the four active vectors and one zero vector is calculated this way, [9].

\[
\begin{bmatrix}
V_α^1 & V_α^2 & V_α^3 & V_α^4 & V_α^5 & T_1 & T_2 V_α^∗ \\
V_β^1 & V_β^2 & V_β^3 & V_β^4 & V_β^5 & T_3 & T_4 V_β^∗ \\
v_κ^1 & v_κ^2 & v_κ^3 & v_κ^4 & v_κ^5 & T_5 & T_6
\end{bmatrix}
\]

Where, \(v_κ^i\) is the projection of the \(i^{th}\) voltage on the \(k^{th}\) plane and \(T_k\) is the dwelling time of the vector \(v_κ^i\) over a sampling period \(T_s\).

The switching sequence of the gate signals are generated according to the dwelling time of the five vectors. Zero vector has to be selected carefully so that only one of the leg change state not more than two in a sampling period.

E. Vector Control

Vector control decouples field flux and armature flux so that they can be controlled separately to control torque or current and power or speed independently. The current control forms an inner loop while seep control forms the outer control for the case considered. The vector control is applied in the synchronous rotating frame so as to use simple PI regulators will result in zero steady-state error since the steady-state currents are dc currents.

The vector space decomposition approach of vector control has been used to control dual three phase induction machines [9][13]. Though using single current controller makes the design easier and need less number of PI regulators, it can not observe the current imbalance. Therefore, to do away with this problem, dual current controller is preferred. The control schematics of the proposed system is shown in Fig. 7.

To design dual current control for each three phase group, the generator voltage equations are derived with respect to synchronous rotating reference frames (d1, q1) and (d2, q2) see Fig. 1.

\[
V_{d1} = r_1 i_{d1} + L_d p \cdot i_{d1} + M_d p \cdot i_{d2} - \omega_r L_{q1} q_1 - \omega_\tau M_{q1} q_2
\]

\[
V_{q1} = r_1 i_{q1} + L_q p \cdot i_{q1} + M_q p \cdot i_{q2} + \omega_r L_{d1} d_1 + \omega_\tau M_{d1} d_1 + \omega_r \sqrt{2} a_M
\]  

(16a)

\[
V_{d2} = r_1 i_{d2} + L_d p \cdot i_{d2} + M_d p \cdot i_{d1} - \omega_r L_{q2} q_2 - \omega_\tau M_{q2} q_1
\]

\[
V_{q2} = r_1 i_{q2} + L_q p \cdot i_{q2} + M_q p \cdot i_{q1} + \omega_r L_{d2} d_2 + \omega_\tau M_{d2} d_1 + \omega_r \sqrt{2} a_M
\]  

(16b)

There is strong coupling between the voltage equations. Since the d and q axis currents are constant at steady state, the current control can be simplified and also control structures is identical for d1 and d2 axes as well as q1 and q2 axes.
By introducing feed forward compensation and assuming fast switching, the inner current controllers can be considered as separate closed loops (decoupled current loop), in which linear control theory can be applied. The Modulus optimum criterion is used to find the PI controller the current control loop. The detailed analysis of synchronous frame decoupled current control can be found in many literatures, [14]-[15]. So, it is not repeated here.

The outer controller, show in Fig. 7, is speed control. The reference speed is assumed to come from maximum point power tracking. The Symmetric Optimum criterion is employed to find the parameters of the PI controller. The permanent magnet flux linkage is at rated value and there is no need to use field weakening; the d axis current reference is kept zero which helps to fully utilize the stator current for torque or power extraction from the turbine.

### III. RESULTS

Independent control of torque and speed is obtained. The average DC link voltage is kept constant as if grid side converter were connected.

The response of the generator-converter is tested first keeping the torque constant at -16 Nm and the reference speed is changed from 100 rad/s to 50 rad/s at 0.4 sec and then to 100 rad/s at 0.68 sec..

Similarly, the system performance is tested for torque change of torque from -16Nm to -10 Nm at 0.6 sec and again to -10 Nm at 0.96 sec as shown below.
IV. CONCLUSION

The use of vector space decomposition or generalized two phase real component transformation makes the modeling of six phase machines easier and also equivalent to that of three phase machines.

The dual synchronous current controller maintains the current in the two groups of three phase systems equal if there is current difference between them.

Having six leg converter increases the controllability of the converter using vector space decomposition SVPWM which results in reduced losses and ripple in the stator and Dc link current.

V. REFERENCES

[6] Sheng-Nian Yeh, Jong-Chin Hwang, Ming-Chih Hsieh, Li-Hsiu Chen “Development of Wind Power Control System for Six-Phase Permanent-Magnet Synchronous Generators”


Dissertations: