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Performance Enhancement of Grid connected PWM Rectifier under Grid Disturbances

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Abstract: ***The voltage distribution system may be disturbed in spite of a stiff system. The front end rectifiers should be controlled to provide immunity to such disturbances. In this paper, virtual flux oriented control algorithm for three phase active rectifier under distorted and unbalanced grid conditions is presented. No voltage measurement is required to implement this control scheme. In spite the grid virtual flux is estimated. The control is based on grid virtual flux estimation without ac voltage sensors. The LCL filters have been acknowledged for reduction in harmonics at switching frequency. However the selection of LCL parameters is tedious task. A complete design for the active rectifier and LCL filter has been given in detail. The virtual flux is utilized to get the voltage and instantaneous power estimation. As the flux is less sensitive to grid voltage disturbances so it provided more robust control of the converter. The control algorithm is simulated in MATAB under two conditions: (a) normal grid voltage and (b) unbalanced and distorted grid voltage. The results demonstrate the balanced and sinusoidal grid current even under grid unbalanced and distorted grid voltages.***

Index Terms: Harmonic distortion, LCL filters, Power quality, PWM Rectifier, VFOC.

I. INTRODUCTION

Three phase voltage source converters are used as in large number of applications as front end rectifiers. To list a few are; in industrial drives, FACTS devices and grid interface applications [1-2]. The current control method provides sinusoidal current. The high switching frequencies are preferred due to certain benefits. Moreover, the high switching frequencies can seed generation of high-order harmonics into the grid. LCL filter is a solution to reduce these switching harmonic components. So, both the design and control techniques of these rectifiers are important to attain optimum results from PWM rectifiers. A complete design for the active rectifier, LCL filter has been given in detail in this paper and the virtual flux oriented control (VFOC) algorithm is described and implemented in MATLAB Simulink. The control techniques of PWM rectifiers are focused on two areas i) to maintain the sinusoidal and unity power factor alternating current. ii) Regulated and ripple free dc voltage. A number of control algorithms are available in literature to fulfil these requirements. Hysteresis current control is known for good dynamic response and its insensitivity to parameter variations [3]. However the switching frequency is variable. The switching frequency is influenced by the load and changes in ac voltage. Moreover it becomes difficult to design the filter parameters with variable switching frequency. The voltage-oriented control (VOC) algorithm needs the coordinate transformation [4-6]. The synchronously rotating frame transformation is used and quadrature axis component is set equal to zero to assure unity input power factor. The internal loops provide better dynamic response [7].The VOC scheme can be implemented without ac voltage sensors. The virtual flux based estimation is applied for this purpose. Feedback linearization is used in [8]. The switching table used to generate PWM signals [9]. The direct power control algorithm is analogous to the direct torque control used in induction motor speed control. The DTC method provides better dynamic behaviour in electric drives [10]. To implement voltage sensor less direct power control (DPC) operation, the virtual flux based estimation can be utilized. This virtual flux direct power control (VF-DPC) showcase better power quality due to sinusoidal current. The pulse width modulation block is not required in DPC, as the switching stated are decided from switching table based on the output of hysteresis active and reactive power controllers. So, it imparts variable switching frequency. In addition to this, to apply digital processing, high sampling frequency is necessary. This may lead complex implementation in industrial applications. The solution to these problems can found by changing the PWM technique used. The switching table is replaced by PWM modulator. In this paper, a PWM based voltage modulator with Voltage Flux Oriented Control (VFOC) is used. But the operation of PWM rectifier under abnormal grid voltage conditions need attention. Filters are generally used in grid connected converters. Usually, an L filter on ac side is connected to improve the current waveform, A high value of inductor may be required in large power converters due switching frequency limitations. On the other hand, a large size inductor causes increase in volume and influences the dynamic behaviour of the system wrongly [11]. An alternative to this problem is LCL filter [12]. The LCL filter requires smaller size of inductance. The high switching frequency harmonics are reduced by using an *LCL* filter [13] [14]. In this paper, the complete design PWM rectifier along with the detailed design procedure of LCL filter is described for 10kW PWM rectifier.

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The VFOC algorithm is implemented in MATLAB/Simulink. The voltage measurement is evaluated by the virtual flux. So no ac voltage sensors are required. As the virtual flux is less sensitive to the grid voltage variations, so it proves to be more robust as compared to VOC algorithm. The simulation results demonstrate the performance of VFOC with LCL filter under normal grid condition as well as under unbalance and distorted grid voltage.

II. MODEL OF THE SYSTEM

The circuit configuration of the PWM converter is shown in Fig. 1. The e_a, e_b and e_c are values of phase voltages of three phase input supply.

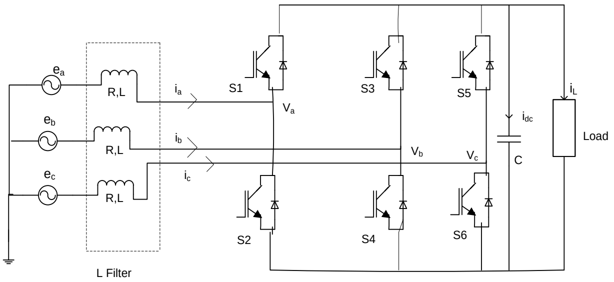

Fig.1 The PWM Rectifier

Where R is the resistance and L is the inductance of the three phase power supply. The line currents drawn from the three phase grid are i_a, i_b and i_c; V_a, V_b and V_c are the pole voltages of the converter; C is the capacitive filter connected on dc side; I_{dc} is the current on the dc side; I_L is the current flowing through the load; R_L is the load resistance; $S_{a,b,c}$ represents the switching states of the converter.

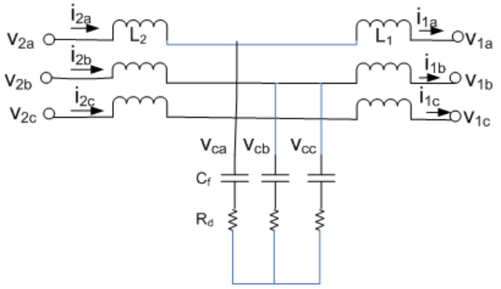

Figure .3 LCL Line Filter

Assuming a balanced power structure in three phase three wire configuration, the Kirchoff's law equations can be written as:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$C\frac{dV_c}{dt} = Si_a + Si_b + Si_c \tag{2}$$

The pole voltage per phase can be written as:

$$v_a = \left(2S_a - \left(S_b + S_c\right)\right)\frac{V_{dc}}{3} \tag{3}$$

$$v_b = \left(2S_b - \left(S_a + S_c\right)\right)\frac{V_{dc}}{3} \tag{4}$$

$$v_c = \left(2S_c - \left(S_a + S_b\right)\right)\frac{V_{dc}}{3} \tag{5}$$

Using Clarke transformation, the balanced three values ($x_{a,b,c}$) can be transformed into stationary $\alpha\beta$-coordinates by using the transformation matrix given below.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \tag{6}$$

III. DESIGN OF PWM RECTIFIER

The design of PWM rectifier mainly consists of selection of switching frequency, dc bus voltage and the input ac inductors. Depending upon the switching frequency the design of the inductor is carried out. However, the LCL filter requires smaller size of inductance. The Design of LCL filter parameters are discussed in detail as below.

A. Switching Frequency

The selection of the switching frequency involves the trade-off between line inductance and input current waveform quality. The selection of digital signal processor also influence the selection of switching frequency as it is the speed of the processor (clock frequency) and analog to digital conversion speed which are highly related with switching and sampling frequency. The general range of switching frequency is considered in between10-20 kHz.

B. Selection of DC Bus Voltage

The minimum dc side voltage needed can be determined by the following equation [15] .

$$V_{dc\ \min} = \sqrt{3}\sqrt{2}V_{LNRMS} = 2.45V_{LNRM} \qquad [7]$$

C. Selection of LCL Filter Parameters

A design procedure of an *LCL* filter is given for a PWM rectifier in this section. The design method is suitable for the control techniques using PI controller in the dc voltage regulation and ac reference current tracking. The main purpose is to decrease switching ripple without changing the PI controller parameters that were used with L filters. This is possible as the additional part LC in the existing L filter reduces high frequency current ripple. However a low value of C does not affect the current controller. Moreover, the current control only affects the low-order current harmonics because of its bandwidth. Thus, an L filter can be upgraded to LCL version with great ease [16]. The effect would be remarkable with a small increase in the cost.

The selection of parameters is very important. The wrong selection of LCL filter may result into very poor response. The resonance condition may reduce the impact of filtering or on the other side may increase of the distortion. The oscillations may be produce due to resonance and increase the distortion. Therefore, the inductors should be carefully designed. Damping should be provided to avoid resonances and current ripple factor taken into consideration.

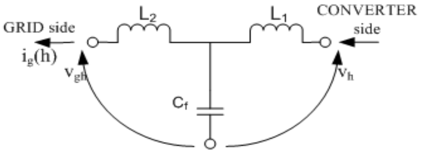

Fig.3. Equivalent single-phase LCL filter at the h harmonic

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The frequency domain analysis is used to compute the ripple attenuation. The value of LCL filter is chosen as the percentage base value [16].

$$Z_b = \frac{(V_n)^2}{P_n} \tag{8}$$

$$C_b = \frac{1}{\omega_n Z_b} \tag{9}$$

Where V_n is the line voltage, ω_n is the frequency of ac supply, and P_n is the real power consumed by the rectifier. The switching frequency and resonance frequency relationship may be written as

$$\omega_{res} = k\omega_{sw} \tag{10}$$

For hth order harmonic component, the single phase filter circuit equivalent can be represented by Fig.3. However, the the resistances are ignored in Fig.3. Where i(h) represents the hth harmonic current and v(h) represents the hth harmonic of voltage, while h_{sw} indicates switching frequency harmonic. As the switching frequency is of the order of kHz, so frequency of the ac mains supply can be considered as very very small or the ac source impedance may be considered as a zero. Furthermore the converter can be examined as a harmonic generator.

Therefore harmonics are generated in the voltage of the converter at the switching frequency whereas the harmonic in grid voltage will be zero, i.e $v(h_{sw}) \neq 0$, $v_g(h_{sw})=0$

The progression of ripple attenuation from converter side to the grid side, is computed as follows:

$$\frac{ig(h_{sw})}{v(h_{sw})} = \frac{(Z_{LC})^2}{\omega_{sw}\left|\omega_{res}-\omega_{sw}{}^2\right|} \tag{11}$$

$$\frac{i(h_{sw})}{v(h_{sw})} \approx \frac{1}{\omega_{sw} L} \tag{12}$$

$$\frac{ig(hsw)}{i(hsw)} = \frac{(Z_{LC})^2}{\left|\omega_{res}^2 - \omega_{sw}^2\right|} \tag{13}$$

Where f_{sw} is switching frequency and $\omega_{sw}=2\pi f_{sw}$

Resonant frequency, $\omega_{res} = L_g \frac{Z_{LC}^2}{L}$,

Switching frequency of harmonic order, $h_{sw}=\omega_{sw} / \omega_n$

Damping is required to lessen the switching frequency ripple. Damping also avoids the resonance. So, a resistor is used in series with the capacitor. However there are some limitations on the filter parameter values as given below [16].

a) The value of C is restricted generally less than 5%.

b) The sum of value of the inductance on converter side and grid side should be smaller than 0.1 pu.

c) The resonant frequency should lie between ten times the grid frequency and 50% of the switching frequency.

d) Passive damping chosen should result into no oscillation.

D. Process of Filter Design

The steps to select the LCL filter are gives as below [16].

1) The ripple in the rectifier current is chosen. The magnitude of inductor L_1 is chosen corresponding to the switching frequency selected above in *A*. The value of inductor L_2 can be computed as below:

$$L_2 = qL_1 \tag{14}$$

2) The capacitor value is determined by selecting the reactive power absorbed. Say b percent of the reactive power (Q) is absorbed at rated values.

$$C_f = rC_b \tag{15}$$

However, the value of capacitor should be less than 5% as stated in the condition (a) above.

3) The ripple reduction is given by

$$\frac{ig(hsw)}{i(hsw)} = \frac{1}{\left|1+q(1-ar)\right|} \tag{16}$$

Here damping of the filter is ignored and assumed a lossless system.

Here a is fixed value. However damping and losses should be taken into consideration. For that the desired attenuation is multiplied by a factor. The sum of the both value of inductance should meet the condition (b). If it doesn't then another value of attenuation factor need to be selected or changes the value of the reactive power in step 2.

4) Now check the value of resonant frequency by the following equation.

$$\omega_{res} = \sqrt{\frac{L_T}{LL_g C_f}} \tag{17}$$

From (10), (14), and (15),

$$k = b\sqrt{\frac{1+q}{qx}} \tag{18}$$

$b=\frac{1}{\omega_{sw}\sqrt{C_b L_g}}$ is a constant.

The value of computed resonant frequency should meet the constraint (c).If it doesn't satisfy (c), then either the reactive power or reduction factor in step 2 or 3 need to be revised.

5) As per the constraint (d) above, passive damping is selected. If the attenuation computed is not suitable, then go back to step (3) and escalate the multiplication factor. If still the attenuation computed is not suitable then start again from step (2) and change the reactive power to high side.

6) Validate the attenuation value for the other load conditions and switching frequencies.

E. Design Example

Let the power rating of VSC be10kW, line voltage, V_n is 415V [17].

Say the switching frequency, f_s selected is 10 kHz.

$$\text{Base Impedance, } Z_b = \frac{(415)^2}{10000} = 17.225\Omega \tag{19}$$

$$\text{Base Inductance, } L_b = \frac{\omega_n}{Z_b} = 54.85\text{mH} \tag{20}$$

$$\text{Base Capacitance, } C_b = \frac{1}{\omega_n Z_b} = \frac{1}{314(17.225)} = 185\mu\text{F} \tag{21}$$

Let converter side inductance, L_1=3.5mH

From equation (7), minimum value of DC link voltage

$$V_{dc} = 587\text{ V} \tag{22}$$

Say higher value selected is 600V.

$$V_{dc} = 600\text{ V} \tag{23}$$

Maximum value of capacitance = $\frac{5}{100}(185^{-6})=9.25\mu\text{F}$

This meets the condition (a).

Let start with a value of 4.625 μF and then, if any condition is not satisfied, escalate it till the maximum value of 9.25 μF

$$\text{So, } C_f=4.625\mu\text{F} \tag{24}$$

Say, a current ripple attenuation = 20% with reference to ripple on the converter side.

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q= 0.157 is calculated using Eq. (17).

Therefore L_2 = (0.157)3.5=0.55mH (25)

Total inductance L_T=3.5+0.55 = 4.05 mH (26)

Which is less than 0.1pu (condition (b)) as,

$$L_T = \frac{4.05}{54.85} = 0.073\,\text{pu},$$

Resonance frequency, $f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_T}{LL_gC_f}}$ = 3.394 kHz (27)

Resonance frequency satisfies the condition (c) above.

The value of capacitive reactance at resonant frequency is 10.137Ω.The value of damping resistance can be chosen as 25% of capacitor impedance.

R_d= 4.5Ω (28)

The parameters of the PWM rectifier computed as above are tabulated in Table 1.

Table 1.PWM Rectifier Parameters

Power rating of VSC	10kW
Line to line Voltage(RMS)	415V
Switching Frequency	10kHz
DC side Voltage	600V
Inductance, L2	0.55mH
Inductance, L_1	3.5 mH
Capacitance(star connection),C_f	4.625µF
Damping, r_d	4.5Ω
Capacitive filter on dc side, C_{dc}	3142µF

III. THE CONTROL ALGORITHM

The virtual flux oriented control is a voltage sensor less algorithm. The scheme of Virtual Flux (VF) is based voltage oriented control (VOC) algorithm, but the ac voltage computed using virtual flux, switching states and dc voltage. Phase lock loop (PLL) is used to avoid the error in the coordinate transformation. The disturbances may occur in the line voltages due to a grid system. High penetration of renewable energy sources such as wind and solar may results into grid line voltage disturbances. Flux vector is not that affected by the variations as the line voltage vector are. As the flux is computed using integration and so low pass capability is benefit associated with it. Also the rotation of flux vector is much smoother than the voltage vector. So, the use of phase lock loop is not required to make the system more robust.

The topology of the system on ac side can be compared with an ac motor (virtual) as shown in Fig. 4. The value of resistance and inductance of filter can be identified as the resistance and leakage inductance of stator winding of the motor. So there would be induced voltages v_{ab},v_{bc},v_{ca} due to virtual air gap flux.. The virtual line flux vector Ψ_L and the line voltage vectors in stationary α-β coordinates are shown in Fig. 5 [17].

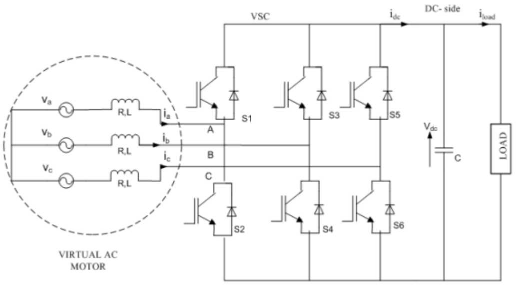

Fig. 4 AC side analogy with ac motor

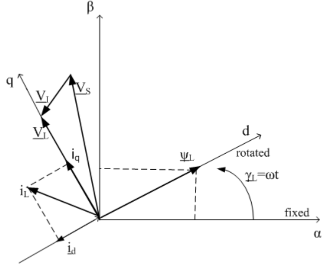

Fig. 5 Flux and Voltage vector diagram

Where Vs denotes the voltage of converter, $\Psi^{\wedge}{}_L$. denotes the flux vector, V_L denotes the line voltage,V_I is the voltage drop across the inductance and i_L is the line curent.

The value of virtual flux can be written as [19]:

$$\hat{\psi}_{L(est)} = \hat{\psi}_s + \hat{\psi}_I \tag{29}$$

The input voltage to the rectifier in stationary α-β coordinates can be estimated as follows

$$v_{s\alpha} = \sqrt{\frac{2}{3}} V_{dc}\left(s_a - \left(s_b + s_c\right)\right) \tag{30}$$

$$v_{s\beta} = \frac{1}{\sqrt{2}} V_{dc}\left(s_a - s_c\right) \tag{31}$$

The virtual flux Ψ_L in stationary α-β coordinates is computed as below using (30):

$$\hat{\psi}_{L\alpha(est)} = \int (v_{s\alpha} + L\frac{di_{L\alpha}}{dt})\,dt \tag{32}$$

$$\hat{\psi}_{L\beta(est)} = \int (v_{s\beta} + L\frac{di_{L\beta}}{dt})\,dt \tag{33}$$

The instantaneous value of the powers (active and reactive) is calculated by

$$p = \omega\left(\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha}\right) \tag{34}$$

$$q = \omega\left(\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta}\right) \tag{35}$$

The angular displacement of the flux (virtual) vector is given by:

$$\sin\psi_{VL} = \frac{\psi_{L\beta}}{\sqrt{\left(\psi_{L\alpha}\right)^2 + \left(\psi_{L\beta}\right)^2}} \tag{36}$$

$$\cos\psi_{VL} = \frac{\psi_{L\alpha}}{\sqrt{\left(\psi_{L\alpha}\right)^2 + \left(\psi_{L\beta}\right)^2}} \tag{37}$$

The block diagram of the control algorithm is shown in Fig. 6. In order to achieve unity power factor on the ac side, the reactive power drawn from the grid should be equal to zero. Therefore the reference value of the quadrature axis component of the current is selected to be zero.

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IV. RESULTS AND DISCUSSIONS

The design of PWM rectifier with LCL filter is carried out for a 10kW power rating. The system is modeled and simulated in the MATLAB/Simulink environment. Sensor-less The control algorithm is simulated under two conditions: case (A)- Normal grid conditions and, case (B)- Unbalanced and distorted grid voltage. The parameters used for simulation are given in Table.1.In case (B), the grid voltage is unbalanced and distortion is 9.84%.

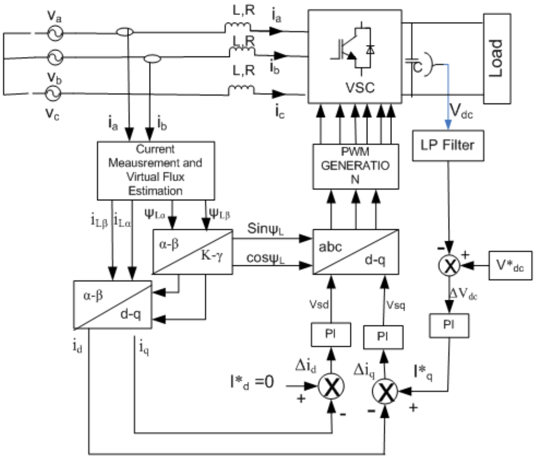

Fig.6 VFOC Scheme

Case (A): Operation under normal grid conditions

The results of the simulation under normal grid conditions are shown in Fig.7 and 8. The dc side voltage is 600 V, same as the desired value. The total harmonic distortion in ac side line current is 1.45% which meets the IEEE standards. The line current is in phase with the line voltage making unity power factor operation.

Case (B): Operation under unbalanced and distorted grid voltage conditions

The parameter used for simulation under unbalance and distorted grid voltage conditions are as given in Table.1 .The grid voltage has unbalance with 9.84% THD as shown in Fig. 10. The simulation results illustrating the performance of the PWM rectifier under unbalance and distorted grid voltage is shown in Fig.9 and 11.

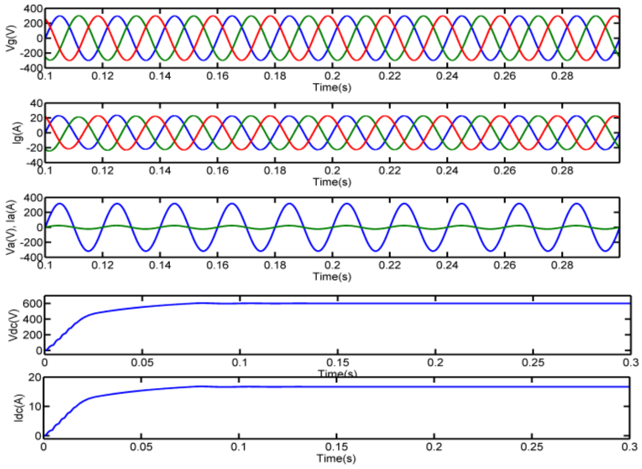

Fig.7 Performance of the PWM Rectifier in case A

The results indicate that the voltage on dc side is 600V which is same as reference value. The total harmonic distortion in the line current is 1.45% which meets IEEE standards. The power factor is unity on the input side i.e at the point of common coupling. It can be seen that the grid current is balanced where as the grid voltage is unbalanced. Thus control scheme works effectively even under unbalanced and distorted grid voltage conditions. Hence the control algorithm proves to be more robust.

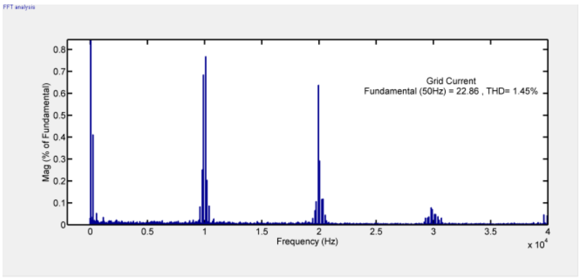

Fig.8 Frequency Spectrum of grid current in case A

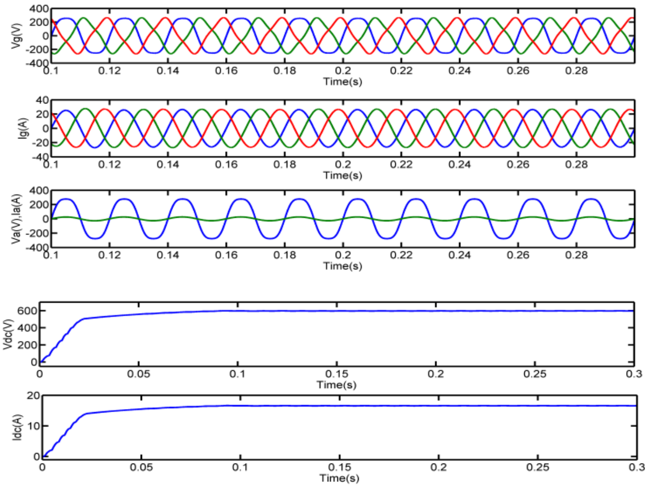

Figure .9 Performance of the PWM Rectifier in case B

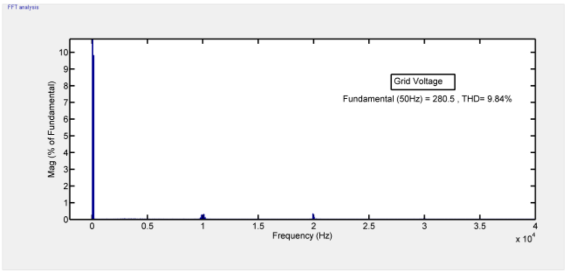

Figure.10 Frequency Spectrum of grid voltage in case B

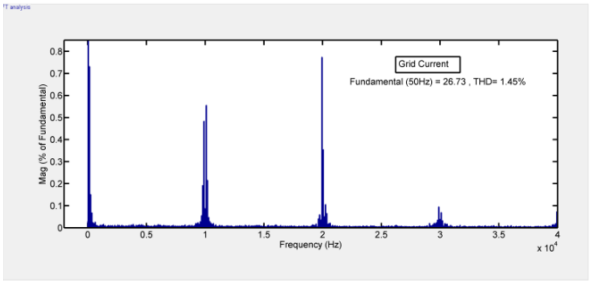

Figure.11 Frequency Spectrum of grid current in case B

V. CONCLUSION

In this paper, virtual flux oriented control algorithm for three phase active rectifier under distorted and unbalanced grid conditions is presented. The result demonstrates the power quality improvement using VFOC algorithm and LCL filter. The design of PWM rectifier and LCL filter is described in detail. An L filter topology can be easily upgraded to LCL version. The control scheme does not use voltage measurement. The VFOC algorithm for three PWM rectifiers has been explained systematically. The control algorithm illustrates dc voltage regulation to the reference value. The total harmonic distortion is less than 5 % which satisfies IEEE standards. The unity power factor operation at PCC is attained. The VFOC scheme is evaluated under normal grid voltage conditions and also with unbalanced and distorted grid voltage. The system under study is simulated using the MATLAB/Simulink. The results indicate demonstrate performance in both cases (A) under normal grid voltage conditions and (B) with unbalanced and distorted grid voltage. The converter output voltage is regulated to the desired voltage, which is 600 V in both cases. The phase voltage and current are in same phase in both cases, thus ensuring unity power factor at the PCC. The grid current is balanced even with unbalanced and distorted grid voltage. The THD of line current is 1.6% under normal grid conditions. Moreover the THD of line current 1.25% under unbalanced and distorted grid voltage conditions. Thus the control scheme is effective under normal as well as abnormal grid conditions. Hence improvement in power quality is achieved even under grid disturbances.

REFERENCES

1. R.P. Stratford. 1980.Harmonic Pollution on Power Systems- A Change in Philosophy. *IEEE Transactions on Industry Applications*. Vol. IA-16, No.5, pp.43-49.
2. S.M. Peeran. and C.W.P. CascaddenApplication, design, and specification of harmonic filters for variable frequency drives. *IEEE Conf.APEC'94*, pp. 909-916.
3. J. R. Rodriguez, J. W. Dixon, J. R. Espinoza, J. Pontt, P. Lezana.2005.PWM regenerative rectifiers: state of the art. *IEEE Transactions on Industrial Electronics*, Vol. 52, No. 1, pp. 5-22.
4. Malinowski, M., Kazmierkowski, M. P., &Trzynadlowski, A. Review and comparative study of control techniques for three-phase PWM rectifiers.*Mathematics and Computers in Simulation*, Vol.63, No.3, pp. 349-361.
5. Kazmierkowski, M. P. 2002.Direct power control of three-phase PWM rectifier using space vector modulation-simulation study. *IEEE International Symposium* on Industrial Electronics, Vol. 4, pp. 1114-1118.
6. Lalili, D., Mellit, A., Lourci, N., Medjahed, B., &Berkouk, E. M. 2011.Input output feedback linearization control and variable step size MPPT algorithm of a grid-connected photovoltaic inverter. *Elsevier Journal onRenewable energy*, Vol.36, No.12, pp.3282-329.
7. Kazmierkowski M.P. and Malesani L.1998.Current control techniques for three-phase voltage-source PWM converters: a Survey. *IEEE Transactions on Industrial Electronics*, Vol.45,No.5,pp.691-703.
8. Mustapha Jamma, Mohamed Barara and Bogdan-Adrian Enache.2016. Voltage oriented control of three-phase PWM rectifier using space vector modulation and input output feedback linearization theory. *Intr Conf 8th Edition ECAI 2016*.
9. T. Noguchi, H. Tomiki, S. Kondo, I. Takahashi. 1998.Direct power control of PWM converter without power-source voltage sensors",*IEEE Transactions on Industry Applications*, Vol. 34, No. 3, pp. 473- 479.
10. P. Habetler, F. Profumo, M. Pastorelli, L. Tolbert.1992.Direct torque control of induction machines using space vector modulation", *IEEE Transactions on Industry Applications*, Vol. 28, No. 5, pp. 1045-1052.
11. Liserre M., Dell'Aquila A., Blaabjerg F.2002.Stability improvements of an LCL-filter based three-phase active rectifier. *IEEE 33rd Annual Power Electronics Specialists Conference*, vol 3, pp. 1195-1201.
12. E. Twining, Holmes D. G.2003.Grid current regulation of a three-phase voltage source inverter with an LCL input filter," *IEEE Transactions on Power Electronics*, vol. 18, No.3, pp. 888-895.
13. Hea-Gwang Jeong, Kyo-Beum Lee, Sewan Choi, and Woojin Choi.2010.Performance Improvement of *LCL*-Filter-Based Grid-Connected Inverters Using *PQR* Power Transformation. *IEEE Transactions on Power Electronics*, Vol. 25, No. 5, pp.1320-1330.
14. Azziddin M. Razali, M. A. Rahman, Glyn George and Nasrudin A. Rahim. 2015.Analysis and Design of New Switching Lookup Table for Virtual Flux Direct Power Control of Grid-Connected Three-Phase PWM AC–DC Converter. *IEEE Transactions on Industry Applications*, Vol. 51, No. 2, pp. 1189-1199.
15. M.P.Kazmierkowski, R. Krishnan and F.Blaabjerg, 2002.*Control in power electronics (selected problems)*, Academic press, USA.
16. Marco Liserre, Frede Blaabjerg, Steffan Hansen. 2005.Design and Control of an *LCL*-Filter-Based Three-Phase Active Rectifier. *IEEE Transactions on Industry Applications*, Vol. 41, No. 5pp.1281-129
17. Sushma Kakkar, Tanmoy Maity and Rajesh Kumar Ahuja, "Power Quality Improvement of PWM Rectifier Using VFOC and LCL Filter" in proc. *ICPCSI-2017*,pp. 1036-1040.

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