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Power quality improvement of Distribution lines using DSTATCOM under various loading conditions

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***Abstract*:** A Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a mis-operation of end user equipments. Utility distribution networks, sensitive industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. With the restructuring of power systems and with shifting trend towards distributed and dispersed generation, the issue of power quality is going to take newer dimensions. Injection of the wind power into an electric grid affects the power quality. The performance of the wind turbine and thereby power quality are determined on the basis of measurements and the norms followed according to the guideline specified in International Electro-technical Commission standard, IEC-61400. The influence of the wind turbine in the grid system concerning the power quality measurements are-the active power, reactive power, variation of voltage, flicker, harmonics, and electrical behavior of switching operation and these are measured according to national/international guidelines. The paper study demonstrates the power quality problem due to installation of wind turbine with the grid. In this proposed scheme STATIC COMPENSATOR (STATCOM) is connected at a point of common coupling with a battery energy storage system (BESS) to mitigate the power quality issues. The battery energy storage is integrated to sustain the real power source under fluctuating wind power. The STATCOM control scheme for the grid connected wind energy generation system for power quality improvement is simulated using MATLAB/SIMULINK in power system block set. Finally the proposed shceme is applied for both balanced and unbalanced linear non linear loads.

Index Terms: International electro-technical commission (IEC), power quality, wind generating system (WGS).

I. Introduction

Electric Power quality is a term which has captured increasing attention in power engineering in the recent years. Eventhough this subject has always been of interest to power engineers,it has assumed considerable interest in the 1990's. Electric power quality means different things for different people. To most electric power engineers, the term refers to a certain sufficiently high grade of electric service but beyond that there is no universal agreement. The measure of power quality depends upon the needs of the equipment that is being supplied. What is good power quality for an electric motor may not be good enough for a personal computer. Usually the term power quality refers to maintaining a sinusoidal waveform of bus voltages at rated voltage and frequency.

The waveform of electric power at generation stage is purely sinusoidal and free from any distortion. Many of the Power conversion and consumption equipment are also designed to function under pure sinusoidal voltage waveforms. However, there are many devices that distort the waveform. These distortions may propagate all over the electrical network. In recent years, there has been an increased use of non-linear loads which has resulted in an increased fraction of non-sinusoidal currents and voltages in Electric Network. Classification of power quality areas may be made according to the source of the problem such as converters, magnetic circuit non linearity, arc furnace or by the wave shape of the signal such as harmonics, flicker or by the frequency spectrum (radio frequency interference). The wave shape phenomena associated with power quality may be characterized into synchronous and nonsynchronous Phenomena. Synchronous phenomena refer to those in synchronism with A.C waveform at power frequency.

The main aspects of electric power quality
May be categorized as:-
a) Fundamental concepts
b) Sources
c) Instrumentation
d) Modeling
e) Analysis
f) Effects

Figure 1 shows some of the typical voltage disturbances.

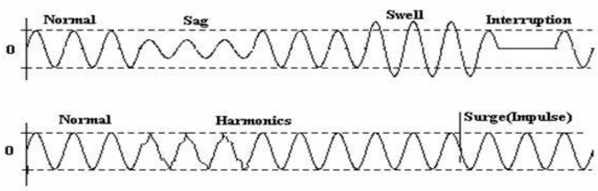

Figure.1 Typical Voltage Disturbances Voltage disturbance as shown in above figure

Table-I

Power Freq Disturbance	Electro Magnetic Interferences	Power System Transient	Power System Harmonics	Electrostatic Discharge	Power Factor
• Low Freq phenomena • Produce Voltage sag / swell	• High freq phenomena • interaction between electric and magnetic field	• Fast, short-duration event • Produce distortion like notch, impulse	• Low frequency phenomena • Produce waveform distortion	• Current flow with different potentials • Caused by direct current or induced electrostatic field	• Low power factor causes equipment damage

Table1 shows the different power quality problems

Custom power Devices like STATCOM (shunt active power filter), DVR and UPQC (combination of series and shunt active power filter) are the latest development of interfacing devices between distribution supply and consumer appliances to overcome voltage/current disturbances and improve the power quality by compensating the reactive and harmonic power generated or absorbed by the load. wind is the most promising DG sources and their penetration level to the grid is also on the rise. Although the benefits of DG includes voltage support, diversification of power sources, reduction in transmission and distribution losses and improved reliability.

The solutions of STATCOM is often used in transmission system. When it is used in distribution system, it is called D-STATCOM（STATCOM in Distribution system). D-STATCOM is a key FACTS controller and it utilizes power electronics to solve many power quality problems commonly faced by distribution systems. Potential applications of D-STATCOM include power factor correction, voltage regulation, load balancing and harmonic reduction. Comparing with the SVC, the D-STATCOM has quicker response time and compact structure. It is expected that the D-STATCOM will replace the roles of SVC in nearly future D-STATCOM and STATCOM are different in both structure and function, while the choice of control strategy is related to the main-circuit structure and main function of compensators [3], so D-STATCOM and STATCOM adopt different control strategy. At present, the use of STATCOM is wide and its strategy is mature, while the introduction of D-STATCOM is seldom reported. Many control techniques are reported such as instantaneous reactive power theory (Akagi et al., 1984), power balance theory, etc. In this paper, an indirect current control technique (Singh et al., 2000a,b) is employed to obtain gating signals for the Insulated Gate Bipolar Transistor (IGBT) devices used in current controlled voltage source inverter (CC-VSI) working as a DSTATCOM. A model of DSTATCOM is developed using MATLAB for investigating the transient analysis of distribution system under balanced/unbalanced linear and non-linear three-phase and single-phase loads (diode rectifier with R and R-C load). Simulation results during steady-state and transient operating conditions of the DSTATCOM are presented and discussed to demonstrate power factor correction, harmonic elimination and load balancing capabilities of the DSTATCOM system [5-10].

II. WIND ENERGY SYSTEM

A simplified diagram representing some of the common types of wind energy systems are shown in Fig.2. From the design perspective it is found that some generators are directly connected to the grid through a dedicated transformer while others in corporate power electronics. Many designs, however, include some level of power Electronics to improve controllability and operating range. Whatever connection configuration is used, each turbine itself has an effect on the power quality of the transmission system. Recent analysis and study shows that the impact of the yaw error and horizontal wind shear on the power (torque) and voltage oscillations is more severe than the effects due to the tower shadow and vertical wind shear.

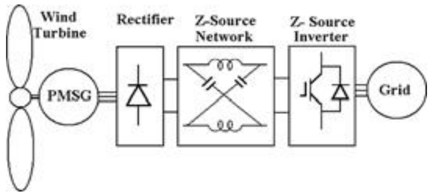

Fig.2 Different types of wind energy system

The above figure shows different types of wind energy system

The new grid comes adopted for wind power integration has identified the problems of integrating large amounts of wind energy to the electric grid. It suggests that new wind farms must be able to provide voltage and reactive power control, frequency control and fault ride-through capability in order to maintain the electric system stability. For the existing wind farms with variable speed, double-fed induction generators (DFIG) and synchronous generators (SG), a frequency response in the turbine control system can be frequency response in the turbine control system can be incorporated by a software upgrade. Wind farms with fixed speed induction generators (FSIG) have to be phased out because they cannot offer the required voltage or frequency control. An overview of the developed controllers for the converter of grid connected system and showed that the DFIG has now the most efficient design for the regulation of reactive power and the adjustment of angular velocity to maximize the output power efficiency. These generators can also support the system during voltage sags. However, the drawbacks of converter-base systems are harmonic distortions injected into the system. Being a single-stage buck-boost inverter, with Z-source inverter can be a good candidate to mitigate the PQ problems for future DG systems connected to the grid Fig(3).

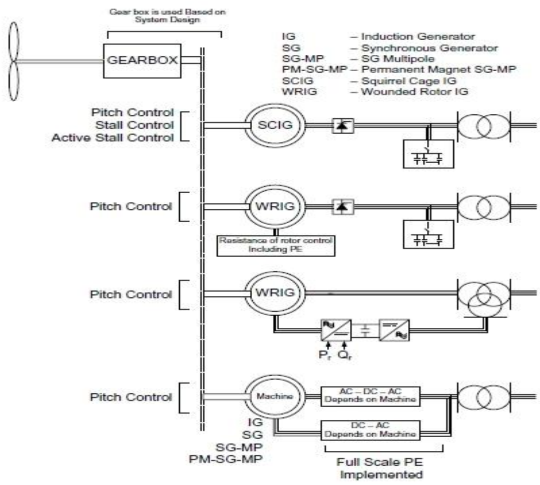

Fig.3 PMSG-base WECS with dc boost chopper and ZSI

Anti- islanding is one of the important issues for grid connected DG system. A major challenge for the islanding operation and control schems is the protection coordination of distribution systems with bidirectional flows of fault current. This is unlike the conventional over-current protection for radial systems with unidirectional flow of fault current. Therefore extensive research in being carried out and an overview of the existing protection techniques with islanding operation and control, for preventing disconnection of DGs during loss of grid, has been discussed.

III. MITIGATION OF PQ PROBLEMS

There are two ways to mitigate the power quality problems-either form the customer side or from the utility side. The first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. Several devices including flywheels, super-capacitors, other energy storage systems, constant voltage transformers, noise filters, isolations transformers, transient voltage surge suppressors, harmonic filters are used for the mitigation of specific PQ problems. Custom power devices(CPD) like DSTATCOM, DVR and UPQC are capable of mitigating multiple PQ problems associated with utility distribution and the end used appliance. The following section of looks at the role of CPDs in mitigating PQ problems in relation to grid integrated with wind energy systems.

IV. Distribution Static Compensator (D-TATCOM)

5.1 System configuration DSTATCOM

DSTATCOM is a shunt-connected custom power device specially designed for power factor correction, current harmonics filtering and load balancing. It can also be used for voltage regulation at a distribution bus. It is often referred to as a shunt or parallel active power filter. It consists of a voltage or a current source PWM converter Fig.4.It operates as a current controlled voltage source and compensates current harmonics by injecting the harmonic components generated by the load but phase shifted by 180 degrees. With an appropriate control scheme, the DSTATCOM can also compensate for poor load power factor.

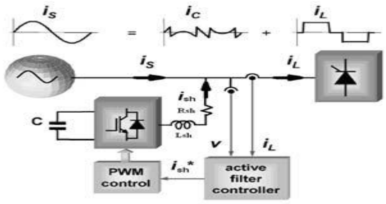

Fig.4 system configuration of DSTATCOM

The system configuration of DSTATCOM above shows figure

When the STATCOM is applied in distribution system is called DSTACOM (Distribution-STACOM) and its configuration is the same, or with small modifications, oriented to a possible future amplification of its possibilities in the distribution network at low and medium voltage, implementing the function so that we can describe as flicker damping, harmonic filtering and hole and short interruption compensation.

Distribution STATCOM (DSTATCOM) exhibits high speed control of reactive power to provide voltage stabilization, flicker suppression, and other types of system control. The DSTATCOM utilizes a design consisting of a GTO- or IGBT-based voltage sourced converter connected to the power system via a multi-stage converter transformer. The DSTATCOM protects the utility transmission or distribution system from voltage sags and/or flicker caused by rapidly varying reactive current demand. In utility applications, a DSTATCOM provides leading or lagging reactive power to achieve system stability during transient conditions.

The DSTATCOM can also be applied to industrial facilities to compensate for voltage sag and flicker caused by non-linear dynamic loads, enabling such problem loads to co-exist on the same feeder as more sensitive loads. The DSTATCOM instantaneously exchanges reactive power with the distribution system without the use of bulky capacitors or reactors.

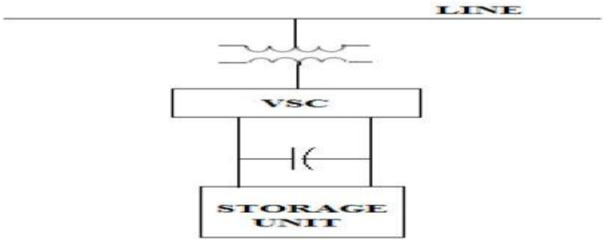

Fig.4 Basic circuit diagram of DSTATCOM

The above figure shows basic circuit diagram of distribution static synchronous compensator.

In most applications, a DSTATCOM can use its significant short-term transient overload capabilities to reduce the size of the compensation system needed to handle transient events. The short-term overload capability is up to 325% for periods of 1 to 3 seconds, which allows applications such as wind farms and utility voltage stabilization to optimize the system's cost and performance. The DSTATCOM controls traditional mechanically switched capacitors to provide optimal compensation on a both a transient and steady state basis. To prevent the unbalanced and distorted currents from being drawn from the distribution bus, a shunt compensator, DSTATCOM, can be used to ensure that the current drawn from the distribution bus is balanced and sinusoidal. A Voltage Source Converter (VSC) is used to realize a DSTATCOM. The structure of the VSC decides the extent of compensation it can provide.

5.2 Voltage Source Converter (VSC)

A voltage-source converter is a power electronic device that connected in shunt or parallel to the system. It can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. The VSC used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. It also converts the DC voltage across storage devices into a set of three phase AC output voltages [8, 9]. In addition, D-STATCOM is also capable to generate or absorbs reactive power. If the output voltage of the VSC is greater than AC bus terminal voltages, D-STATCOM is said to be in capacitive mode. So, it will compensate the reactive power through AC system and regulates missing voltages. These voltages are in phase and coupled with the AC system through the reactance of coupling transformers. Suitable adjustment of the phase and magnitude of the DSTATCOM output voltages allows effectives control of active and reactive power exchanges between D-STATCOM and AC system. In addition, the converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage [10].

5.3 Controller for DSTATCOM

The three-phase reference source currents are computed using three-phase AC voltages (*v*ta, *v*tb and *v*tc) and DC bus voltage (*V*dc) of DSTATCOM. These reference supply currents consist of two components, one in-phase (*I*spdr) and another in quadrature (*I*spqr) with the supply voltages. The control scheme is represented in Fig. 5. The basic equations of control algorithm of DSTATCOM are as follows.

5.3.1 *Computation of in-phase components of reference supply current*

The instantaneous values of in-phase component of reference supply currents (*I*spdr) is computed using one PI controller over the average value of DC bus voltage of the DSTATCOM (*v*dc) and reference DC voltage (*v*dcr) as

$$I_{spdr} = I_{spdr\,(n-1)} + K_{pd}\{V_{de\,(n)} - V_{de\,(n-1)}\} + K_{id} V_{de\,(n)}$$

where Vde(*n*) □Vdcc-Vdc*n*) denotes the error in Vdcc and average value of Vdc *Kpd* and *Kid* are proportional and integral gains of the DC bus voltage PI controller. The output of this PI controller (*I*spdr) is taken as amplitude of in-phase component of the reference supply currents. Three-phase in-phase components of the reference supply currents (*i*sadr, *i*sbdr and *i*scdr) are computed using the in-phase unit current vectors (*u*a, *u*b and *u*c) derived from the AC terminal voltages (*v*tan, *v*tbn and *v*tcn), respectively.

$$U_a = V_{ta}/V_{tm} \quad U_b = V_{tb}/V_{tm} \quad U_c = V_{tc}/V_{tm}$$

where *V*tm is amplitude of the supply voltage and it is computed as

$$V_{tm} = \sqrt{[(2/3)(V_{tan}^2 + V_{tbn}^2 + V_{tcn}^2)]}$$

The instantaneous values of in-phase component of reference supply currents (*i*sadr, *i*sbdr and *i*scdr) are computed as

$$I_{sadr} = I_{spds} U_a \quad I_{sbdr} = I_{spdr} U_b \quad I_{scdr} = I_{spdr} U_c$$

5.3.2 *Computation of quadrature components of reference supply current*

The amplitude of quadrature component of reference supply currents is computed using a second PI controller over the amplitude of supply voltage (*v*tm) and its reference value (*v*tmr)

$$I_{spqr\,(n)} = I_{spqr\,(n-1)} + K_{pq}\{V_{ac\,(n)} - V_{ac\,(n-1)}\} + K_{iq} V_{ac\,(n)}$$

Where Vac = VtmcVmc(n) denotes the error in Vtmc and computed value *Vtmn* from Equation (3) and Kpq and Kiq are the proportional and integral gains of the second PI controller.

$$W_a = \{-U_b + U_C\}/\{\sqrt{3}\}$$
$$W_b = \{U_a\sqrt{3} + U_b - U_c\}/\{2\sqrt{3}\}$$
$$W_c = \{-U_a\sqrt{3} + U_b - U_c\}/\{2\sqrt{3}\}$$

Three-phase quadrature components of the reference supply currents (*i*saqr, *i*sbqr and *i*scqr) are computed using the output of second PI controller (*I*spqr) and quadrature unit current vectors (*w*a, *w*b and *w*c) as

$$i_{saqr} = I_{spqr} W_a, i_{sbqr} = I_{spqr} W_b, i_{scqr} = I_{spqr} W_c,$$

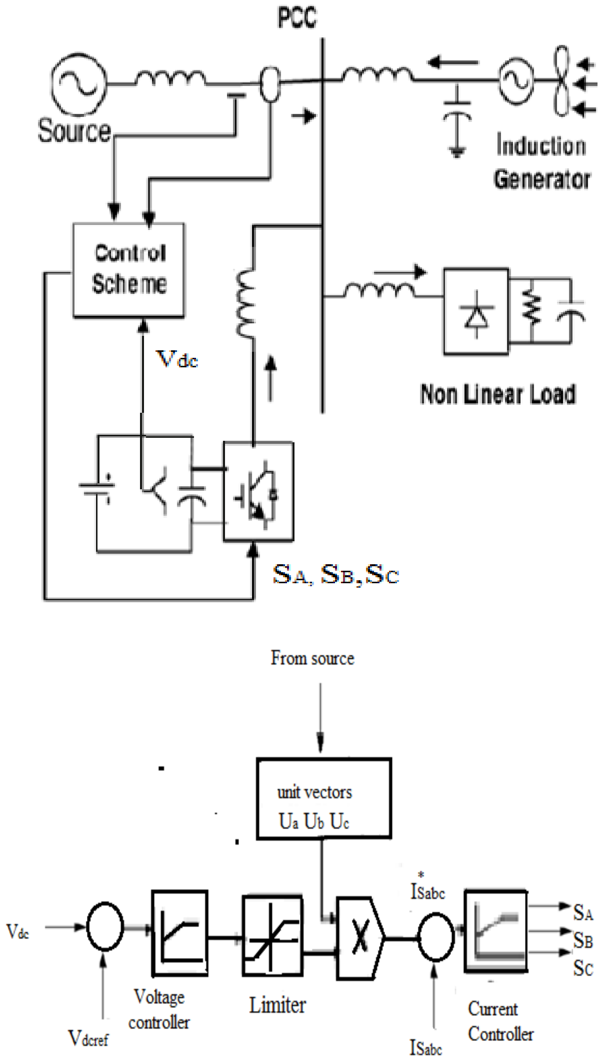

Figure. 5 Control methods for DTSATCOM

5.3.3 Computation of total reference supply currents

Three-phase instantaneous reference supply currents (*i*sar, *i*sbr and *i*scr) are computed by adding in-phase (*i*sadr, *i*sbdr and *i*scdr) and quadrature components of supply currents (*i*saqr, *i*sbqr and *i*scqr) as

$$i_{sar} = i_{sadr} + i_{saqr}, \quad i_{sbr} = i_{sbdr} + i_{sbqr},$$
$$i_{scr} = i_{scdr} + i_{scqr}$$

A hysteresis pulse width modulated (PWM) current controller is employed over the reference (*i*sar, *i*sbr and *i*scr) and sensed supply currents (*i*sa, *i*sb and *i*sc) to generate gating pulses for IGBTs of DSTATCOM.

V. MATAB/SIMULINK MODELING OF DSTATCOM

6.1 Modeling of Power Circuit

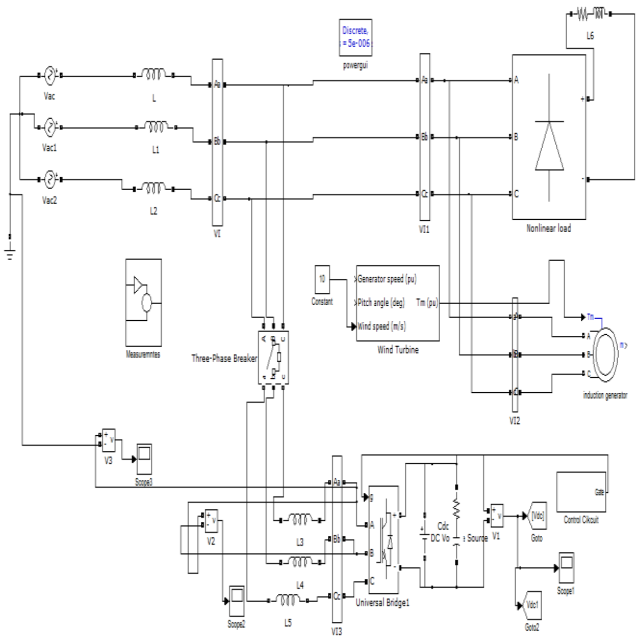

Figure. 6 Matlab/Simulink Model of DSTATCOM

Fig. 6 shows the complete MATLAB model of DSTATCOM along with control circuit. The power circuit as well as control system are modelled using Power System Blockset and Simulink. The grid source is represented by three-phase AC source. Three-phase AC loads are connected at the load end. DSTATCOM is connected in shunt and it consists of PWM voltage source inverter circuit and a DC capacitor connected at its DC bus. An IGBT-based PWM inverter is implemented using Universal bridge block from Power Electronics subset of PSB. Snubber circuits are connected in parallel with each IGBT for protection. Simulation of DSTATCOM system is carried out for linear and non-linear loads. The linear load on the system is modelled using the block three-phase parallel R-L load connected in delta configuration. The non-linear load on the system is modelled using R and R-C circuits connected at output of the diode rectifier. Provision is made to connect loads in parallel so that the effect of sudden load addition and removal is studied. The feeder connected from the three-phase source to load is modelled using appropriate values of resistive and inductive components.

5.1 Modeling of Control Circuit

Fig. 7 shows the control algorithm of DSTATCOM with two PI controllers. One PI controller regulates the DC link voltage while the second PI controller regulates the terminal voltage at PCC. The in-phase components of DSTATCOM reference currents are responsible for power factor correction of load and the quadrature components of supply reference currents are to regulate the AC system voltage at PCC.

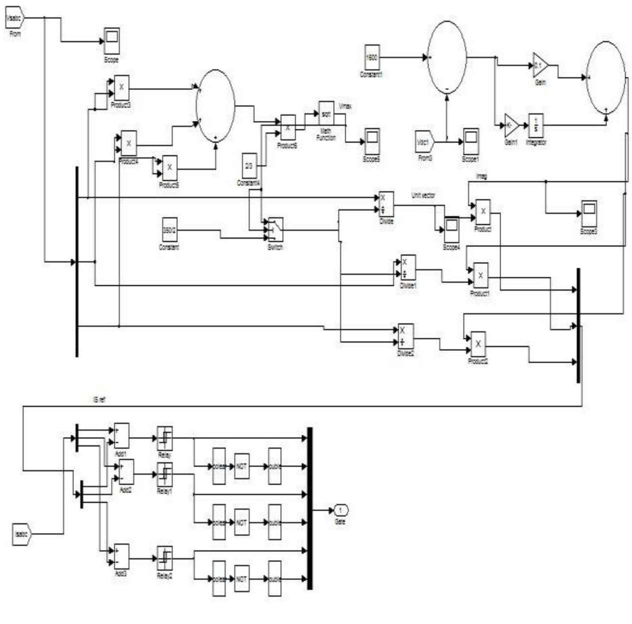

Figure. 7 Control Circuit

The output of PI controller over the DC bus voltage (*I*spdr) is considered as the amplitude of the in-phase component of supply reference currents and the output of PI controller over AC terminal voltage (*I*spqr) is considered as the amplitude of the quadrature component of supply reference currents. The instantaneous reference currents (*i*sar, *i*sbr and *i*scr) are obtained by adding the in-phase supply reference currents (*i*sadr, *i*sbdr and *i*scdr) and quadrature supply reference currents (*i*saqr, *i*sbqr and *i*scqr). Once the reference supply currents are generated, a carrierless hysteresis PWM controller is employed over the sensed supply currents (*i*sa, *i*sb and *i*sc) and instantaneous reference currents (*i*sar, *i*sbr and *i*scr) to generate gating pulses to the IGBTs of DSTATCOM. The controller controls the DSTATCOM currents to maintain supply currents in a band around the desired reference current values. The hysteresis controller generates appropriate switching pulses for six IGBTs of the VSI working as DSTATCOM.

VI. SIMULATION RESULTS

Here Simulation results are presented for four cases. In case one load is balanced non linear, case two load is unbalanced non linear, case three load is balanced linear and in case four unbalanced linear load is considered.

6.1 Case one

Performance of DSTATCOM connected to a weak supply system is shown in Fig.5 for power factor correction and load balancing. This figure shows variation of performance variables such as supply voltages (*v*sa, *v*sb and *v*sc), terminal voltages at PCC (*v*ta, *v*tb and *v*tc), supply currents (*i*sa, *i*sb and *i*sc), load currents (*i*la, *i*lb and *i*lc), DSTATCOM currents (*i*ca, *i*cb and *i*cc) and DC link voltage (*V*dc).

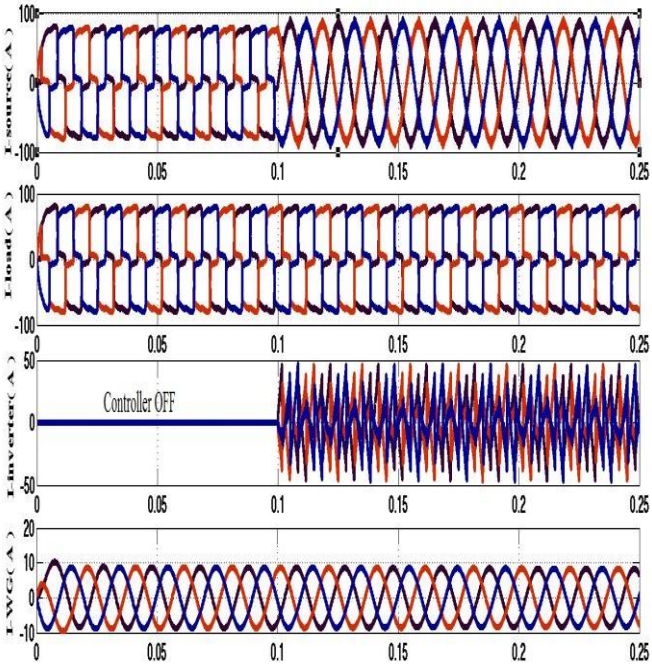

Figure. 8 Simulation results for Balanced Non Linear Load
(a) Source current. (b) Load current. (c) Inverter injected current.
(d) wind generator (induction generator) current.

Fig. 8 shows the source current, load current and compensator current and induction generator currents plots respectively. Here compensator is turned on at 0.1 seconds.

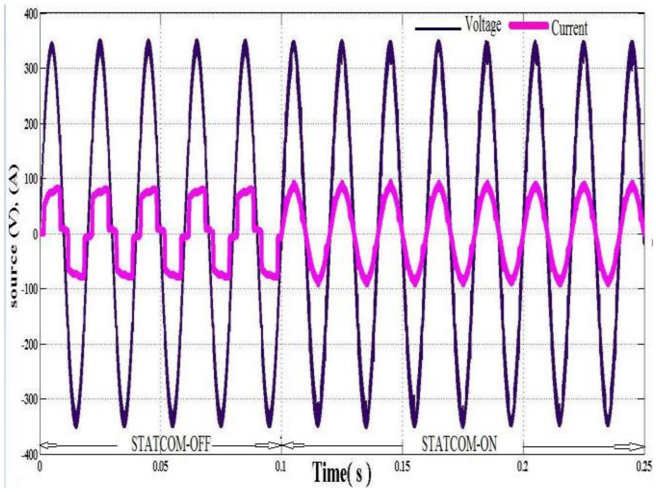

Figure. 9 Simulation results power factor for Non linear Load

Fig. 9 show the power factor it is clear from the figure after compensation power factor is unity.

6.2 Case two

Un Balanced three-phase non-linear load is represented by three-phase uncontrolled diode bridge rectifier with pure resistive load at its DC bus. Fig. 10 shows the transient responses of distribution system with DSTATCOM for supply voltages (*v*sabc), supply currents (*i*sabc), load currents (*i*la, *i*lb and *i*lc), DSTATCOM currents (*i*ca, *i*cb and *i*cc) along with DC link voltage (*V*dc) and its reference value (*V*dcr) at rectifier nonlinear load.

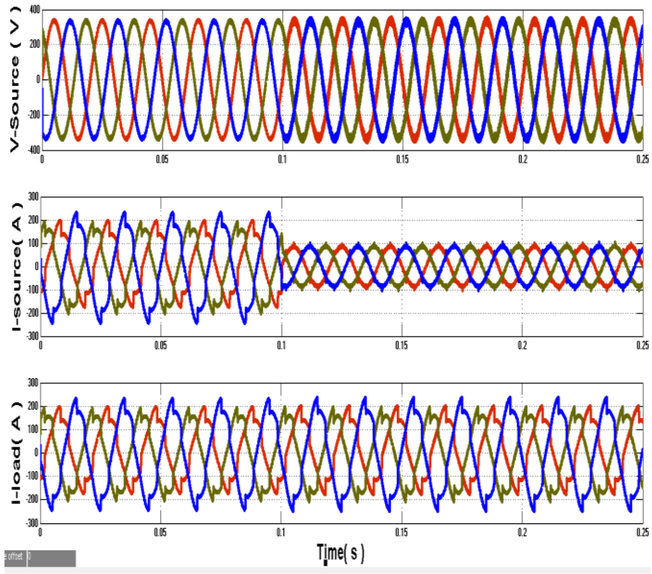

Figure. 10 Simulation results Non- Linear Unbalanced Load
(a) source voltage (b) source current (c) load current

Fig.10 shows the unbalanced non linear load case. From the figure it is clear that even though load is unbalanced source currents are balanced and sinusoidal.

7.3 Case three

Performance of DSTATCOM connected to a weak supply system is shown in Fig.11 for power factor correction and load balancing. This figure shows variation of performance variables such as supply voltages (*v*sa, *v*sb and *v*sc), terminal voltages at PCC (*v*ta, *v*tb and *v*tc), supply currents (*i*sa, *i*sb and *i*sc), load currents (*i*la, *i*lb and *i*lc), DSTATCOM currents (*i*ca, *i*cb and *i*cc) and DC link voltage (*V*dc).

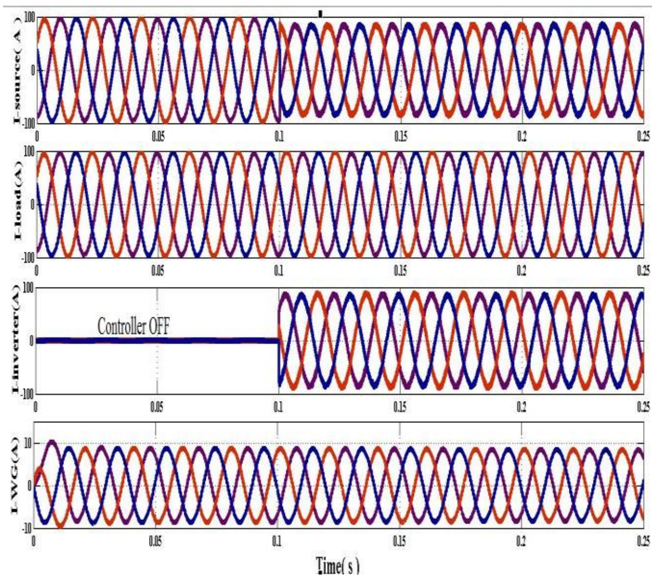

Figure. 11 Simulation results for Balanced Linear Load
(a) Source current. (b) Load current. (c) Inverter injected current.
(d) wind generator (induction generator) current.

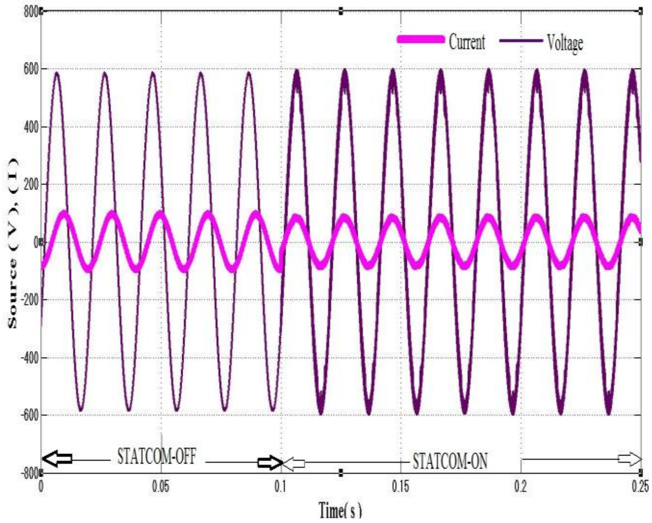

Figure. 12 Simulation results power factor for linear Load

Fig. 12 shows the power factor it is clear from the figure after compensation power factor is unity.

7.4 Case four

Un Balanced three-phase linear load is represented by three-phase uncontrolled diode bridge rectifier with pure resistive load at its DC bus. Fig. 10 shows the transient responses of distribution system with DSTATCOM for supply voltages (*v*sabc), supply currents (*i*sabc), load currents (*i*la, *i*lb and *i*lc), inverter current (Iina, Iinb, *Iinc*) DSTATCOM currents (*i*ca, *i*cb and *i*cc) along with DC link voltage (*V*dc) and its reference value (*V*dcr) at rectifier linear load.

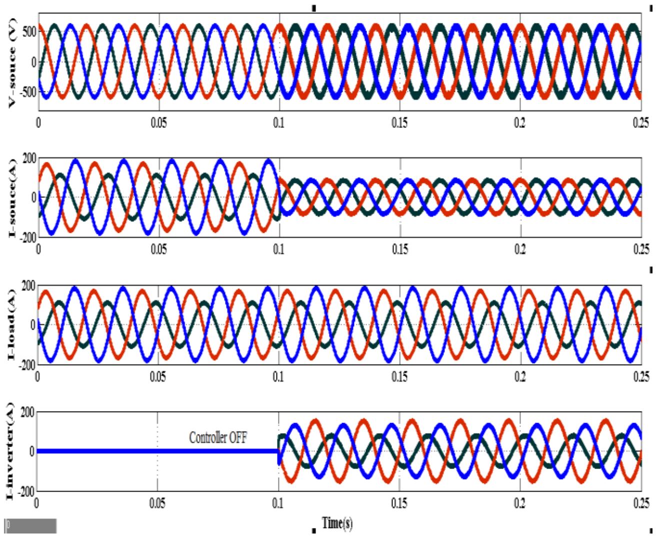

Figure. 13 Simulation results for unbalanced linear Load

VII. Conclusion

DSTATCOM system is an efficient mean for mitigation of PQ disturbances introduced to the grid by DERs. DSTATCOM compensator is a flexible device which can operate in current control mode for compensating voltage variation, unbalance and reactive power and in voltage control mode as a voltage stabilizer. The latter feature enables its application for compensation of dips coming from the supplying network. The simulation results show that the performance of DSTATCOM system has been found to be satisfactory for improving the power quality at the consumer premises. DSTATCOM control algorithm is flexible and it has been observed to be capable of correcting power factor to unity, eliminate harmonics in supply currents and provide load balancing. It is also able to regulate voltage at PCC. The control algorithm of DSTATCOM has an inherent property to provide a self-supporting DC bus of DSTATCOM. It has been found that the DSTATCOM system reduces THD in the supply currents for non-linear loads. Rectifier-based non-linear loads generated harmonics are eliminated by DSTATCOM. When single-phase rectifier loads are connected, DSTATCOM currents balance these unbalanced load currents.

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