Voltage Compensation Scheme for Standalone Distributed Wind Energy Conversion System

Amarjeet Singh*[1] and Shivangee Shukla[2]

ABSTRACT

The Wind generation system has potential application for the grid support that could be utilized in rural areas. However, continuous variation of wind speed results in severe power quality problems, especially in a stand-alone village network. In distributed generation, wind power system can cause sub harmonic and interharmonic components to appear in the spectrum of voltage and currents. These harmonics can cause flicker, overload, and interference, on the electronic equipments. This paper proposes Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. This could be used to improve the power quality in a rural load fed from a wind driven permanent magnet synchronous generator (PMSG). The reference voltage is tracked by voltage source converter using a switching band scheme. A method of extracting the phasor symmetrical components that contain both integer and non integer harmonics and complex Fourier transform relation is proposed. In this paper, it is demonstrated that this device can tightly regulate the voltage at the load terminal when load draws integer, non integer harmonic current and sag and swell in the source side.

***Key words** : – Dynamic voltage restorer (DVR), wind turbine generator, power quality.*

1. INTRODUCTION

Power quality is an issue that is becoming very important to electricity consumers at all levels of usage. Sensitive equipment and non-linear loads are now more common place in both the industrial sectors and the domestic environment. Power distribution systems, ideally, should provide their customers with an uninterrupted power at rated sinusoidal voltage, however, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of power supplies. The generation of harmonics in power system is primarily due to the presence of non-linear elements and operation of the system in the non linear operating range of equipments. Some of the main sources of harmonics generation in a power system are power converters, static var compensators, arc furnace loads etc. [5-7].

In some cases large converter system generates not only characteristics harmonics but also non characteristics harmonics and interharmonics which causes poor quality of power supply. Interharmonics measurement and analysis in electrical power system are of particular importance, which provides clear understanding of causes and effects of wave form distortion. Whenever significant harmonic voltage or current distortions are observed in a power system, it is necessary to detect dominant harmonic sources between network and consumer. Correct identification of harmonic source locations is essential

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for designing effective harmonic mitigation means and for determining the responsibility of the parties involved. For compensation of voltage distortion and sag/swell of load voltage caused by harmonics and sub harmonics we propose a series compensator (DVR).

Dynamic Voltage Restorer (DVR) detects the voltage sag/swell and injects a voltage in series with line to mitigate the harmonic component and restore the load voltage with a desired magnitude [8]. For control and operation of DVR we stipulate that real power supplied by the device in the steady state is zero. Based on this stipulation, the reference of the voltage that is to be injected in series is generated. This requires on line extraction of the fundamental positive sequence component of the terminal voltage based on the sample values. A method of extracting the phasor symmetrical components that contain both integer and non-integer harmonics and complex Fourier transform relations is proposed. Once the reference voltages are generated, they are tracked by voltage source converter using a switching band scheme [9].

2. WIND ENERGY CONVERSION SYSTEM

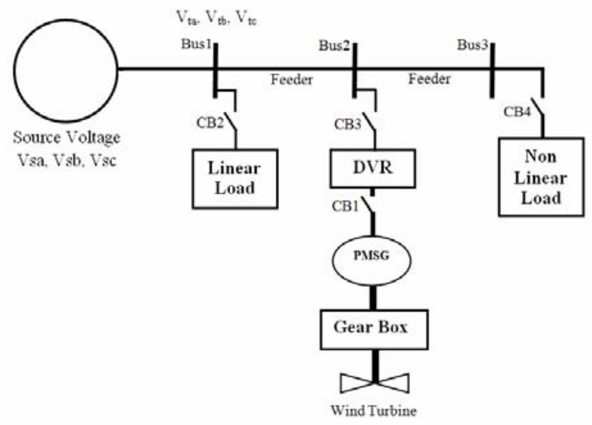

Fig .1. Wind energy conversion system

The basic block diagram of the wind energy conversion system is shown in Fig. 1. It consists of the wind turbine, gearbox, and permanent magnet synchronous generator (PMSG), feeder, linear and non linear loads. The function of the wind turbine is to capture power from the wind by means of the aerodynamically designed blades and convert it into rotating mechanical power that it can be used to drive a generator. The amount of output mechanical power in (watts) captured from the wind turbine is given by the usual cube law equation [10].

$$P_M = \frac{1}{2}\rho A C_p V_W{}^3 \tag{1}$$

The mechanical torque in (N-m) is given by

$$T_M = \frac{P_M}{W_M} \tag{2}$$

Where, A is the wind turbine rotor swept area in (m^2), R is the blade radius in (m), V_W is the speed of the wind in (m/s), W_M is the mechanical speed of the wind turbine in (rad/s), C_P is the power coefficient and ρ is the air density in kg/m^3. Synchronous generator with variable speed turbines allows the turbines to operate over a wider range of speed maintaining optimum tip speed ratio. This allows maximum power conversion [11] [12].

3. FUNDAMENTAL SEQUENCE COMPONENT EXTRACTION ALGORITHM

The on-line extraction of the fundamental sequence components has been discussed in [13], when the signal contains integer harmonics. These are obtained through sampling and averaging the instantaneous measured samples of the signal. To explain this, consider the three phase instantaneous voltages (v_a, v_b *and* v_c) having fundamental, integer and non-integer harmonic components.

$$v_a = v_{ma}\left[\sin\left(wt\right) + \frac{1}{n}\sin\left(nwt\right) + \frac{1}{m}\sin\left(mwt\right)\right] \tag{3}$$

$$v_b = v_{mb}\begin{bmatrix}\sin\left(wt - 120^o\right) + \frac{1}{n}\sin\left(n\left(wt - 120^o\right)\right) \\ + \frac{1}{m}\sin\left(m\left(wt - 120^o\right)\right)\end{bmatrix} \tag{4}$$

$$v_c = v_{mc}\begin{bmatrix}\sin\left(wt+120^o\right)+\frac{1}{n}\sin\left(n\left(wt+120^o\right)\right)\\ +\frac{1}{m}\sin\left(m\left(wt+120^o\right)\right)\end{bmatrix} \tag{5}$$

In the above equation n is an integer and m is an non-integer. The fundamental phasor voltages of the instantaneous voltages of above equations are

$$V_a = \frac{v_{ma}}{\sqrt{2}}\angle 0^o \quad ,V_b = \frac{v_{mb}}{\sqrt{2}}\angle -120^o,\ V_c = \frac{v_{mc}}{\sqrt{2}}\angle 120^o \tag{6}$$

Note that variables in lower case letters indicate the instantaneous values of the variable while those in upper case letters indicate the phasor quantities of the corresponding variables.We shall now use following symmetrical components transformation matrix in which subscript 0, 1 and 2 denotes the zero, positive and negative sequence respectively.

$$\begin{bmatrix}Va0\\Va1\\Va2\end{bmatrix} = \frac{1}{\sqrt{3}}\begin{bmatrix}1 & 1 & 1\\1 & a & a^2\\1 & a^2 & a\end{bmatrix}\begin{bmatrix}Va\\Vb\\Vc\end{bmatrix}$$

(7)

Where $a = e^{j120^0}$. This results following three fundamental phasor symmetrical components for the voltages given in (6)

$$Va0 = \frac{1}{\sqrt{6}}\left[Vma + Vmb\angle -120^0 + Vmc\angle 120^0\right] \tag{8}$$

$$Va1 = \frac{1}{\sqrt{6}}\left[Vma + Vmb + Vmc\right] \tag{9}$$

$$Va0 = \frac{1}{\sqrt{6}}\left[Vma + Vmb\angle 120^0 + Vmc\angle -120^0\right] \tag{10}$$

Now consider a periodic signal x (t) that can be expressed in the exponential form of complex Fourier series as

$$x(t) = \sum_{n=-\infty}^{n=\infty} c_n e^{jnwt}$$

Where w is the fundamental frequency and coefficient c_n is given by

$$c_n = \frac{1}{T}\int_t^{t+T} x(t)\, e^{-jnwt}\, dt \tag{11}$$

If $x(t) = \sqrt{2}\,A\sin(wt+\phi)$ then

$$A = |A|e^{j\theta} = \frac{\sqrt{2}}{T}\int_t^{t+T} x(t)\, e^{-j(wt-\pi/2)}\, dt \tag{12}$$

In a similar way, the fundamental phasor sequence components *(F_{a0}, Fa1 and Fa2)* can be calculated from the measured sample as given by (13)

$$\begin{bmatrix}Fa0\\Fa1\\Fa2\end{bmatrix} = \frac{\sqrt{2}}{T\sqrt{3}}\int_t^{t+T}\begin{bmatrix}1 & 1 & 1\\1 & a & a^2\\1 & a^2 & a\end{bmatrix}\begin{bmatrix}Va\\Vb\\Vc\end{bmatrix} e^{-j(wt-\pi/2)}\, dt \tag{13}$$

Now integrating the 2nd row of (17) we get

$$Fa1 = Va1 + \frac{\sqrt{2}}{T\sqrt{3}}\int_t^{t+T}\left(fn + jgn + fm + jgm\right)dt \tag{14}$$

Where the function f_n contains the terms of $\cos\left[(n+1)wt\right]$ and $\cos\left[(n-1)wt\right]$, the function $g_{n,}$ contains $\sin\left[(n+1)wt\right]$ and $\sin\left[(n-1)wt\right]$ terms. If the samples contain only integer harmonics *(f_m , g_m =0)* then $f_{a0} = V_{a0}$, $f_{a1} = V_{a1}$ and $f_{a2} = V_{a2}$.

From the instantaneous samples of voltages, the values of F_{a1} at each sampling instant from the integral (14) is obtained, and denoting these values as $F_{a1\,(k)}$ and output of filter as $V_{a1\,(k)}$, where k is the discrete time index.

The filter out put is then given by

$$\begin{aligned}v_{a1}(k) &= -a_1 v_{a1}(k-1) - \ldots\ldots - a_p v_{a1}(k-p)\\ &+ b_0 F_{a1}(k) + b_1 F_{a1}(k-1) + \ldots\ldots + b_p F_{a1}(k-p)\end{aligned} \tag{15}$$

In similar way the fundamental phasor, zero and negative sequence component can be recovered by filtering from the 1st and 3rd row of equation (13). Now we can obtain fundamental phasor voltages at each discrete instant k by using inverse of transformation used in (7) as

$$\begin{bmatrix} Va(k) \\ Vb(k) \\ Vc(k) \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} Va_0(k) \\ Va_1(k) \\ Va_2(k) \end{bmatrix} \qquad (16)$$

The instantaneous voltage waveform can be reconstructed using phasors calculated from (16).

4. RECONSTRUCTION OF FUNDAMENTAL COMPONENET

Let us now add 5th and 7th harmonic components to the fundamental voltages with magnitudes that are inversely proportional to their harmonic numbers as shown in (3), (4) & (5). In addition, a 50% dc component has been added to the phase a voltage. Therefore three voltages are given by the following instantaneous equations

$$v_a = 0.5 + \sqrt{2}\left[\sin\left(wt\right) + \frac{1}{5}\sin\left(5wt\right) + \frac{1}{7}\sin\left(7wt\right)\right]$$

$$v_b = 0.5 * \sqrt{2}\left[\begin{array}{r} \sin\left(wt - 120^o\right) + \frac{1}{5}\sin\left(5\left(wt - 120^o\right)\right) \\ + \frac{1}{7}\sin\left(7\left(wt - 120^o\right)\right) \end{array}\right]$$

$$v_c = 0.3 * \sqrt{2}\left[\begin{array}{r} \sin\left(wt + 120^o\right) + \frac{1}{5}\sin\left(5\left(wt + 120^o\right)\right) \\ + \frac{1}{7}\sin\left(7\left(wt + 120^o\right)\right) \end{array}\right]$$

We now extract the fundamental rms sequence component using (13) as shown in Fig 2 in which the actual and the extracted fundamental voltages are plotted. The effect of filtering out dc component is seen in phase a.

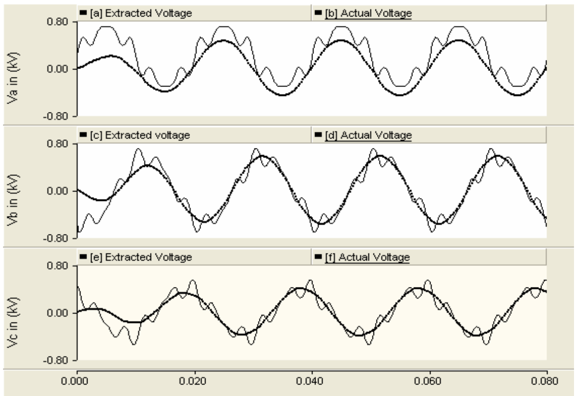

Fig .2. Fundamental voltage component

$$v_a = \sqrt{2}\left[\sin\left(wt\right) + 0.3\sin\left(2.4wt\right) + 0.5\sin\left(3.8wt\right)\right]$$

$$v_b = \sqrt{2}\left[\begin{array}{r} \sin\left(wt - 120^o\right) + 0.3\sin\left(2.4\left(wt - 120^o\right)\right) \\ + 0.5\sin\left(3.8\left(wt - 120^o\right)\right) \end{array}\right]$$

$$v_c = \sqrt{2}\left[\begin{array}{r} \sin\left(wt + 120^o\right) + 0.3\sin\left(2.4\left(wt + 120^o\right)\right) \\ + 0.5\sin\left(3.8\left(wt + 120^o\right)\right) \end{array}\right]$$

It can be seen that none of the reconstructed waveforms are sinusoidal because integrals of the resulting frequency components do not vanish in half a cycle as shown in Fig 3. Therefore suitable value of averaging time must be chooses for non integer multiples of fundamental frequency.

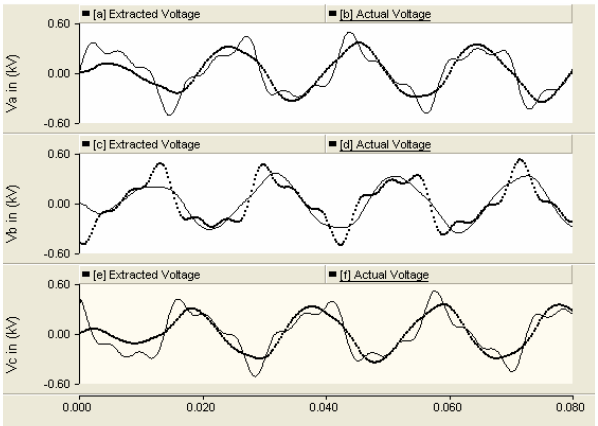

Fig. 3. Fundamental voltage component

5. SWITCHING CONTROL

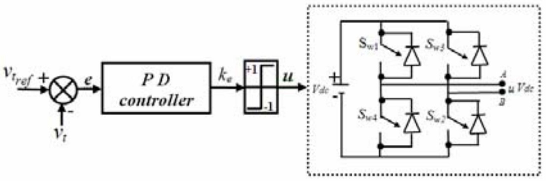

Fig. 4. Switching control scheme

Switching band control scheme can be used only when the control variable $u_{c(k)}$ is available. An H bridge converter is capable of supplying V_{dc}, 0, $-V_{dc}$ across its output. Let us define the following upper and lower levels of switching band i.e., $V_{up} = u_{c(k)} + h \text{ and } V_{dn} = u_{c(k)} - h$ (17)

The three level switching control is obtained from (18) and resulting output is given in Fig 5.

$$\begin{aligned} &\text{if } v_{ref} \geq 0 \text{ then}\\ &\qquad u = +1 \text{ for } v_{cf} < v_{dn}\\ &\qquad u = 0 \text{ for } v_{cf} > v_{up}\\ &\text{else if } v_{ref} < 0 \text{ then}\\ &\qquad u = -1 \text{ for } v_{cf} > v_{up}\\ &\qquad u = 0 \text{ for } v_{cf} < v_{dn} \end{aligned} \tag{18}$$

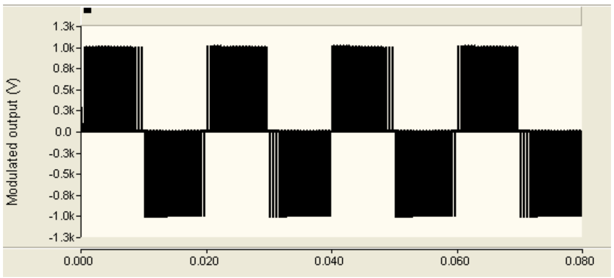

Fig. 5. Modulated converter output voltage

6. SIMULATION RESULTS

Case1: Let us consider a unbalanced case, the rms values of source voltages are chosen as 400, 380 and 420 V (peak) with a fundamental system frequency of 50 Hz for phases a, b and c respectively as shown in Fig 6. In addition to this 5th and 7th harmonics are also added to the source voltage with their magnitudes being inversely proportional to their harmonic number. DVR is connected to feeder for compensation of load voltage. Terminal voltage and its extracted fundamental components are shown in Fig 7. Load voltages are shown in Fig 8. It can be seen that load voltage become sinusoid and harmonic free when DVR is connected to grid terminal. It can be concluded that the DVR works satisfactorily for unbalanced and distorted supply voltages.

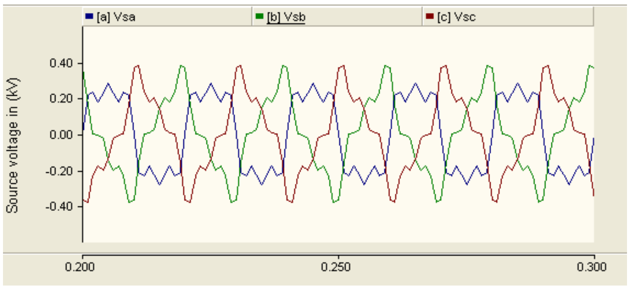

Fig. 6. Source voltage

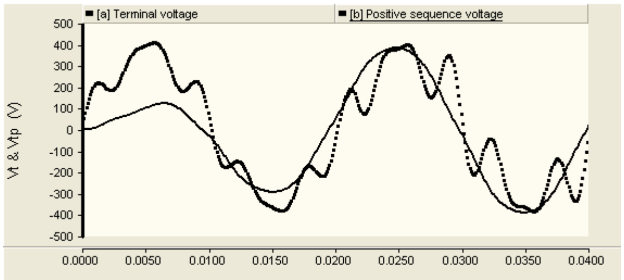

Fig. 7. Terminal voltage and positive sequence voltage

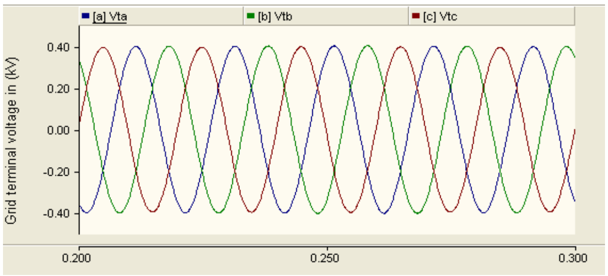

Fig. 8. Load voltage

Case 2: Let us consider a balance case in which the rms value of source voltage is 282 V with a fundamental system frequency of 50 Hz for phases a,b and c respectively as shown in Fig 9. A three phase diode rectifier, harmonic producing load is connected to source. DVR is connected to grid terminal for compensation of load voltage. Terminal voltage and its extracted fundamental components are shown in Fig 10. Load voltages are shown in Fig 11. It can be seen that load voltage become sinusoid and harmonic free when DVR is connected to grid terminal. It can be concluded that the DVR works satisfactorily for unbalanced and distorted supply voltages.

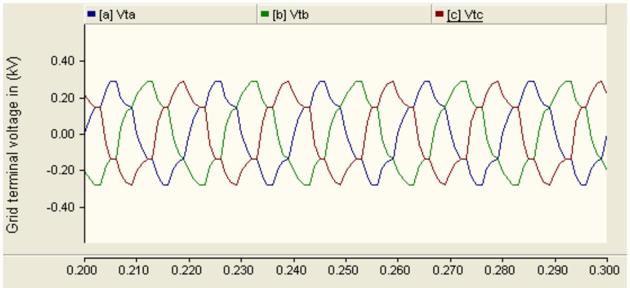

Fig. 9. Source voltage

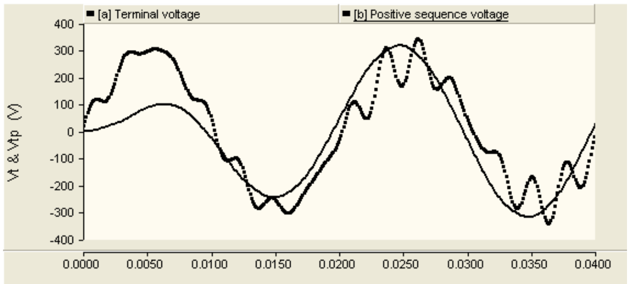

Fig. 10. Terminal voltage and positive sequence voltage

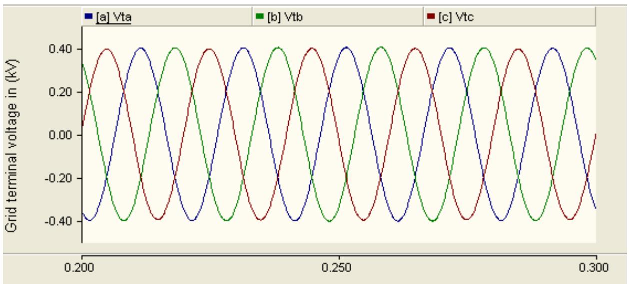

Fig. 11. Load voltage

Case 3: Simulation is carried out with a non linear load of diode bridge rectifier with (R & C) connected in parallel. Source voltage drops to 30% of its nominal value (from 30 ms to 40 ms). Fig 12 shows the load voltages, injected voltages and source voltages. It is evident that DVR is quick to respond to correct the voltage sag by injecting appropriate three phase voltage component with phase shift voltage to correct the supply voltage.

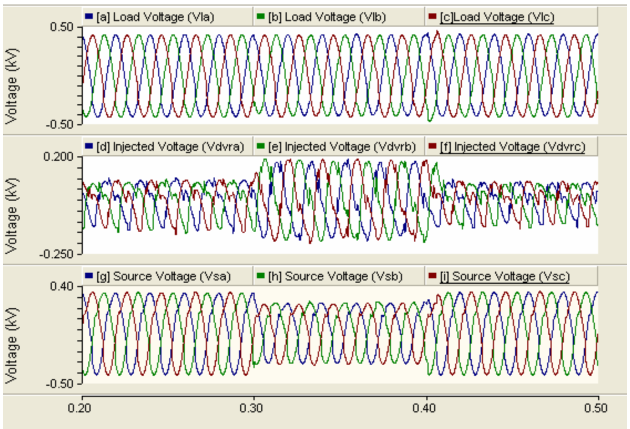

Fig.12. [a,b,c] Load voltages, [d,e,f] Injected voltages, [g,h,i] sources voltages

7. CONCLUSION

Renewable energy sources have the ability to provide cheap and clean electric power in rural areas. Wind energy is one of the top growing renewable energy technologies in the world. The variation of output power with the variation of wind speed can cause significant power quality issues, especially in the case of a standalone generation system, with dynamic and nonlinear loads. This paper proposes a systematic study of a dynamic voltage regulator that can tightly regulate voltage at the load terminals against any variation in the supply side voltage while consuming no real power in the steady state. DVR operation is discussed when load draws both integer, non-integer harmonic current and sag, swell in supply voltage. An algorithm is proposed for extracting phasor symmetrical components from the samples that contains both integer and non integer harmonics. This extraction algorithm is easy to use and can be implemented on-line.

TABLE-I
Distrubition System Parameters

Parameters	**Numerical value**
Source voltage (L-G)	400 V (peak)
Grid terminal voltage	400 V (peak)
Frequency f	50 Hz
Feeder impedance Ls, Rs	23 mH, 0.8 Ω
Transformers	1 kV/.440 kV, 2.1MVA
Filter element Cf, Lf	*70 µF,* 10 mH,
Common dc link voltage V_{dc}	1.5 kV
Load	Linear: phase- (40.0+j 10) Ω Nonlinear: R = 50.0 Ω, C = 220.0µF, L = 5.0 mH

REFERENCES

[1] Rubyna K. Brenden, Wajeeh Hallaj, Ganesh Subramanian, Sony Katoch, “Wind Energy Roadmap”, *PICMET 2009 proceedings, Portland, Oregon, USA*, pp.2548-2562, Aug 2009.

[2] Klaus-Dieter Dettmann, Steffen Schostan, Detlef Schulz, “Wind Turbine Harmonics caused by Unbalanced Grid Currents”, *Compatibility in power electronics,2007, CPE 07*, Jun 2007.

[3] Dos Reis F S, Islam S, Tan K Ale J V, Adegas F D, Tonkoski Jr R, “Harmonic Mitigation in Wind Turbine Energy Conversion Systems”, *IEEE conference in industrial electronics society,2004* ,pp.3100-3105, Nov 2004.

[4] T Aboul-Seoud, J Jatskevich, “Improving power quality in remote wind energy systems using battery storage”, *IEEE Conference in Electrical and computer engineering, 2008, CCECE 2008*, pp.1743-1746, May 2008.

[5] Arindam Ghosh, Amit K. Jindal *and* Avinash Joshi,” Operation and Control of a DSTATCOM in the Presence of Non-Integer Harmonics”, *IEEE Conference in convergent technologies for Asia pacific region*, pp.43-47, Oct 2003.

[6] Taekhyun Kim, Adam Wang, Edward J. Powers, W. Mack Grady, and AriArapostathis1, “Detection of flicker caused by high frequency interharmonics”, *IMTC 2007 IEEE Instrumentation and Measurement Technology Conference Warsaw, Poland,* pp. 1-5, May 2007.

[7] N Hamzah,M R Muhamad, P M Arsad, “Investigation On The Effectiveness Of Dynamic Voltage Restorer For Voltage Sag Mitigation”, *5th Student conference on research and development -SCORED 2007*, pp., Year 2007.

[8] Chris Fitzer, Mike Barnes and Peter Green, “Voltage Sag Detection Technique for a Dynamic Voltage Restorer”, *IEEE Transactions on Industry Application*, pp.203-212, Year 2004.

[9] Arindam Ghosh and Gerard Ledwich, “Structures and control of a dynamic voltage regulator”, *IEEE Trans. Ind. Electronics,* pp.1027-1032, year 2001.

[10] F Blaabje Z Chen, R Teodorescu, “Power electronics in wind turbine system”, *IEEE Transactions in power electronics and motion control conference*, IPEMC, 2006.

[11] M Haque, K M Muttaqi, and M Negnevitsky, “Control of a Stand Alone Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator”, *Power and engg society general meeting, 2008*, pp. 1-9, Jul 2008.

[12] V. Sheeja, P. Jayaprakash, Bhim Singh and R. Uma, “Stand Alone Wind Power Generating System Employing Permanent Magnet Synchronous Generator”, *IEEE conference in sustainable technologies, 2008, ICSET 2008*, pp.616-621, Nov 2008.

[13] A. Ghosh and G. Ledwich, *Power Qualiry Enhancement using Custom Power Device,* Kluwer Academic Publishers, Boston, 2002.