Abstract

In this paper, implementation of SVPWM switching technique for a constant frequency, variable speed wind turbine is carried out. The modeling and simulation is done using MATLAB/Simulink for doubly-fed induction generator. The total harmonic distortion for various parameters like stator current, rotor speed and electro-magnetic torque of this wind electric generator has been obtained. The reduction in distortion level is higher compared to other pulse width modulation techniques.

Keywords: Control Strategy, DFIG, SVPWM, THD

1. Introduction

The limitations in integrating the wind energy with solar energy or diesel generators with the goal of attaining reliable and uninterruptible energy supply are1. The maintenance of DC link voltage constant in real time is not presumable2. Harmonic factors in calculating Total Harmonic Distortion (THD) is not considered3. New control strategies challenging the problems in controlling frequency, voltage and other electrical quantities are not considered4. Variable speed variable pitch DFIG based wind turbine system are not dealt in detail5. The magnitude of rotor and stator voltage vectors decide the asynchronous torque and the synchronous torque. The synchronous torque depends on torque angle δ between stator and rotor space vectors, while it is not considered for asynchronous torque6. Three level VSI using SVPWM techniques in which the switching frequency varies widely with variable speed drive frequency, a main drawback in three level scheme7. Comparison of SVPWM and SPWM switching techniques is done using PSCAD8. The electromagnetic torque is higher than the rated value9. Fast Fourier Transform (FFT) analysis for THD has not been done in this paper10. SVPWM switching techniques is used for PMSG, but it has low efficiency compared to DFIG11. Voltage oriented control has been dealt in combination with direct power control for hybrid scheme constituting wind driven generators and PV modules12 this paper, the simulation of DFIG with SVPWM switching technique has been carried out. The THD in variable speed wind power generation system using DFIG is found using FFT analysis. The reliability of complete wind turbine system using DFIG has been analyzed by Markov Process13. Using Particle swarm optimization technique, three important control parameters such as pitch angle, rotor speed and stator voltage has been adjusted and the appropriate controllers are tuned14. Various parameters like wind speed, solar irradiation, marine velocity are taken and program in MATLAB platform to get improved voltage and real power15. A lookup table is done using different speed and

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different loads using neural network for standalone load to obtain constant stator voltage\textsuperscript{20}. In order to get optimum power improved controller in wind turbine is used based on human mind’s emotional learning is considered\textsuperscript{21}. Sliding mode control strategy is used in machine side converter and grid side converter because of that cost is reduced and complication is extensively reduced\textsuperscript{22,23}

The FFT analysis has been done for the most important electrical and mechanical quantities such as rotor speed, stator current and electromagnetic torque which determines the performance characteristics of DFIG. The boost converters and inverters are utilized as ac-dc-ac converters for the variable speed wind power generation system. The variable frequency obtained from the DFIG is converted into the fixed frequency output irrespective of the variable wind speed and generator output. The level of harmonics in the inverter circuit is largely reduced with the implementation of space vector modulation. Thus the simulation is developed to demonstrate the effectiveness of the system. The stator flux and the rotor speed can be improved by selecting suitable control strategy using SVPWM in order to get the maximum output. The complete model is simulated under variable speed operation using MATLAB/Simulink/Sim Power Systems to study the overall performance characteristics of DFIG.

This paper is organized in such a way that the section 2 overviews the static and dynamic characteristic of DFIG. Various control strategies employed in DFIG are discussed in section 3. section 4 describes the SVPWM control technique and its simulation results. section 5 concludes with future implements and scopes.

2. Performance Characteristic of DFIG

DFIG is a multiphase wound rotor and a multiphase slip ring assembly with brushes for accessing the rotor windings. Stator winding is directly connected to the three-phase grid and the rotor winding is fed from the grid through a back to back voltage source converter. The term ‘Doubly Fed’ refers to the fact that the stator voltage is supplied from the grid and the rotor voltage is induced by the power converter. This system allows a variable-speed operation over a large range.

Doubly fed machines are typically used in applications that require varying speed of the machine’s shaft in a limited range around the synchronous speed. The superior feature of DFIG compared to the ordinary induction generators is that the active power obtained is both from stator and rotor windings, i.e. the rotor winding in DFIG contributes additional energy exchange between DFIG and grid.

Also it is able to equally import from utility grid and export the reactive power by means of power electronic converter. This leads to power system stability and allows the machine to support the grid during several voltage disturbances such as low voltage ride through. Any dc electric generator can be connected to power network by adjusting its open-circuit terminal voltage to match the network voltage by either adjusting its speed or its field excitation; the exact engine speed is not critical. In order to control speed and excitation, both the amplitude and the timing of the network voltage should be matched with an ac generator. Controlling of rotor voltages and currents enables the induction machine to remain synchronized with the grid although the wind speed varies. A wind turbine with the varying speed utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during low wind speed conditions. DFIG control is performed by different control gains and network voltage control through stator side and rotor side converters in order to attain stability in wind turbine operation.

During any fault, the current can be limited by various algorithms, series and dynamic voltage restorer be necessary been proposed for fault ride through, FRT in active crowbar in rotor circuit. The key factor of DFIG used as a wind electric generator is that it can be operated at variable speed mode keeping the amplitude and frequency of the generated voltage constant. Optimization of power generated as a function of the wind speed and the virtual elimination of sudden variations in the rotor torque and generated output power can be done easily in order to get a unity power factor. The converter compensates the difference between the mechanical and electrical frequencies by injecting a rotor current with a variable frequency. Hence, the operation and behavior of the DFIG is governed by the power converter and its controllers.

2.1 Static Characteristics

In wind power system, the mechanical power to be delivered to the electrical system is determined as:

\[ P_m = 0.5 \rho A C_p (\lambda, \phi) r_w^3 \]
Where, \( C_p \) depends on the tip speed ratio \( \lambda \), and pitch angle \( \beta \): 

\[ \lambda = \frac{\omega_r R}{\nu_w} \]

### 2.2 Dynamic Characteristics

DFIG can be operated as a hybrid of an asynchronous and synchronous machine. As a synchronous generator, its torque depends mainly upon the torque angle \( \delta \) between the rotor voltage and the stator feed voltage vector and as an asynchronous machine it depends on the slip \( s \). The generator fed both from the stator and the rotor sides produces electromagnetic torque as a function of rotational speed. The expression of electromagnetic torque in the stationary mode is given by:

\[ T = \frac{3}{2} pL_m \left( I_{rd} I_{sq} - I_{rq} I_{sd} \right) \]

Where:
- \( L_m \) – mutual inductance
- \( I_{rd} \) – rotor direct-axis current
- \( I_{sq} \) – stator quadrature-axis current
- \( I_{rq} \) – rotor quadrature-axis current
- \( I_{sd} \) – stator direct-axis current

To calculate the torque in the steady state mode, the stator and the rotor current vector components in asynchronous operation as well as the rotor voltage in reference frame dq axis in synchronous mode need to be considered.

The mathematical equation for the electromagnetic torque in the steady state can be obtained as:

\[ T_g = T_s + T_r + T_{sr \cos} + T_{sr \sin} \]

Where, \( T_s \) – asynchronous torque component due to feed on stator and \( T_r \) – Torque component due to feed on rotor;

\( T_{sr \cos} + T_{sr \sin} \) – Synchronous torques caused by the excitation of rotor voltage vector components. The addition of the asynchronous torques \( T_s \) and \( T_r \) are approximately equal in magnitude with the synchronous torque, but have opposite signs. Consequently, the amount and the sign of the total generator torque are mainly determined by the synchronous torque component.

### 2.3 Torque/Speed Curve of DFIG

Asynchronous torque component depends on stator voltage and rotor voltage representing constant values but different in sign, while synchronous torque component substantially determines total generator torque. Hence the total DFIG electromagnetic torque is obtained by adding both the components.

The synchronous torque components \( T_{sr \cos} \), \( T_{sr \sin} \) and the total DFIG torque \( T_g \) depends on the angle \( \delta \), the asynchronous components \( T_s \) and \( T_r \) are independent of \( \delta \). For angles \( \delta = 90^\circ \) and \( 270^\circ \), the synchronous component of the torque \( T_{sr \cos} \) is zero and for angles \( \delta = 0^\circ \) and \( 180^\circ \) the synchronous component of the torque \( T_{sr \sin} \) obtained is zero. The magnitude and sign of the total torque is determined by the synchronous component \( T_{sr \cos} \) for angles \( \delta = 90^\circ \) and \( 270^\circ \). The total electromagnetic torque \( T_g \) should be negative for angle \( \delta = 90^\circ \) and positive for angle \( \delta = 270^\circ \).

### 3. Control Strategies in DFIG

Generally ac drives require high power, variable voltage and variable frequency supply for their operation. Pulse width modulation techniques have been used to achieve variable voltage and variable frequency in ac-dc and dc-ac converters. This technique has been also used in applications such as static frequency changers SFC, uninterruptible power supplies UPS, DFIG etc. Some major PWM techniques in DC/AC inverters are Sinusoidal PWM (SPWM), Triangular wave sampling-Natural sampling, Uniform sampling, calculation based on equal area criterion, selective harmonics elimination, hysteresis control, Space Vector Modulation SVM or SVPWM, Random PWM and Current Controlled PWM (CCPWM) techniques. The main purpose of pulse width modulation technique in power inverters is to control the output voltage. Change in pulse-widths for middle and boundary pulses are obtained to improve inverter operation with less generation of harmonics. The most widely used PWM schemes for DFIG are carrier-based sinusoidal PWM and space vector PWM.

#### 3.1 Sinusoidal Pulse Width Modulation Technique

SPWM is the mostly used method in motor control and inverter application. In SPWM technique, three sine waves \( U_r \) and a high frequency triangular carrier wave \( U_c \) are used to generate PWM signal in three phase inverter. The three phase sinusoidal signal is called reference signal and they are mutually 120° phase shifted with each other.
Some drawbacks of SPWM technique is that the total harmonic distortion is more, modulation index is less, current produced is less and hence the above drawbacks are overcome by using SVPWM technique.

4. Simulation of SVPWM Switching Techniques

Space Vector Pulse Width Modulation is normally developed as vector approach to Pulse Width Modulation for three phase inverters. SVPWM has a unique feature that it tackles all the major issue related to the SPWM techniques such as computational complexity, synchronization, total harmonic distortion, dc bus voltage balancing and common mode voltage. Therefore, the proposed SVPWM method is suitable for high-power applications as it eliminates sub harmonics by maintaining synchronization, improves THD through various waveform symmetries. Avoiding harmonics can prevent the overheats and malfunction in sensitive systems. The space vector PWM has been increasingly used recently. In this modulation, three separate modulators for each of the three phases are not used but processed with the complex reference voltage vector as a whole.

The general topology of three phase voltage source inverter is shown in Figure 2. The IGBT switches in the same leg of VSI should not be turned on rather it will cause DC supply short circuited. So the switching operation is made complementary within the same leg. In SVPWM technique, eight switching states are included in the inverter, out of eight, two are zero switching states or zero vectors V0 and V7 and other six are non-zero switching state or active state V1 to V6. The switching vectors along with the corresponding line to line voltage are given in the Table 1.

To implement SVPWM switching technique, a revolving reference voltage Vector (Vref) is provided as voltage reference instead of three phase modulating waves. While plotting the eight voltage vectors in complex plane, the six active vectors (V1 to V6) form the axes of a hexagon as shown in Figure 3, supplies power to the load. The other two zero vectors (V0 and V7) are located in the origin and supply no power. The reference vector is taken between the two adjacent active switching vectors and one or both of the zero vectors. This voltage vector (Vref) is used to modulate the inverter output. Vref is shown in the first sector of the two adjacent voltage vectors namely V1 and
V2. Vref-MAX is the maximum amplitude of Vref within the modulation limit, beyond which may cause non-linear over-modulation.

The switching state vector V1 is applied for an interval t1, V2 for t2 and the two zero vectors V0 and V7 for interval t0, t7 respectively. So the total sampling interval:

\[ TS = t1 + t2 + t0 + t7 \]

In this same manner the total sample interval for remaining active vectors can be found. Resolving Vref and V1, V2 along the \( \alpha-\beta \) axis and by equating voltage-time integrals we get:

\[ |Vref| \cdot t \cdot \cos \gamma = |V1| \cdot t1 + |V2| \cdot t2 \cdot \cos \frac{\pi}{3} \]

\[ |Vref| \cdot t \cdot \sin \gamma = |V2| \cdot t2 \cdot \sin \frac{\pi}{3} \]

Dividing both sides of equation above by Vdc and substituting \( \frac{V_{ref}}{V_{dc}} = a \), we get

\[ t \cdot \sin \gamma = \frac{\sqrt{3}}{2} \cdot t2 \]

Or \( t2 = 2a \cdot t \cdot \sin \gamma \cdot \sqrt{3} \)

and \( t \cdot \cos \gamma = t1 + \frac{1}{2} \cdot t2 \)

Substituting the value of t2 from equation 12 in 13 and multiplying both sides of resulting equation by, we obtain \( \frac{\sqrt{3}}{2} \)

\[ t1 = \frac{2at}{\sqrt{3}} \cdot \sin \left( \frac{\pi}{3} - \gamma \right) \]

\[ t0 = t7 = ts - (t1 + t2) \]

Where \( a = \text{modulation index} = \left| \frac{V_{ref}}{V_{dc}} \right| \)

The vector in the first sector can be determined by the switching patterns of time interval i.e t0, t1, t2 and t7 respectively. The four time intervals change simultaneously when Vref goes from one sector to another for a particular modulation index say a. The full cycle is completed by six similar sectors with label 1, 2 and so on up to 6. As Vref move over to sector 2, the inverter remains in switching state vector V2 for time interval t1 and in V3 for time t2. For sector 3, V3 for t1 and V4 for t2 and so on.

The block diagram of SVPWM as in Figure 4, constitutes three-phase diode rectifier, braking chopper,
Space Vector Modulation Technique Applied to Doubly Fed Induction Generator

three phase inverter, induction motor, speed control and SVM block. The speed controller block is used to control the motor slip. In order to generate the required inverter voltage and frequency, the error in rotor speed this is computed by comparing the actual motor speed and the reference speed. The latter frequency is also used to generate the demanded inverter voltage in order to maintain the motor V/F ratio constant.

A simple simulation has been carried out in VSI Induction motor drive implementing the Space Vector PWM with the three phase source as in Figure 5.

The significant data obtained from the simulation results are as shown in Figure 6. The simulation using various Simulink/Sim power system blocks can be viewed in the following Figure 8.

The various blocks used for simulation can be explained as follows: A 3 phase, 460 V, 50 Hz voltage source has been used and its output voltage is rectified and boosted further and given to the three phase voltage source inverter and finally connected to the stator side of the DFIG. The gate pulse to the inverter is given after measuring the speed of the magnetic flux of stator and torque using speed control and direct torque control blocks. Three phase output voltage from the measurement block is applied to the asynchronous machine of 7.5kW, 400V, 50 Hz, 1440 rpm. The rotor speed is compared with the reference speed in the speed controller block. The magnitude of the voltage and frequency measured from the speed of the rotor is given to SVPWM block. The SVPWM block will generate the required inverter voltage and frequency. The gate pulses for the inverter is determined by the on and off periods of the switching pattern. The inverter output is further fed to the grid converter and then to the load. The significant data obtained from the simulation results are as shown in Figure 8.

Figure 4. Block diagram of SVPWM.

Figure 5. Space vector PWM VSI induction motor drive.

Figure 6. Response of stator current, wm, electromagnetic torque and bus voltage.

Figure 7. Simulation of DFIG with space vector PWM.
4.1 FFT Analysis for SVPWM

The FFT analysis has been done using power gui in Simulink tool. The various quantities like rotor speed, electromagnetic torque and stator current have been taken for analysis.

![Figure 8](image1.png)  
**Figure 8.** Simulated results.

![Figure 9](image2.png)  
**Figure 9.** FFT analysis for rotor speed.

![Figure 10](image3.png)  
**Figure 10.** FFT analysis for electromagnetic torque.

![Figure 11](image4.png)  
**Figure 11.** FFT analysis for stator current $I_a$.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Simulation results for DFIG</th>
<th>SPWM</th>
<th>SVPWM</th>
<th>Total Harmonic distortion, THD in %</th>
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<td></td>
<td>SPWM</td>
<td>SVPWM</td>
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<tr>
<td>1</td>
<td>Rotor speed $\omega_m$</td>
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<tr>
<td>3</td>
<td>Electromagnetic torque, $T_e$ in p.u</td>
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<td>$-0.5$</td>
<td>240.94</td>
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</tbody>
</table>

Table 2. Simulated results

5. Conclusions

SVPWM is widely used in variable speed drive applications. The simulation results are compared and analyzed by plotting the output harmonic spectra of rotor speed, stator current and electromagnetic torque and computing their Total Harmonic Distortion (THD) which is given in Table 2. Also this method of PWM...
generation gives better utilization of dc bus voltage for inverter and digital realization. In this algorithm total harmonic distortion are reduced due to rapid switching inherent. The THD is more or less equal for rotor speed while for electromagnetic torque it drastically reduced in SVPWM.

Future work can be done by using DSP control, intelligent control technique like FIS, ANFIS, GA Artificial neural network.

6. References