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Diode Clamped Multi-Level Inverter Controller Connected To A DFIG Wind Turbine Configured DVR to Get Smoother Output Voltages

K. Ramesh, K. Jithendra Gowd

Abstract**:** ***The proposed technique in this paper is to remunerate system imbalance voltage utilizing the doubly fed induction generator (DFIG). In this, a diode clamped multi-level inverter or neutral clamped inverter in addition to dynamic voltage restorer employed to compensate the voltage unbalance. To remunerate the unbalanced voltage at the coupling point (PCC), the symmetrical per phase technique is used to calculate the current components of negative sequence required to remunerate the unbalanced voltages at coupling point. By using this technique, the torque oscillations in the machine are avoided by applying voltage at the stator of the machine. By using multi-level inverter (MLI), the smoother output voltages are obtained for the small amount of sequence currents. The two converters, one is at grid side (GSC) and other is at rotor of the machine (RSC) are the components used to inject the sequence components into the machine. This technique is validated by the simulation results which improves the smoother output voltages at PCC by reducing the oscillations in the electromagnetic torque.***

Keywords: Dynamic voltage restorer (DVR), Multi-level* inverter *(MLI), Coupling Point (PCC), Grid side converter (GSC), Rotor side converter (RSC)

I. INTRODUCTION

DFIG is a best solution for this type of generation. It can run below or above the synchronous speed. In the recent years wind energy has extended its requirement in the electrical power networks. So, there are some requirements to interconnect the wind turbine generators. But there are some power quality issues also arise, voltage unbalance a common problem. The DFIG wind turbines are most successful variable wind turbines. Here a little amount of imbalance in voltage at the grid results the unbalance of machine currents which leads to heating of windings in the machine, insolation, fluctuations of electromagnetic torque are arises high mechanical stress.

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So, voltage unbalance is considered major problem in power quality in the DFIG wind turbine systems. In this paper RSC and GSC are employed for the compensation of unbalance in the voltage at the grid side. However, by injecting the current component of negative sequence, there produce torque oscillations which are undesirable. So, the diode clamped MLI is used to avoid torque oscillations by controlling the voltage at the stator side of the machine. There is an employment of DVR with series grid side converter to remunerate the unbalances of the voltage in addition to decrease torque oscillations. But there are some limitations on the configuration of DVR with series grid side converter, this is applicable to low power ranges. These are not employed in prolonged reactive power deficiencies. It may lead to collapse of voltage. This configuration does not have the flexibility to use for the large power ratings. So, by considering these facts a neutral clamped inverter is employed for flexibility and better performance.Neutral clamped inverter gives better results for same amount of sequence component values used in the configuration of DVR with series grid side converter. The multi-level inverter provides flexibility to use for the large power rating machines also. The multi-level inverter providing exact output voltage level by using multiple lower levels as DC as input. This inverter produces smoother output voltages by using number of levels of DC as its input. This is main advantage of multi- level inverter. In this paper Diode clamped multi-level inverter is proposed because it has certain advantages over other MLI. In this multi-level inverter back to back inverters can be used and pre charged capacitors are used. The main advantage is that it has high efficiency at the fundamental frequency. It can also applicable to static variable compensation. The familiar application is that interfacing of high voltage DC and AC transmission lines is possible. For high power devices it can be used to control the speed variations.The converter at rotor side (RSC) is to remunerate the unbalance currents at the coupling point (PCC) by inserting unbalanced currents. The converter at grid side is primarily accountable for continuing the constant DC link voltage. The multi-level inverter is to decrease the fluctuations in the electromagnetic torque by controlling the voltage at the stator.

II. COMPENSATION OF UNBALANCED VOLTAGE

The transmission lines which are untransformed and the distribution of load in an asymmetrical way are the main causes of unbalances in the voltages.

This voltage unbalance is severely affected the electronic equipment of customers. The unbalance percentage is given by the below equation. The below equation (1) is the standard definition unbalance percentage given by the National Electrical Manufacturers Association.

Here, the European standards given the voltage unbalance factor to represents the severity of unbalance. It is given by:

$$Unbalance(\%) = \frac{\text{maximum deviation from average}}{\text{average of three phase-to-phase voltage}} \times 100 \quad (1)$$

$$VUF(\%) = \frac{V_2}{V_1} \times 100, \quad (2)$$

V1 represents positive sequence (PS) voltage and V2 represents negative sequence (NS) voltage.

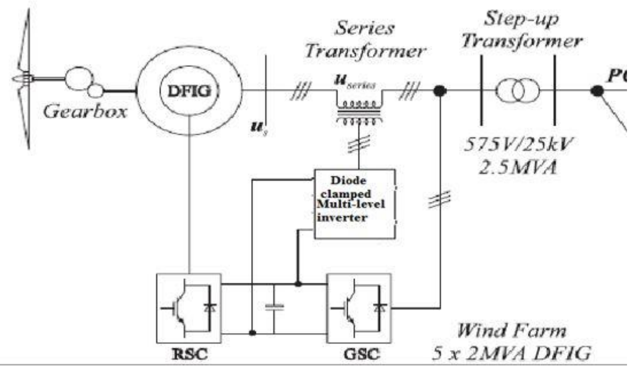


Fig (1). DFIG with MLI coupled.

To compensate the torque oscillations due to voltage unbalance at grid side has a solution, that is compensation of voltage component of negative sequence by injecting the voltage from multi-level inverter. The reduction of unbalance coupling point voltage done by introducing a current component of NS which is controlled by the impedance of the grid. For lower levels of unbalance in coupling point voltage, the NS current is supplied by only GSC and multi-level inverter reduces the unbalance in the voltage at machine terminals for smooth operation.

For the more imbalance in voltage at coupling point, when GSC operational boundaries are exceeded the RSC backing GSC to inject the NS current through stator into grid. The MLI use can provide more power wanted to injecting the NS current by RSC and allows reduction of torque fluctuations by providing a specified voltage at terminals of stator.

III. DYNAMIC MODEL OF ASYNCHRONOUS MACHINE

The dynamic model is represented in the fig.2, this machine is a two-axis rotating frame. where, ω1 is the synchronous frequency, ωr is the frequency of rotor and (ω1−ωr) is the slip frequency. magnetizing inductance is denoted by Lm, leakage inductance of stator is denoted by Lσs, and leakage inductance of rotor is denoted by Lσr. The values are in per unit (p.u) systems.

$$U^+_{sdq} = R_s I^+_{sdq} + \frac{d\psi^+_{sdq}}{dt} + j\omega_1 \psi^+_{sdq} \quad (3)$$

$$U^+_{rdq} = R_r I^+_{rdq} + \frac{d\psi^+_{rdq}}{dt} + j(\omega_1 - \omega_r)\psi^+_{rdq} \quad (4)$$

The stator and rotor fluxes are;

$$\psi^+_{sdq} = L_s I^+_{sdq} + L_m I^+_{rdq} \quad (5)$$

$$\psi^+_{rdq} = L_m I^+_{sdq} + L_r I^+_{rdq} \quad (6)$$

The inductances of the stator and rotor are given by;

$$L_s = L_m + L_{\sigma s} \quad (7)$$

$$L_r = L_m + L_{\sigma r} \quad (8)$$

Ignoring the losses in the stator resistance Rs, the stator voltage can be:

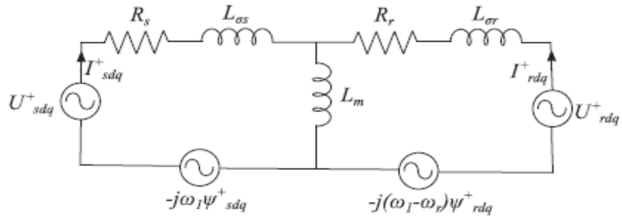


Fig 2. circuit representation of wound rotor machine

$$U^+_{sdq} \approx \frac{d(\psi^+_{sdq+})}{dt} + j\omega_1(\psi^+_{sdq+}) \quad (9)$$

From equation (5), the stator current I^+_{sdq} can be obtained.

$$I^+_{sdq} = (\psi^+_{sdq} + L_m I^+_{rdq})/L_s \quad (10)$$

The stator real and reactive power are consist as;

$$P_s = -Re\left(U^+_{sdq}\hat{I}^+_{sdq}\right) \quad (11)$$

$$Q_s = -Im\left(U^+_{sdq}\hat{I}^+_{sdq}\right) \quad (12)$$

The electromagnetic power can be found by the total power extracted from the voltage sources $j\omega_1\psi^+_{sdq}$ and $j(\omega_1 - \omega_r)\psi^+_{rdq}$:

$$P_e = -Re\left(j\omega_1\psi^+_{sdq}\hat{I}^+_{sdq} + j(\omega_1 - \omega_r)\psi^+_{rdq}\hat{I}^+_{rdq}\right)$$

$$P_e = -\omega_r(L_m/L_s)Im\left(\psi^+_{sdq}\hat{I}^+_{sdq}\right) \quad (13)$$

From P_e, electromagnetic torque is found:

$$T_e = P_e/\omega_r \quad (14)$$

The chosen work is based on the “d” axis matched to the phase “a” of the stator’s voltage. So, quadrature component of the stator’s voltage U^+_{sdq+} hold to zero.

3.1. Dynamic d-q model decomposition of DFIG:

A traditional variable F can be characterized to speak to a vector in the stator stationary axis frame(αβ)s:

$$F_{\alpha\beta}(t) = F_{\alpha\beta+}(t) + F_{\alpha\beta-}(t)$$

$$F_{\alpha\beta}(t) = \left|F_{\alpha\beta+}(t)\right|e^{j(\omega_1 t+\varphi_+} + \left|F_{\alpha\beta-}(t)\right|e^{-j(\omega_1 t+\varphi} \quad (15)$$

The PS and NS components are denoted by the symbols “+” and “- “. The underlying stage movements of the PS and NS parts are denoted by "φ+" and "φ−".

$$F_{dq}^{+} = F_{\alpha\beta} e^{-j\omega_1 t} \quad (16)$$

$$F_{dq}^{-} = F_{\alpha\beta} e^{j\omega_1 t} \quad (17)$$

$$F_{dq}^{+} = F^{r}{}_{\alpha\beta} e^{-j(\omega_1 - \omega_r)t} \quad (18)$$

$$F_{dq}^{-} = F^{r}{}_{\alpha\beta} e^{j(\omega_1 - \omega_r)t} \quad (19)$$

The equations of stator variables are rewriting as in decomposed form. In this condition, the rotation of the NS elements rotates at double the speed in the reverse direction of the stator's flux.

$$F_{sdq}^{+} = F_{sdq+}^{+} + F_{sdq-}^{+}$$

$$F_{sdq}^{+} = F_{sdq+}^{+} + F_{sdq-}^{-} e^{-j2\omega_1 t} \quad (20)$$

Rehashing this procedure to the variable of rotor, yet alluding its segments to positive rotor source context (rdq)+, rotating at ωr frequency, equivalent is:

$$F_{rdq}^{+} = F_{rdq}^{+} + F_{rdq-}^{+}$$

$$F_{rdq}^{+} = F_{rdq}^{+} + F_{rdq-}^{+} e^{-j2\omega_1 t} \quad (21)$$

Substitute equation (20) in voltage of stator Eq. (9), it is conceivable revised U_{sdq}^{+} in the accompanying decomposed structure:

$$U_{sdq}^{+} \approx \frac{d(\psi_{sdq+}^{+} + \psi_{sdq-}^{-} e^{-j2\omega_1 t})}{dt} + j\omega_1(\psi_{sdq+}^{+} \psi_{sdq\psi_{sdq+}^{+}}^{-} {}_{-} e^{-j2\omega_1 t})$$

$$U_{sdq}^{+} \approx j\omega_1(\psi_{sdq+}^{+} \psi_{sdq-}^{-} e^{-j2\omega_1 t}) \quad (22)$$

The stator current equation also does the same

$$I_{sdq}^{+} = (\psi_{sdq+}^{+} + \psi_{sdq-}^{-} e^{-j2\omega_1 t}) L_s - L_m (I_{sdq+}^{+} + I_{sdq-}^{-} e^{-j2\omega_1 t}) / L_s \quad (23)$$

By substituting the decomposed type equation of rotor current and stator flux in equation (13), electromagnetic power obtained with two pulsating components parts with frequency 2ω1:

$$P_e = P_{e,dc} + \left(P_{e,\cos(2)} \cos(2\omega_1 t) + P_{e,\sin(2)} \sin(2\omega_1 t)\right) \quad (24)$$

Where

$$\begin{bmatrix} P_{e,cos2} \\ P_{e,sin2} \end{bmatrix} = -\frac{L_m W_r}{L_s} \begin{bmatrix} \Psi_{sq-}^{-} & -\Psi_{sd-}^{-} & \Psi_{sq+}^{+} & -\Psi_{sd+}^{+} \\ -\Psi_{sd-}^{-} & -\Psi_{sq-}^{-} & \Psi_{sd+}^{+} & \Psi_{sq+}^{+} \end{bmatrix} \begin{bmatrix} I_{rd+}^{+} \\ I_{rq+}^{+} \\ I_{rd-}^{-} \\ I_{rq-}^{-} \end{bmatrix} \quad (25)$$

The equations (11) and (12) can also decomposed as:

$$P_s = P_{s,dc} + \left(P_{s,\cos(2)} \cos(2\omega_1 t) + P_{s,\sin(2)} \sin(2\omega_1 t)\right) \quad (26)$$

$$Q_s = Q_{s,dc} + \left(Q_{s,\cos(2)} \cos(2\omega_1 t) + Q_{s,\sin(2)} \sin(2\omega_1 t)\right) \quad (27)$$

Where

$$\begin{bmatrix} P_{s,cos2} \\ P_{s,sin2} \\ Q_{s,cos2} \\ Q_{s,sin2} \end{bmatrix} = -\frac{1}{L_s} \begin{bmatrix} U_{sd-}^{-} & U_{sq-}^{-} & U_{sd+}^{+} & U_{sq+}^{+} \\ U_{sq-}^{-} & -U_{sd-}^{-} & -U_{sq+}^{+} & U_{sd+}^{+} \\ U_{sq-}^{-} & -U_{sd-}^{-} & U_{sq+}^{+} & -U_{sd+}^{+} \\ -U_{sd-}^{-} & -U_{sq-}^{-} & U_{sd+}^{+} & U_{sq+}^{+} \end{bmatrix} \begin{bmatrix} \Psi_{sd+}^{+} \\ \Psi_{sq+}^{+} \\ \Psi_{sd-}^{-} \\ \Psi_{sq-}^{-} \end{bmatrix} + \frac{L_m}{L_s} \begin{bmatrix} U_{sd-}^{-} & U_{sq-}^{-} & U_{sd+}^{+} & U_{sq+}^{+} \\ U_{sq-}^{-} & -U_{sd-}^{-} & -U_{sq+}^{+} & U_{sd+}^{+} \\ U_{sq-}^{-} & -U_{sd-}^{-} & U_{sq+}^{+} & -U_{sd+}^{+} \\ -U_{sd-}^{-} & -U_{sq-}^{-} & U_{sd+}^{+} & U_{sq+}^{+} \end{bmatrix} \begin{bmatrix} I_{rd+}^{+} \\ I_{rq+}^{+} \\ I_{rd-}^{-} \\ I_{rq-}^{-} \end{bmatrix}$$

The above matrix equation number is (28)

IV. STRATEGY OF CONTROLLED TECHNIQUE

Proposed technique is to utilizing the capabilities of three converters in a harmonized solution. The equivalent plan plus the operations of every converter is explained as:

Counterbalanced the imbalanced voltage: The GSC converter is made to interject NS current. when its limit is exceeded, the RSC is come into action for injecting current component of negative sequence.

Decrement of electromagnetic torque oscillations: The multi-level inverter gives the sufficient negative sequence voltage to stator to avoid or eliminate the oscillations in torque.

Extra source of power: The GSC operational power is not sufficient in some conditions. The required power is supplied by the multi-level inverter to handle the DFIG in higher slip condition. The multi-level inverter gets the power from the power grid to beat the boundary of operation.

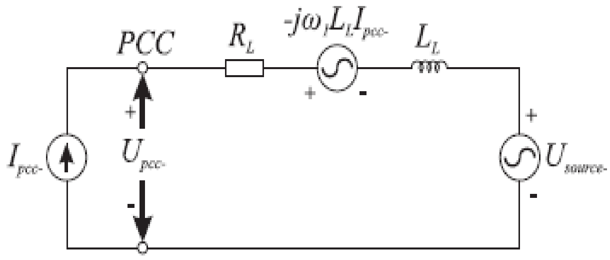


Fig.3. System circuit

4.1. control operation of GSC:

The operation of the NS component by the GSC has a function to interject a current component of negative sequence to counterbalance the voltage imbalance at coupling point.The first step in this process is to provide the reference values for the NS current component to decrease the imbalance in coupling point voltage. The voltage and current component of negative sequence at the coupling point are I_{PCC-} , U_{PCC-}, separately. The voltage U_{PCC-} is acquired by the figure 3:

$$U_{PCC-} = U_{source-} + R_L I_{pcc} - j\omega_1 L_L I_{PCC} + L_L dI_{PCC-}/dt \quad (29)$$

In the stable condition, the resistive voltage loss is neglected, then equation of the coupling point NS voltage is given by:

$$U_{Pcc-d} = U_{source-d} + \omega_1 L_L I_{PCC-q}$$
$$U_{Pcc-q} = U_{source-q} + \omega_1 L_L I_{PCC-d} \qquad (30)$$

The negative sequence PCC voltage is reduced to zero (Upcc−dq = 0) in (30) to achieve the negative sequence current at PCC (Ipcc−dq) :

$$I_{PCC-q} = -U_{source-d}/\omega_1 L_L \qquad (31)$$
$$I_{PCC-d} = -U_{source-q}/\omega_1 L_L$$

In this strategy, when the apacity of the GSC is lower than capacity needed for counteract, the control operation of RSC is driven.

4.2. control operation of RSC

Stator current is used by the RSC to assist the GSC for the control of NS current. RSC is interjecting the imbalance form of voltage in rotor to adjust the NS currents at stator. Figure 4 represents the RSC governing of NS current.

This control assimilates the dq axis stator negative sequence current (I_{sd-} and I_{sq-}) is calculated by the multiple second order generalized integrator associated to frequency locked loop (MSOGI-FLL) previously gotten values.

After comparing, the rotor negative sequence voltage ($U_{rd-}{}^{*} and U_{rq-}{}^{*}$) is obtained.

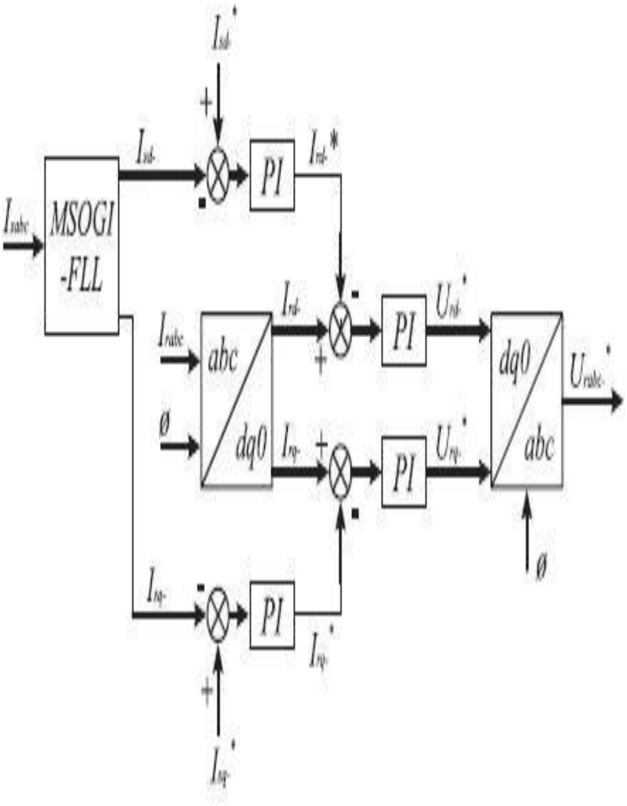


Fig 4: RSC governing circuit.

4.3. MLI control:

The MLI is used in this paper is a 3- level neutral clamped inverter. The controller has 4 switches, 2 diodes are consisting in each leg of MLI. There are 3 legs in this 3-level diode clamped MLI. All switches work in a complementary operation. The diodes in this MLI are used to make use of mid-point voltage. The DC link voltage is divided into three levels of voltages, are +Vdc/2, 0, -Vdc/2. The capacitor voltages are equal to Vdc/2.

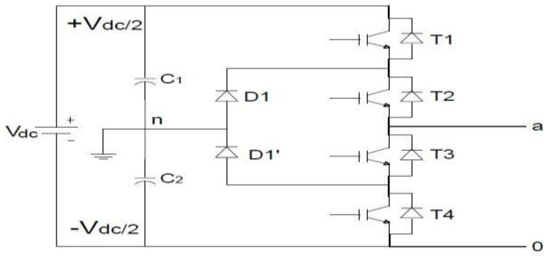


Fig 5: diode clamped MLI

The multi-level inverter is mainly to synthesize sinusoidal voltages obtained from capacitors. The 3-level inverter is also named as "neutral clamped inverter".

Table 1: MLI operational table

Switch State	*State*	*Pole Voltage*
T1=ON,T 2=ON T3=OFF,T 4=OFF	S=+ve	Vao=Vdc/2
T1=OFF,T 2=ON T3=ON,T 4=ON	S=0	Vao=0
T1=OFF,T2=OFF T3=ON,T 4=ON	S=-ve	Vao=-Vdc/2

The output phase voltages has three states, are +Vdc/2, 0, -Vdc/2. When the signal is positive then T1, T2 are ON and T3, T4 are OFF. If signal is 0, then T1 is OFF and T2, T3, T4 are ON. And when the signal or voltage is negative, then T1, T2 are OFF and T3, T4 are ON. This process is similar to all 3 legs of the MLI.

V. PERIODS OF CONTROL

To eliminate zero sequence currents to flow into the grid, the network is supported with 120kv voltage-controlled source, a mutual inductance and 25kv/120kv Y-Δ transformer.

When oscillating power attain 0.13 p.u, then injection of NS current is limited. From this limit the RSC control for negative sequence current is activated in a harmonized way. And in other side, the GSC power is also limited. If 0.18 p.u power of GSC is reached, then MLI is acts responsibly to provide extra power insists by the converters.

1. In the period 1, from 0 to 4 seconds, no control is activated and a 7.5% of VUF is injected at the 120kv voltage-controlled voltage source.
2. In the period 2, from 4 to 8 seconds, control of GSC is activated to inject the current component of negative sequence and it is limited when GSC pulsating power component with $2\omega_1$ passed 0.13 p.u. Application of NS voltage of MLI to cancel stator voltage imbalance is came into action.
3. In the period 3 from 8 to 12 seconds the control of RSC is activated for the injection of current component of negative sequence.
4. In the period 4 from 12 to 16 seconds, the control of MLI is come into action to decrease the electromagnetic torque oscillations caused by negative sequence control of RSC.

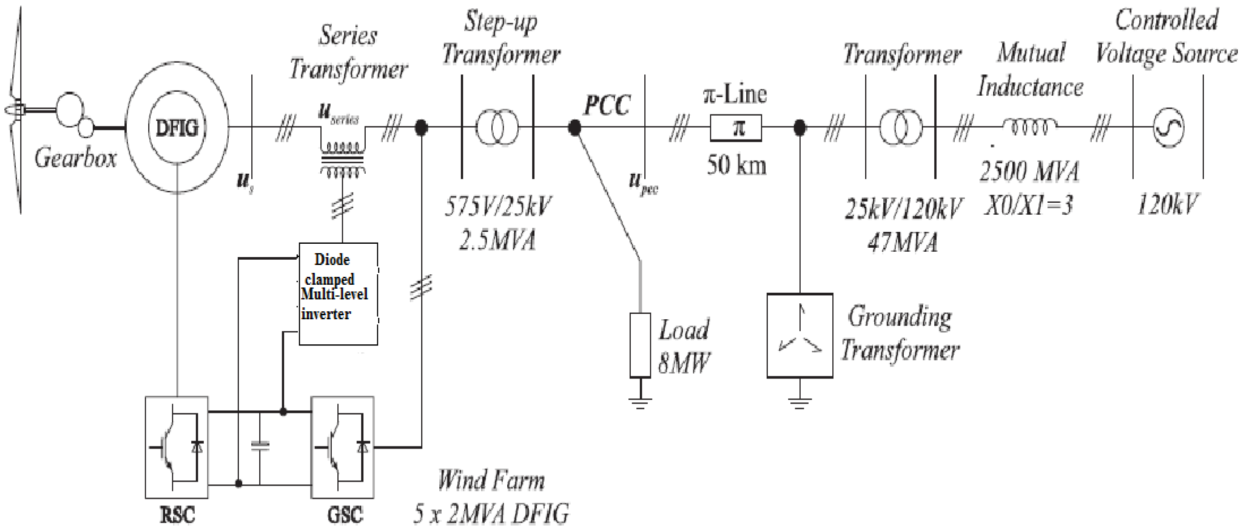


Fig 6 :Neutral clamped inverter base test grid

The ceaseless component of MLI power is amenable for voltage of DC link control if power of GSC attain its bound. Figure (a) to figure (f), the stator of DFIG wind turbine propagate the unbalance have in the voltage to current in period 1. MLI compensate imbalance in the voltage and consequently the current component of the negative sequence is also removed. In periods 3 and 4 the RSC control for negative sequence is activated and the current of the stator is counterparts the injection of NS current of the GSC.

Table 2: DFIG data

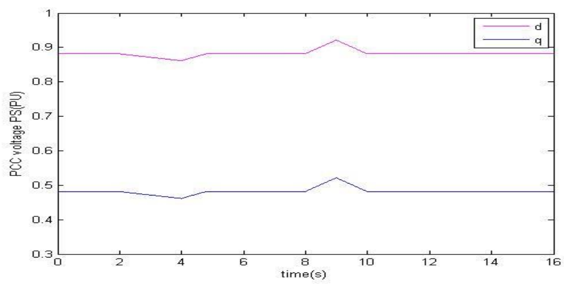
Asynchronous generator	Rated power Rated voltage Rotor rated voltage Rated frequency Rs Rr Lls Llr Inertia constant Pair of poles	2MVA 575 V 1975V 60 Hz 0.023Ω 0.016Ω 0.18 H 0.16 H 0.685 3
DC link	Cdc Base value of the DC voltage	0.3 F 1.3 kv

Figure (g) represents negative sequence current of RSC is accountable for the controlling of NS current of the stator. Current component of the NS is developed by imbalance at voltage of the stator in the period 1. The MLI decreases the NS voltage of the stator and reduces the unbalance at current of the rotor. The RSC infuse the necessary current component of the NS at the rotor of DFIG to give the wanted current component of NS at stator in the period 3. In period 4, the MLI changes the voltage component of NS of stator to counterbalance the fluctuations in the torque, the NS current is changed by RSC at armature of the machine to maintain the NS current of the stator stabilized.

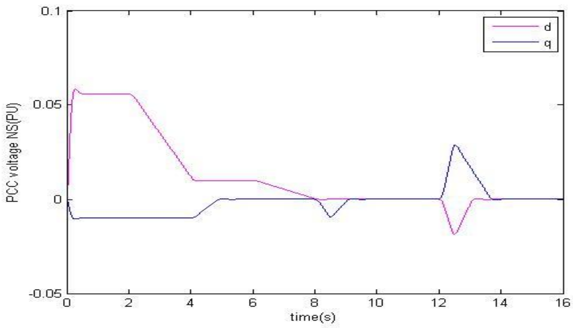
Figure (h), in period 1, the NS control of the GSC is incapacitate, then the NS current of the GSC becomes almost zero. Interjection of the NS current by converter of grid side (GSC) into grid to decrease the unbalance in the voltage is active in the period 2. Here the capacity of the GSC to infuse the current component of the NS is no sufficient to totally counterbalance the unbalance voltage at coupling point, so the NS current of the grid side converter (GSC) is maintained maximum in the periods 2, 3, 4. The current component of the NS required to remunerate unbalance voltage at coupling point hinge on the short circuit capacity at coupling point. In this way, because of harmonized operation of the NS of the GSC and RSC, the counterbalance of the unbalance in the voltage at the PCC is accomplished in the periods 3 and 4.

Figures (i) and (j) are the electromagnetic torque and rotor armature angular speed of DFIG. The fluctuations are observed in the period 1 and in the period 2 the torque gets it original shape after the elimination of the unbalance at the terminals of the stator. At the time of RSC control is activated with not having exact stator voltage injected by the MLI, the increased torque oscillations are observed in the period 3. The MLI control is activated in the period 4 to reduce the oscillation to normal. The apparent powers of RSC, GSC, and MLI are shown in the figures (k), (l), (m). The behavior of DC link voltage at the time of three converters operating in all three stages is shown in figure (n).

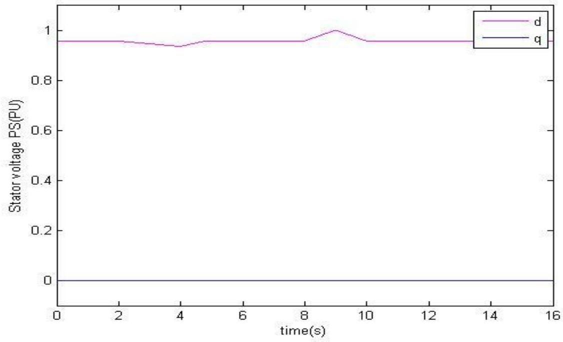
VI. RESULTS:



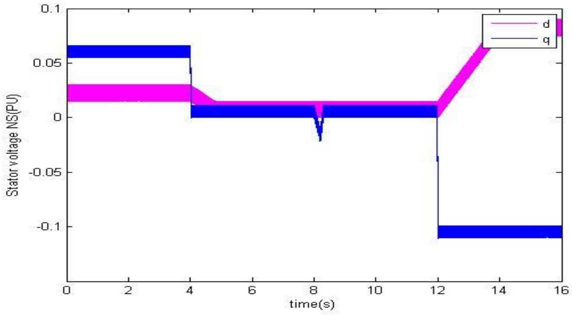
Figure(a): coupling point PS voltage



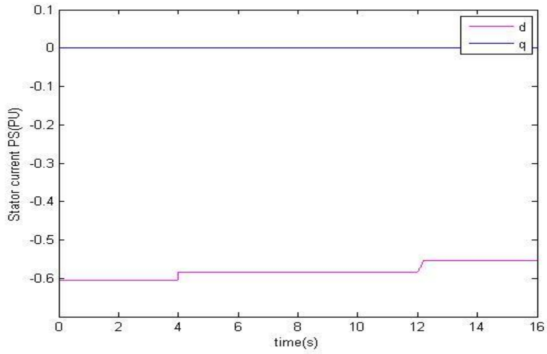
Figure(b): coupling point NS voltage voltage



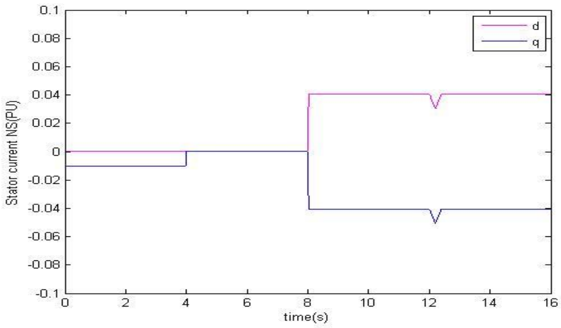
Figure(c): stator PS voltage



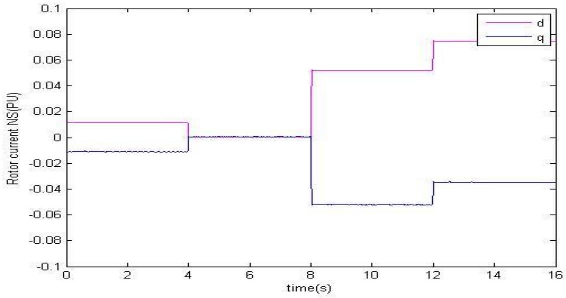
Figure(d): stator NS voltage



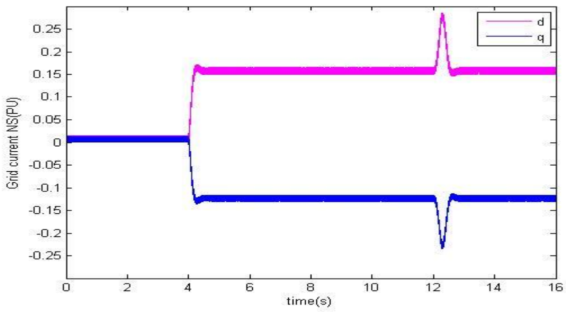
Figure(e): stator PS current



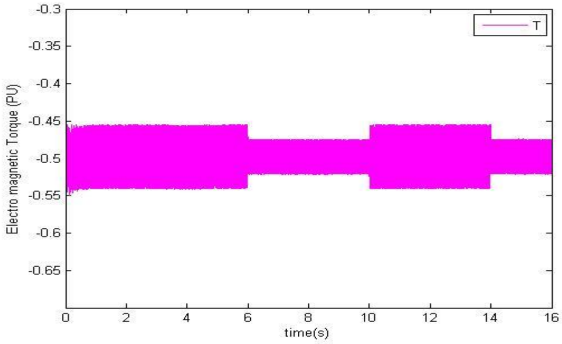
Figure(f): stator NS current



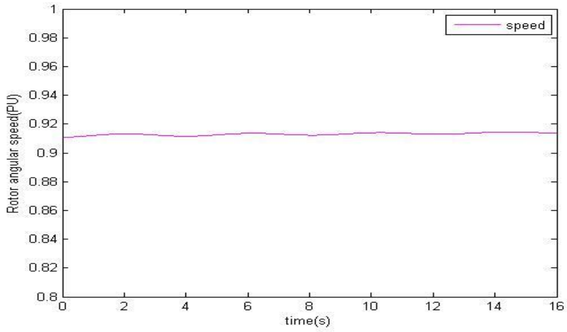
Figure(g): rotor NS current



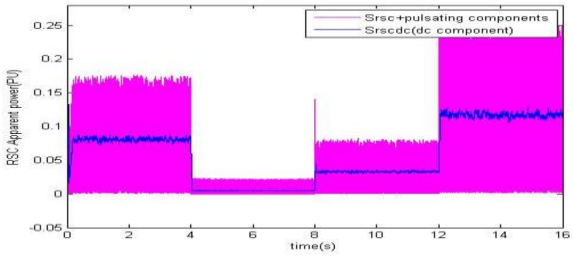
Figure(h): GSC NS current



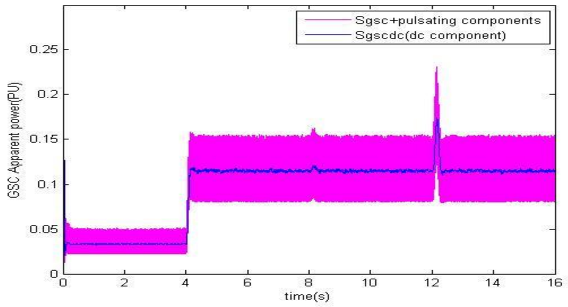
Figure(i): electromagnetic torque



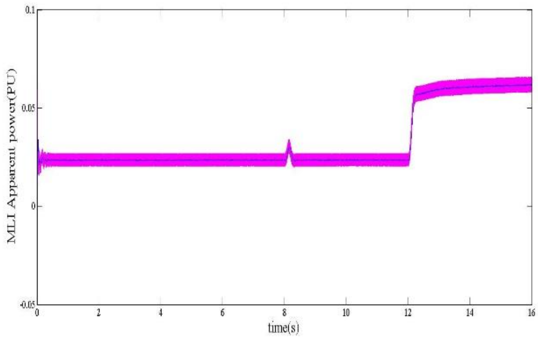
Figure(j): rotor angular speed



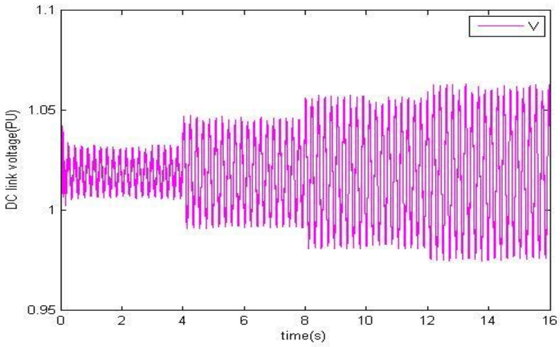
Figure(k): RSC apparent power



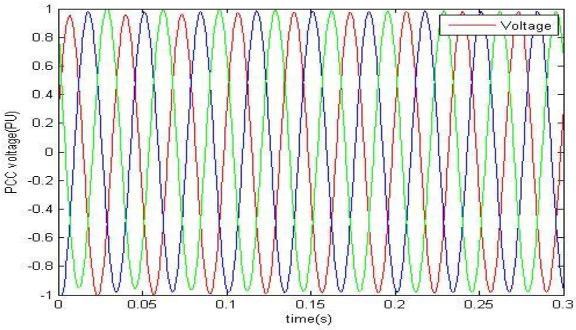
Figure(l): GSC apparent power



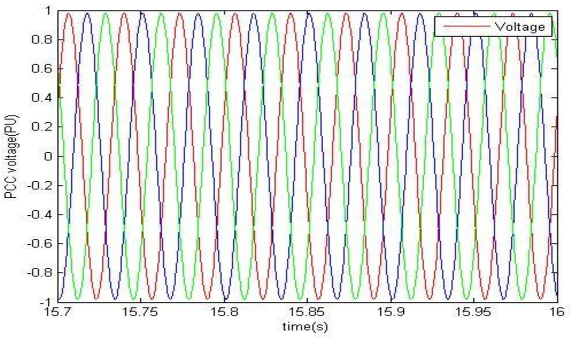
Figure(m): MLI power



Figure(n): DC link voltage



Figure(o): PCC voltage without compensation



Figure(p): PCC voltage with compensation

VII. CONCLUSION

The operational technique presented in this paper for voltage imbalance compensation utilizing a DVR-based design in DFIG, comprising of a arrangement MLI associated with the DFIG. Connected system permits the counterbalance the voltage unbalance at coupling point yet in addition to expand the functional scope of the techniques beforehand recommended that depends altogether lingering intensity of GSC. That methodology is extremely viable to dissemination control frameworks correspondingly exposed to voltage imbalance and touchy burdens to voltage imbalance. In this way, exhibited procedure enhances and gives better performance relating with the past techniques, not just the limit of NS current infusion by the DFIG yet in addition the functional scope of the operation. The 3-level neutral clamped inverter has flexibility to higher power rating machine also. In addition to compensation of voltage unbalance, this method eliminates oscillations in electromagnetic torque.

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