Comparative analysis of 2-level & 3-level SVPWM Controlled DFIG

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Abstract: **Wind Energy is one of the favorable renewable energy resources and the multilevel inverter has been proven to be one of the important enabling technologies in wind energy conversion system (WECS) utilization. Wind energy conversion system with utilization grid systems are getting more and more widespread with the increase in the energy demand and the concern for the environmental pollution around the world. With multilevel inverters harmonic content gets reduced and with more levels the output approaches the sine wave. The voltage stress also gets reduced. In this paper we are trying to implement a WECS with Multilevel voltage source inverters using Space vector pulse width modulation (SVPWM). The need of several sources on the DC side of the converter makes multilevel technology attractive for WECS applications.**

Keywords: DFIG, SVPWM, Multli Level Inverter

I. INTRODUCTION:

In response to the new grid code requirements, several DFIG models have been suggested recently, including the full-model which is a 5th order model. These models use quadrature and direct components of rotor voltage in an appropriate reference frame to provide fast regulation of voltage. The 3rd order model of DFIG which uses a rotor current, not a rotor voltage as control parameter can also be applied to provide very fast regulation of instantaneous currents with the penalty of losing accuracy. Apart from that, the 3rd order model can be achieved by neglecting the rate of change of stator flux linkage (transient stability model), given rotor voltage as control parameter. Additionally, in order to model back-to back PWM converters, in the simplest scenario, it is assumed that the converters are ideal and the DC-link voltage between the converters is constant. Consequently, depending on the converter control, a controllable voltage (current) source can be implemented to represent the operation of the rotor-side of the converter in the model. However, in reality DC-link voltage does not keep constant but starts increasing during fault condition. Therefore, based on the above assumption it would not be possible to determine whether or not the DFIG will actually trip following a fault.

In a more detailed approach, actual converter representation with PWM-averaged model has been proposed, where the switch network is replaced by average circuit model, on which all the switching elements are separated from the remainder of network and incorporated into a switch network, containing all the switching elements. However, the proposed model neglects high frequency effects of the PWM firing scheme and therefore it is not possible to accurately determine DC-link voltage in the event of fault. A switch-by-switch representation of the back- to-back PWM converters with their associated modulators for both rotor- and stator-side Converters has also been proposed. Tolerance-band (hysteresis) control has been deployed. However, hysteresis controller has two main disadvantages: firstly, the switching frequency does not remain constant but varies along the AC current waveform and secondly due to the roughness and randomness of the operation, protection of the converter is difficult. The latter will be of more significance when assessing performance of the system under fault condition. The important features associated with a wind energy conversion system are:

- Available wind energy.
- Type of wind turbine employed
- Type of electric generator and power electronic circuitry employed for interfacing with the grid.

II. DOUBLY-FED INDUCTION GENERATOR

The DFIG is connected to the medium voltage (MV) level of the power system by a step-up transformer. Since the 1ine side converter typically requires an additiona1transformer to match the converter output voltage to the line voltage, either two, 2-winding transformers or one, 3-winding transformer may be used Fig. 1.

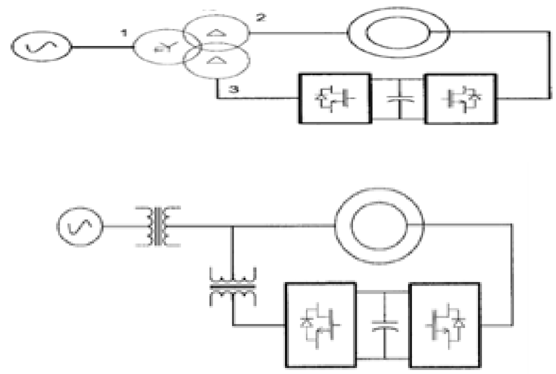

Fig. 1 Connection of the DFIG to the MV network using: (a) 2-winding transformers , (b) 3-winding transformer

The wind energy conversion system (WECS) using a DFIG has two back-to-back voltage source converters connect the stator windings to the rotor windings and as previously mentioned, a transformer is required between the line side converter and the supply. Control of the dc bus voltage is accomplished by the line side converter while the rotor side converter controls both the speed and the pf of the machine. The line side converter may also deliver reactive power and thus, together with the rotor side converter dictates the generator pf. The summary of the control objectives of the two converters as well as the machine are given below in Table I.

TABLE I. SWITCHING STATES FOR EACH PHASE LEG OF TWO LEVEL INVERTER

Converter	**Objective**	***Var* Regulation**	**Reactive power source**	**Speed control**
Rotor side	P_S, Q_S control	Yes	Yes	Using P_{rotor}
Supply side	Regulated dc bus	Yes	Yes	No

A. Steady-State Equivalent Circuit

the induction machine can be represented by it steady-state equivalent circuit as givin below

$$\begin{bmatrix} 1 & R_s + X_s & 0 \\ 1 & 0 & {R_r}/{s} + X_r \\ 1 & jX_m & jX_m \end{bmatrix} \begin{bmatrix} V_m \\ I_s \\ I_r \end{bmatrix} = \begin{bmatrix} V_s \angle 0^0 \\ {V_r}/{s} \angle \delta_r \\ 0 \end{bmatrix} \quad (1)$$

If the stator side voltage is used as the angle reference then the remainder of the quantities can be defined assuming a fixed stator voltage magnitude and given the required real and reactive power. From *Ps* and *Qs*, one can then define the magnitude and phase of the current, I_s as follows:

$$\text{Re}\,(i_s) = \frac{P_s}{V_s} \quad (2)$$

$$\text{Im}\,(i_s) = -\frac{Q_s}{V_s} \quad (3)$$

Then using (1), the first and third row equations are used to find *Ir*, followed by the second to find the required voltage applied at the rotor terminals. This apparently elementary study forms the basis for transient control of the rotor side converter. reverse transformations, however, the control algorithm follows from this simple analysis.

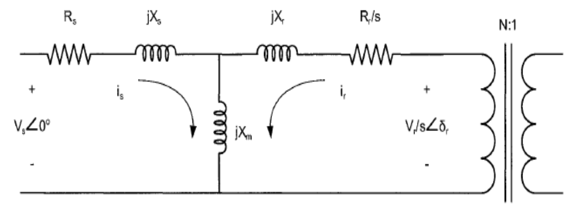

Fig. 2 Wound rotor induction machine equivalent circuit

III. MODULATION TECHNIQUES:

As in 3-level NPC inverter, modulation strategies can be framed into two main parts, shown in fig 3.

B. Space Vector Pulse-Width Modulation

There are various variations of SVM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms.

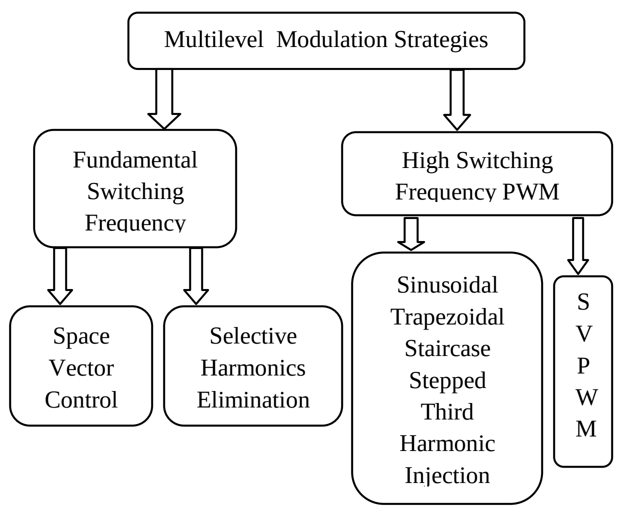

Fig.3 Overviews of different modulation strategies

IV. PRINCIPLE OF SPACE VECTOR PWM FOR TWO LEVEL INVERTER

All eight possible switching vectors for a three-leg inverter using space vector modulation. An example V_{ref} is shown in the first sector.

TABLE II. SWITCHING COMBINATION AND SWITCHING STATES FOR A THREE-LEVEL INVERTER (ONE PHASE-LEG)

S1x	**ON**	**OFF**	**OFF**
S2x	**ON**	**ON**	**OFF**
S3x	**OFF**	**ON**	**ON**
S4x	**OFF**	**OFF**	**ON**
Vx0	**VDC**	**0**	**-VDC**
Switching State	**P**	**O**	**N**

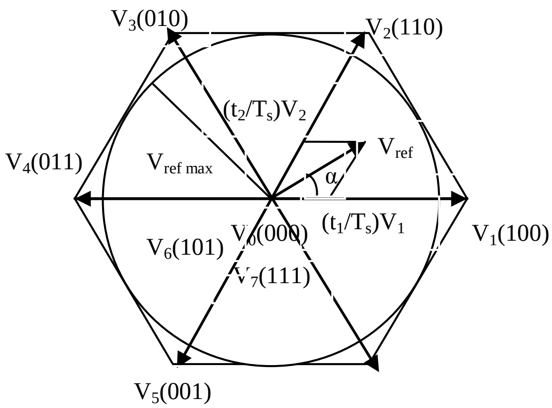

Fig.4 Space vector representation

TABLE III. SWITCHING STATES FOR EACH PHASE LEG OF TWO LEVEL INVERTER

Switching States	**A**			**b**			**C**		
	S1	**S2**	**V_{an}**	**S3**	**S4**	**V_{bn}**	**S5**	**S6**	**V_{cn}**
1	ON	OFF	V_{DC}	ON	OFF	V_{DC}	ON	OFF	V_{DC}
0	OFF	ON	0	OFF	ON	0	OFF	ON	0

Table III shows that the switches can be ON or OFF, meaning 1 or 0. The switches 1,3,5 are the upper switches and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (Va, Vb, Vc) is positive (+VDC). If the upper switches are zero, then the terminal voltage is zero).

$$T_1 = \frac{\sqrt{3}\,.T_Z.|V_{ref}|}{V_{dc}}\left(sin\left(\frac{\Pi}{3} - \alpha + \frac{n-1}{3}\Pi\right)\right)$$

$$= \frac{\sqrt{3}\,.T_Z.|V_{ref}|}{V_{dc}}\left(sin\left(\frac{\Pi}{3} - \alpha\right)\right)$$

$$= \frac{\sqrt{3}\,.T_Z.|V_{ref}|}{V_{dc}}\left(sin\frac{n\Pi}{3}.cos\alpha - cos\frac{n\Pi}{3}.sin\alpha\right)$$

$$\& \; T_2 = \frac{\sqrt{3}\,.T_Z.|V_{ref}|}{V_{dc}}\left(sin\left(\alpha - \frac{n-1}{3}\Pi\right)\right)$$

$$= \frac{\sqrt{3}\,.T_Z.|V_{ref}|}{V_{dc}}\left(sin\alpha.\,cos\frac{n-1}{3}\Pi - cos\alpha.\,sin\frac{n-1}{3}\Pi\right) \quad \& \; T_0 = T_z - (T_1 + T_2);$$

Where, n= 1 to 6 (That is sector 1 to 6) and $0 \leq \alpha \leq 60^{\circ}$

V. SPACE VECTOR PULSE WIDTH MODULATION FOR THREE-LEVEL CONVERTERS

The advantages of three-level converters instead of two-level inverter are summarized below.

- The output waveform resembles the sinusoidal waveform more. This also means that the harmonic distortion is decreased.
- Smaller *V*, which means reduced stress on the motor bearings.
- The clamping diodes limit the voltage across the OFF-state

One big downside of the higher level inverter is the neutral point balancing problem.

For a three-level three-phase inverter there are 27 switching states. As for the two-level inverter the reference vector is given with the help from three voltage vectors. For the three-level converter each sector also is divided into 4 regions, specifying the output even more. Based on the magnitude the voltage vectors can be defined as

$$V_{ref} = \frac{2}{3}(V_{a0} + V_{b0}\,e^{j2/3\pi} + V_{c0}\,e^{-j2/3\pi}$$

$$V_{ref} = V\,e^{j(w0t-y0)} = V_0 < \theta_0$$

V_{ref} can be described with the three nearest voltage space vectors. This selection is based on the magnitude of the V_{ref} and its angle.For one cycle:

$$V_{ref} = T_1 V_x + T_2 V_y + T_3 V_z$$

T_a, $T_b$and T_c for sector 1, region 3

If V_2 is chosen as the reference axis (maximum magnitude as units) the voltage vectors on the axis can be described as:

$$V_x = V_1 = 0.5,\; V_y = V_3 = \frac{\sqrt{3}}{2}e^{j6},\; V_z = V_4 = 0.5\,e^{j\pi/3}$$

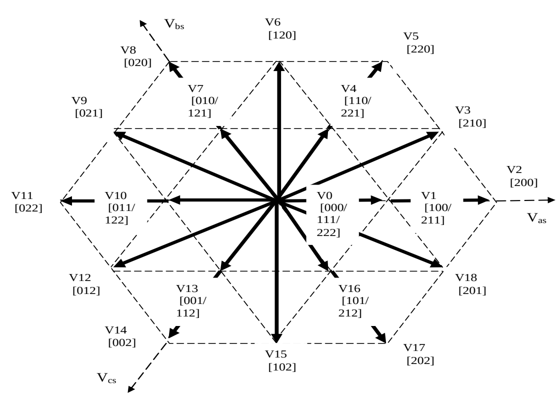

Fig.5 Space Vector Representation (For 3-Level)

And the reference vector as:

$$V_{ref} = V_u e^{j\theta}$$

$$\text{Wher} \quad V_u = \frac{V}{\frac{4}{3}Vdc}$$

V_{ref} in forms of the real and imaginary axis:

$$V_u(\cos(\theta) + j\sin(\theta)) = 0.5\,T_1 + \frac{\sqrt{3}}{2}[\cos(\frac{\pi}{6}) + j\sin(\frac{\pi}{6})]T_2 + 0.5[\cos(\frac{\pi}{3}) + j\sin(\frac{\pi}{3})]T_3$$

Dividing the formula in real and imaginary parts eases the calculations for the duty cycles:

Real part:

$$0.5\,T_1 + \frac{\sqrt{3}}{2}\cos(\frac{\pi}{6})\,T_2 + 0.5\cos(\frac{\pi}{3})\,T_3 = V_u\cos(\theta)$$

Imaginary part:

$$\frac{\sqrt{3}}{2}\sin(\frac{\pi}{6})T_2 + 0.5\sin(\frac{\pi}{3})\,T_3 = V_u\sin(\theta)$$

The duty cycles is then given in form of:

$$T_1 = 1\text{-}2\,(\frac{2V_u}{\sqrt{3}})\sin(\theta) = 1\text{-}2.a.\sin(\theta)$$

where, $(\frac{2V_u}{\sqrt{3}})$ is modulation index a

$$T_2 = 2.a.\sin(\theta+\frac{\pi}{3}) - 1$$

$$T_3 = 2.a.\sin(\theta-\frac{\pi}{3}) + 1$$

The region selection is done as in [17]. The regions are given as:

$V_\alpha + \frac{\sqrt{3}}{3}V_\beta - \frac{Vdc}{3} < 0$ for sector 1. If this is not fulfilled, the vector is in region 2:

$V_\alpha - \frac{\sqrt{3}}{3}V_\beta - \frac{Vdc}{3} > 0$ If none of the above are true, the vector is in region 3:

$V_\alpha - \frac{\sqrt{3}}{6}V_{dc} < 0$ If none of these are fulfilled the vector is in region 4.

VI. MODELING & SIMULATION OF CONTROLLED DFIG

In this chapter first the model of SVPWM based two level inverter is taken up,. Then the simulation of SVPWM 3-level pulse in open loop and the simulation of grid connected DFIG with simple vector control and SVPWM control techniques are shown.

a) *Model Of Dfig:*

The control of the DFIG consists of two separate control algorithms, which together realize the overall function of the system.

b) *Converter Controls:*

The two converters are controlled separately using two separate control algorithms..

c) *Current Control:*

Current control technique using an inverter is pulse width modulation based linear feedback control.

d) *Real And Reactive Power Control:*

The real and reactive power control of the stator is realized by the control of the rotor side currents.The sequence of the control is outlined below.

e) *Line Side Converter Control:*

The line side converter control consist of generation of d and q current references using the dc voltage error and the reactive power references.Figure-6 shows the output waveform of space vector based two level inverter & figure-7 shows the output voltage waveform of 3-level inverter. The output of the inveter is directly connected to the 3-phase ac generator known as grid.

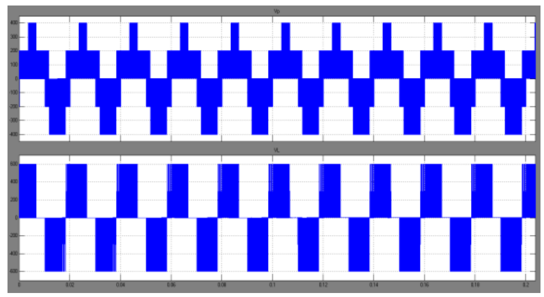

Fig.6. Level SVPWM output line voltage and phase voltage.

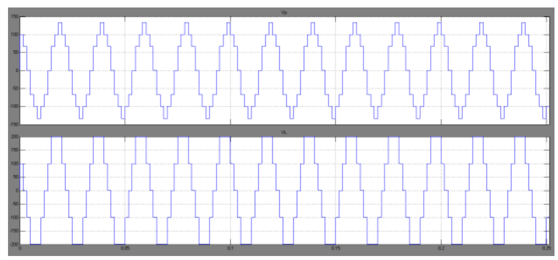

Fig.7. Level SVPWM output line voltage and phase voltage

f) *Simulation Results Of Vector Control 2-Level Dfig (Dq-Reference Frame) :*

Simulation shows that at 0.03 sec the voltage falls to 0.5 pu at this instant there is small transients occur, at instant 0.03 sec the real power is 10 MW and gradually it decreases from 10 MW to 5 MW ie. Half of the instant it seems from th result that active power is maintained constant.At instant 0.13 sec when fault removes and the system regain initial voltage ie. 1 pu and again active power absorbed by the wind turbine increases and finally comes to steady state.The variation of reactive power of wind turbine shows that at instant 0.03 sec the reactive power is initially negative and gradually rises and comes to near about zero pu.During this condition the DC link voltage fluctuate oscillatory and comes to steady state at 0.09 sec. hence reactive power is also constant and near about zero pu. At 0.13 sec when fault removes the reactive power becomes negative max again. During this instant capacitor voltage decreases which means it supplies active power.

g) *Simulation Results Of Svpwm Control 2-Level Dfig (High Frequency/ Rotating Reference Frame):*

Simulation results shows that the voltage generated by the DFIG with 2-level SVPWM has more components of disturbances. It means there is requirement of the implementation of a filter.

The variation of active and reactive power of 2-level DFIG with SVPWM is similar to the variation of active and reactive power of simple 2-level SVPWM technique for DFIG is better than the simple 2-level stationary(dq) reference frame control for DFIG.

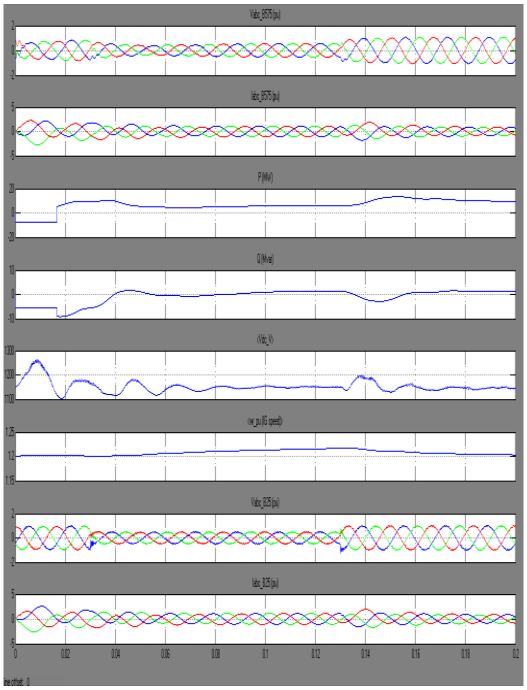

Fig.8 Results of Vector control 2-level DFIG (dq-reference frame)

The initial variation in DC link voltage V_{dc} is least in 2-level SVPWM (rotating reference frame) controlled DFIG as compared to the 2-level & 3-level DFIG with stationary reference controlled.

h) Simulation Results Of Vector Control 3-Level Dfig (Dq-Reference Frame):

Results of three level DFIG module *are* slightly similar to the results of tow level DFIG. But there is additional advantage that the THD of output of inverter is less than the THD of output of inverter for 2-level DFIG module.

The fluctuations in V_{dc} (DC link voltage) in 3-level is smaller than the fluctuation in V_{dc} for 2-level stationary reference frame controlled DFIG, and maintaining the DC voltage constant.The reactive power (Q) is very near to the desired value which is Q=0, whenever the active power is similar to 2-level during healthy condition and during fall in grid voltage to 0.5 pu. Hence after analysis of results of 2-level and 3-level dq reference frame controlled DFIG, The conclusion come is 3-level dq controlled DFIG is better than the 2-level dq controlled DFIG.

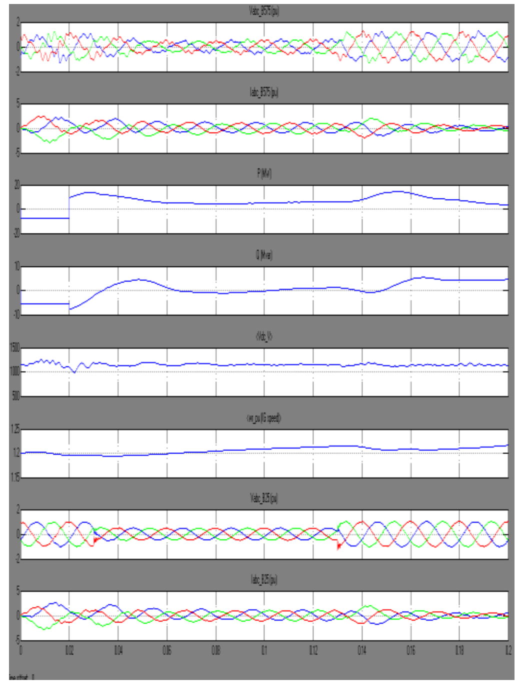

Fig.9 Results of Vector control 2-level DFIG (High Frequency/ Rotating reference Frame)

i) Svpwm Control 3-Level Dfig (High Frequency/ Rotating Reference Frame):

Simulation results shows that the DC link voltage is too small (≈ 0) and is maintained at 3V. this shows capacitors are fails to charge and also fails to maintain the reference voltage of 1100 V.We also see that in the time range of 0.06 to 0.14 sec the active power is consistent to near about zero(0) pu value and reactive power is negative (-2 pu) throughout the range which shows that DFIG supplies the reactive power but fails to supply the active power to the grid and behaves like a load. The reason of active power to zero is DC link capacitor is fails to charge to voltage 1150V.From the variation in W_r it is also clear that the speed of the rotor of DFIG is increases gradually from 1.2 pu to 1.25 pu, Which is undesirable from mechanical stability point of view to maintain the voltage of the system.

VII. CONCLUSION

As seen from the simulation results the 2-level stationary reference controlled DFIG gives good results but THD of the voltage generated is high. Whenever the results of 3-level stationary reference controlled DFIG gives results better than the the 2-level stationary reference frame controlled DFIG, also

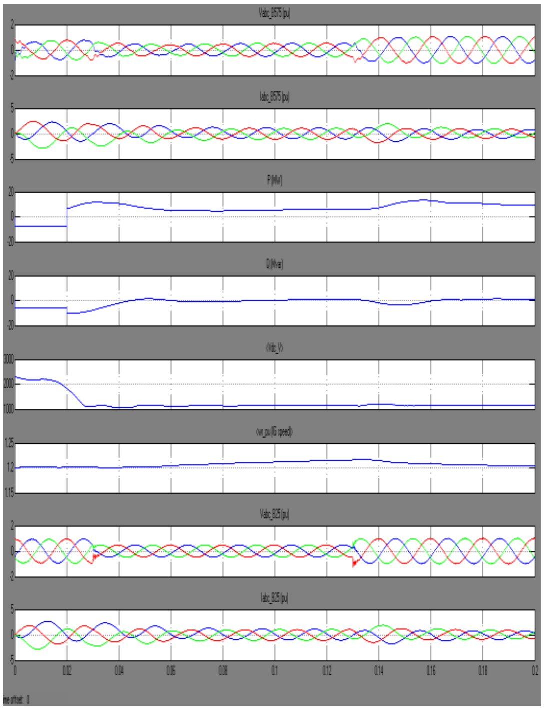

Fig.10 Results of Vector control 3-level DFIG (dq-reference frame)

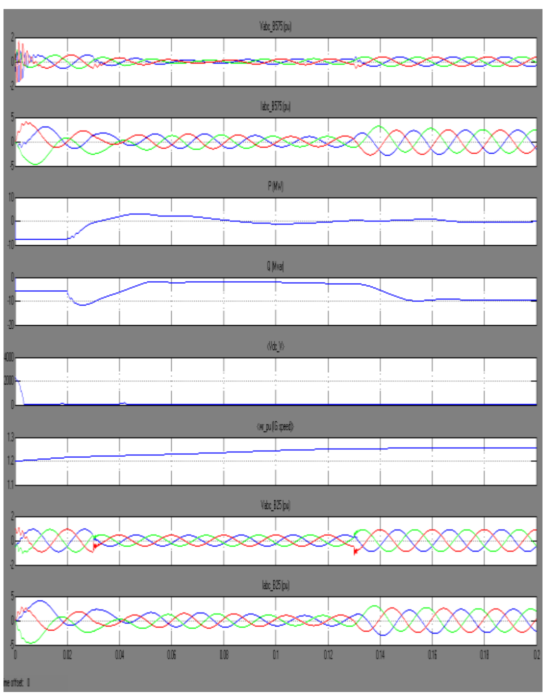

Fig.11 Results of Vector control 3-level DFIG (High Frequency/ Rotating reference Frame)

THD of 3-level inverter is lesser than the THD of two level, hence cost of filter is reduced. capacitor. Due to this problem the 3-level rotating reference frame controlled DFIG is fails to maintain the active power generated by DFIG and also the flow of reactive power.

TABLE IV. THD COMPARISON OF GRID SIDE CONVERTER VOLTAGE FOR DIFFERENT CONTROL TECHNIQUES USED IN DFIG.

Sr. no.	**Type of converter**	**Control Strategy**	**THD**
1	2-level	Stationary Reference frame (dq)- Vector Control	84.89
2	2-level	Rotating Reference frame (αβ)- SVPWM	66.04
3	3-level	Stationary Reference frame (dq)- Vector Control	38.35
4	3-level	Rotating Reference frame (αβ)- SVPWM	16.31

Table IV shows that the THD of phase voltage for 3 level inverter is smaller than the THD of phase voltage for 2 level inverter. But three level SVPWM suffers from serious drawback of balance charging of DC link voltage, Which shows a serious fall in the active power of the DFIG and also the speed of the wind turbine is higher than for 2-level SVPWM. The overall conclusion of the study is the stationary reference frame (dq) in 3-level gives better results than the all other control techniques discussed in this paper. Because the voltage levels at the capacitor terminal are different, the current supplied by the capacitors also different. When operating at unity power factor, the discharging time for inverter for each capacitor is different. Such a capacitor charging profile repeats every half cycle, and the result is unbalance capacitor voltages between different levels. This voltage unbalance problem in a multilevel converters can be resolved by using batteries.

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