Enhancement in Power Quality in Distribution Network with the Collaboration of Solar Energy and DSTATCOM

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***Abstract*: Now a days the power quality (PQ) has become a main concern for both utilities and customers. The integrations of renewable energy sources such as wind and solar energy into the utility grid affects the quality of the power supplied. The utilities or other power providers have to provide a high quality of their service to retain or attract the customers. Efficient power quality (PQ) monitoring and improvement system can help to achieve this goal. The power quality improvement can be achieved by the use of distribution static compensator (DSTATCOM) in the utility grid. The distribution static compensator is shunt custom power device which is used in the distribution system for compensation of reactive power at point of common coupling, current compensation and improvement of power factor.**

This work presents the design of synchronous reference theory based control of the DSTATCOM for the power quality improvement in the utility grid in the presence of solar PV energy. A capacitor and battery bank is used as the DC bus in the design of DSTATCOM. The DSTATCOM has been implemented for the enhancement of power quality in the presence of the solar energy during various operational events. The events include the tripping/reclosing of feeder, switching ON/OFF the capacitor bank, switching ON/OFF the inductive-resistive load. The proposed methodology has been carried out with the help of a test system comprising of the voltage source and load connected at the point of common coupling (PCC).The proposed methodology has been carried out in the MATLAB/ Simulink environment using an IEEE-13 bus test system.

I. INTRODUCTION

This manuscript focussed on the power quality improvement in the distribution utility network using distribution static compensator (DSTATCOM) in the presence of solar PV energy penetration. Recently, power quality is a big issue at the load end in distribution system due to grid integration of renewable energy sources which are uncertain in nature. The major part of load in the power distribution system are linear/nonlinear, balanced/ unbalanced or combination of both. These loads increase the burden on system by deliver reactive power and injecting harmonics which affect the performance of other loads connected to the same utility end. Moreover, unbalanced load cause unbalanced voltages at the utility end. In recent years, use of power converters in adjustable speed drives, power supplies etc. is continuously increasing. These equipments draw harmonic currents from AC mains and increase the supply demands. Some power quality problems related with these loads include harmonics, high reactive power burden, load unbalancing, voltage variation etc. A wide range of literature on power quality problems for classification, suitable corrective and preventive actions to identify these problems has been reported. A variety of custom power devices are developed and successfully implemented to compensate various power quality problems in a distribution system [1]. These custom power devices are categorized as the DSTATCOM (Distribution Static Compensator),

DVR (Dynamic Voltage Restorer) and UPQC (Unified Power Quality Conditioner). The DSTATCOM is a shunt-connected device, which can mitigate the current and voltage related power quality problems. These custom power devices may be explored for the improvement of PQ disturbances in the modern power systems with high level of renewable energy penetration. The power quality at the point of common coupling is given by standards such as IEEE-519-1992, IEEE-1531-2003 and IEC- 61000, IEC- SC77A etc [2]. The effectiveness of DSTATCOM depends upon the used control algorithm for generating the switching signals for the voltage source converter. Momentary voltage sags and interruptions are by far the most common disturbances that adversely effect on electric customer process operations in large distribution system. When PQ problems are arising from nonlinear customer loads such as arc furnaces, welding operations, voltage flicker and harmonic problems can affect the whole distribution feeder [3]. Several devices have been designed to minimize or reduce the impact of these variations. Custom power is formally defined as the employment of power electronic or static controllers in distribution systems rated up to 38 kV for the purpose of supplying a level of reliability or power quality that is needed by electric power customers who are sensitive to power variations. Custom power devices or controllers, include static switches, inverters, converters, injection transformers, master-control modules and energy-storage modules that have the ability to perform current-interruption and voltage-regulation functions within a distribution system [4]. The neutral current is compensated by three phase four wire DSTATCOM along with voltage regulation or power factor correction with harmonics elimination and load balancing. Many topologies of DSTATCOM are reported in the literature to compensate the neutral current with three phase four wire such as a 4-leg VSC, three single-phase VSC, 3-leg VSC with split capacitor [5].

Some comprehensive survey of the research work reported on the topic of power quality improvement in the distribution network with solar energy penetration using distribution static compensator are:

A methodology on the power quality events such as voltage sag, voltage swell, harmonics and capacitor switching which deteriorate the sinusoidal waveforms and decrease power quality as well as network reliability has been reported in [6]. These power quality disturbances affect the consumer as well as equipment performance. A DSTATCOM has been used to compensate power quality problem such as voltage fluctuation, unbalanced load, and harmonics in distribution system in the presented methodology. A DVR is proposed for voltage sag and swell protection, voltage balancing and compensating the voltage harmonic distortions while UPQC is applied for compensating for load current harmonic, reactive power compensation, power factor correction, correcting no load current and regulating DC circuit voltage. In [7], presented the methodology related to the various types of custom power devices and successfully implemented these devices to compensate the various power quality problems in a distribution system. These custom powe r devices used in the proposed methodology can be classified as DSTATCOM, DVR and UPQC. The DSTATCOM is a shunt connected device which can mitigate the current related power quality problems. In [8], authors has proposed methodology on an electrical distribution system facing undesirable power quality disturbances due to different types of linear/nonlinear loads on supply system. .In [9],author have discussed the new topology for power quality improvement with contribution of DSTATCOM integrated for the improvement of reactive power for voltage regulation. In [10], authors have proposed a technique for power quality improvement based on 3P4W DSTATCOM star/delta transformer connection to mitigate the neutral current, power quality, balance the unbalance load, reactive power and harmonics. In [11], authors have proposed that a neural-network (NN) controlled distribution static compensator (DSTATCOM) using a dSPACE processor is implemented for power quality improvement in a three-phase four-wire distribution system. . In [12] authors have explained the new topology for power quality improvement in a three-phase four wire distribution system consisting of an H-bridge VSC and a star/delta transformer. Star/delta transformer provides isolation for H-bridge. In [13] author has described a new topology for voltage regulation or power factor correction by reactive power compensation along with harmonics elimination or neutral current compensation in three-phase four-wire distribution system with star/delta transformer. In. [14] authors have explained the design of power quality conditioner to connect with 3P4W system for neutral current compensation by using new control strategy purposed for series active power filter (APF) is based on unit vector template generation to compensate the neutral current compensation, to compensate different power quality problem. In [15], authors have described about to mitigate the power quality problems with new proposed system with VSC isolated with a star hexagon transformer. In [16] a methodology has been presented to describe a technique for investigating voltage sag, swell, load switching, feeder tripping and re-closing. . In [17], authors have proposed a technique for power quality improvement in the presence of solar PV power generation using Stockwell transforms and fuzzy–c means clustering. In [18] authors have explained the distribution static compensator topology design consideration, future development, and potential application are investigated for power quality improvement. In [19] authors have explained how the power system affected by various kind of power quality problem such as neutral current, reactive power, unbalance load, these problems affect the problem of today’s high tech industrial equipment. These problems have been overcome by DSTATCOM with different configuration. In [20] authors have proposed a new topology for DSTATCOM that can be operated with a new flexible operated system by which voltage control mode DSTATCOM can force the voltage of a distribution bus to be balanced sinusoids. . In [21], authors described about the problem and mitigation technique with instantaneous symmetrical theory, Neutral current compensation with Zig-zag Transformer and balanced and the unbalanced load, reactive power improvement with DSTATCOM. In [22], the authors presented application of supervised learning algorithms based on different neural network topologies for detection and classification of the faults in transmission lines in power system. Different wavelet transforms on different Multi Resolution Analysis levels are applied for detection of the potential features from the voltage waveforms of the Phasor Measurement Units (PMUs). These wavelet transforms are then applied to several neural networks classification engines to classify faults.

Followings are the research objectives of this manuscript:

Design of synchronous reference frame theory (SRF) based control algorithm for the control of DSTATCOM for power quality improvement in distribution utility network with solar energy penetration.

Implementation of the proposed SRF theory based DSTATCOM for PQ improvement during operational events in the distribution network with solar PV energy penetration. The investigated events include the feeder tripping/reclosing, switching ON/OFF of capacitor banks and switching ON/OFF of resistive-inductive loads.

The proposed research work has been carried out using MATLAB/Simulink using IEEE-13 bus test system modified by integrating the solar PV system.

II. TEST SYSTEM AND METHODOLOGY

The proposed test system utilized as distribution network is described in this section. The solar PV system of capacity 500 kVAr is integrated to the proposed test system for the methodology of power quality improvement. The methodology power quality improvement using the DSTATCOM under various operating scenarios has been carried out using the proposed test system. A standard IEEE-13 bus test system is used as a distribution system. The original system is a 60 Hz, 5 MVA, operated at two voltage levels of 4.16 kV and 0.48 kV. The test system is modified to incorporate the solar PV system on the bus 680 of test system as described in Fig.1. Bus 680 is used as point of common coupling (PCC) for the integration of the solar PV system. The solar PV system is integrated to the proposed test system through transformer represented by the symbol XSP The proposed test system of the distribution network is connected to conventional generator using a substation transformer. The transformer connected between the nodes 633 and 634 is represented by the symbol XFM. . Switch between the nodes 671 and 692 is realized using a three phase circuit breaker. The voltage regulator used between the buses 650 and 632 is realized using an on load tap changer transformer.

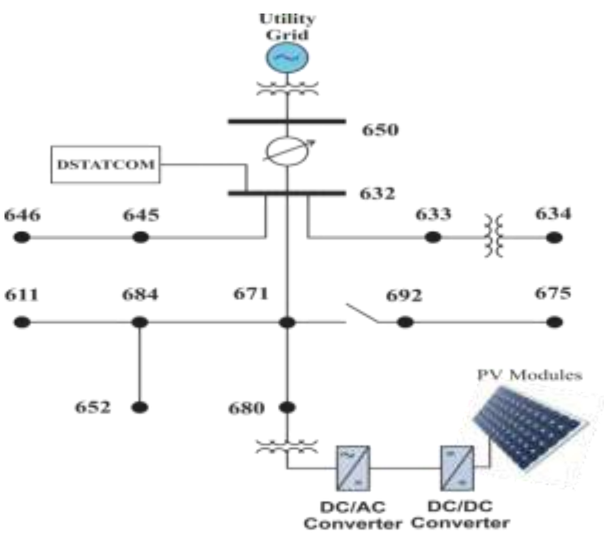

Fig.1. Distribution system incorporated with solar PV system and DSTATCOM

2.1 Solar PV System

The solar PV array consists of 66 parallel strings. In each string there are five solar PV modules connected in series. At standard test conditions (STC), each module has the technical data as detailed: Voc = 64.2V, Isc =5.96A, Vmp = 54.7V, Imp = 5.58A, Rs = 0.037998Ω, Rp =993.51Ω, $Isat$ = 1.1753e−8A, Iph = 5.9602A. The converter of solar PV plant has dc-dc boost converter which increases dc output voltage of PV array from 273.5V to 500V. The output of the dc-dc boost converter is given as input to the dc-ac inverter which converts 500V dc to 260V ac three phase supply. A filter with series branch having resistance of 2mΩ and inductance of 0.25mH, and shunt capacitor branch of 100 $kVAr$ are used at the output terminals of inverter to filter out the harmonic components. This solar PV system is integrated to the IEEE-13 bus test system on bus 680 using a transformer designated as XSPV. The rated capacity of the proposed solar PV system is 1 MW.

2.2 Proposed DSTATCOM

The three-leg topology of three-phase three-wire distribution static compensator with battery bank proposed for power quality improvement in the distribution test feeder is shown in Fig.2. The point of common coupling (PCC) is selected between the utility grid and the IEEE-13 bus test feeder for integration of the proposed DSTATCOM. This distribution static compensator consists of AC inductor, ripple filter, dc link capacitor, battery bank, and three-leg voltage source converter. Insulated gate bipolar transistors (IGBTs) with anti-parallel diodes are used as switches of the voltage source converter (VSC). The combination of six switches in Fig.2.represents the voltage source converter. A battery bank is connected in parallel with the dc link capacitor.

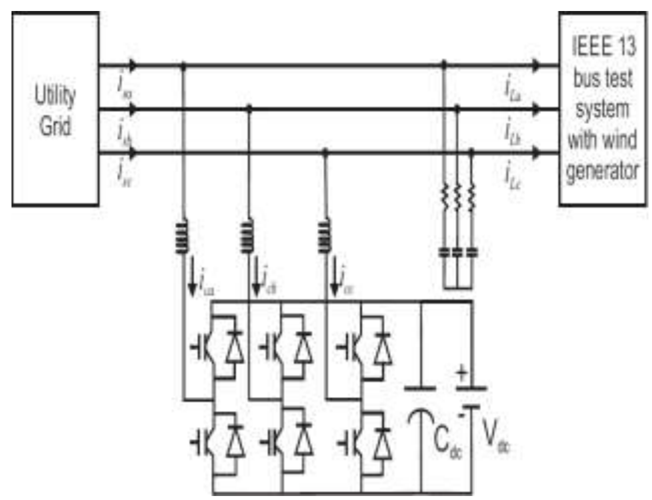

Fig 2. Proposed DSTATCOM with BESS

The controller for VSC of the DSTATCOM generates reference source currents using SRF theory with carrier based pulse width modulation (PWM) technique. SRF theory based controller involves the sensing of line voltages and load currents. Reactive power component of fundamental reference source current is generated by subtracting reactive power component from output of the PI controller. These active and reactive power components of fundamental reference source currents are used to generate three-phase fundamental reference source currents. The active and reactive power components of fundamental reference source currents are used to generate the three-phase reference source currents using inverse Park's and Clark's transformation. The reference source currents obtained are compared with the source currents (Isa; Isb; Isc) captured at PCC and current error signal is generated. This error signal is used to generate the pulse width modulation (PWM) signals by hysteresis PWM controller which is utilized as gate signal for the IGBT of voltage source converter.

2.3 Proposed Approach for PQ Mitigation

The proposed approach for power quality improvement in the distribution network with solar PV energy penetration has been implemented with the help of following steps.

- The methodology of the voltage and total harmonic distortions of voltage and current has been performed in the presence of solar PV system during various operational events.
- The DSTATCOM with battery energy storage system has been installed on the bus 632 of test system. The methodology of the voltage and total harmonic distortions of voltage and current has been performed in the presence of solar PV system during various operational events with DSTATCOM. Percentage deviations have been carried out to methodology the improvement in the power quality.
- The total harmonics distortions of voltage signal (THDv) and current supplied by the DG sources at PCC (THDi) are calculated using fast Fourier transform (FFT).
- The methodology of the powers flows has also been carried out in the presence of the DSTATCOM.

III. SIMULATION RESULTS AND DISCUSSION

This section presents the simulation results related to the power flows in the presence of DSTATCOM in the test system.

3.1 Feeder Tripping

The tripping of feeder has been simulated at 0.33s by opening the circuit breaker between the nodes 671-692. The DSTATCOM has been kept connected on the bus 632 of the test system and solar PV is integrated to the test system on the bus 680 of the test system. The power supplied by the substation transformer (source) is shown in Fig.3. It is observed that the power supplied by the source has been decreased just after the tripping the feeder. The feeder reclosed at 0.667 s by closing the circuit breaker between the nodes 671-692. It is observed that the power transients are observed at the time of the feeder reclosing but not at the time of the feeder tripping.

The power supplied drawn by the load (IEEE-13 bus test system) is shown in Fig. 4. It is observed that the power drawn by the load has also been decreased just after tripping the feeder. This is due to the reduced load on the IEEE-13 bus test system. It is also observed that the power transients are observed at the time of the feeder reclosing at 0.667 s by closing the circuit breaker between the nodes 671-692 but not at the time of the feeder tripping.

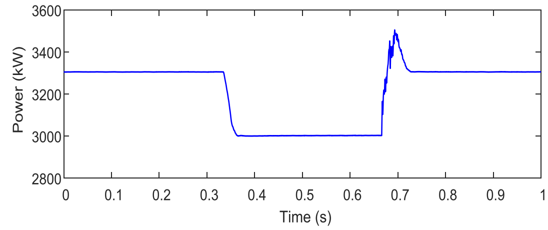

Fig. 3 Power supplied by the source (substation transformer) during feeder tripping

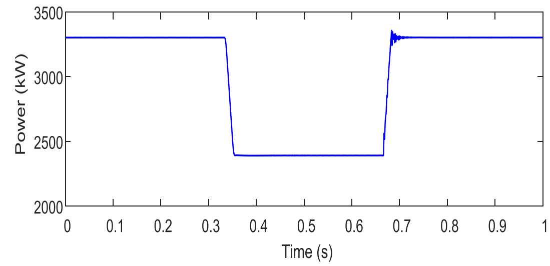

Fig.4. Power taken by the load during feeder tripping

The power supplied drawn by the DSTATCOM during feeder tripping is shown in Fig. 5. It is observed that there is no power exchange between the IEEE-13 bus test system and DSTATCOM during the normal power of the system. However, during the time feeder remains tripped the power drawn by the DSTATCOM is approximately 600 kW.

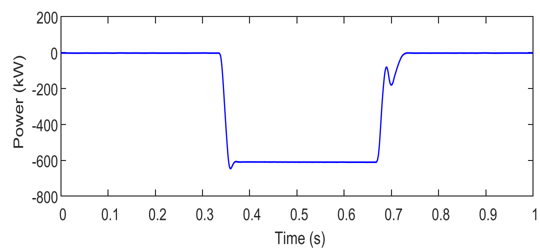

Fig. 5. Power supplied by the DSTATCOM during feeder tripping.

The power supplied by the solar PV system during the feeder tripping is shown in Fig. 6. It is observed that the power supplied by the solar PV system almost constant having the value of 980 kW. However, at the time of feeder tripping and reclosing small magnitude power transients have been observed. These transients affect the quality of the power supplied to the customers.

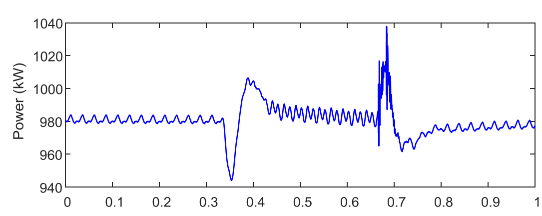

Fig.6. Power supplied by the solar PV system during feeder tripping.

The rms values of the voltage on the point of common coupling of the DSTATCOM i.e. the bus 680 of the IEEE-13 bus test system in the presence of the DSTATCOM has been shown in the Fig. 7.

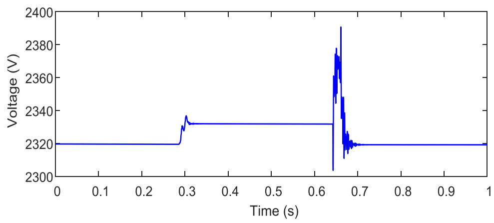

Fig.7. Voltage in the presence of DSTATCOM during feeder tripping.

The rms values of the voltage on the point of common coupling of the DSTATCOM i.e. the bus 680 of the IEEE-13 bus test system in the absence of the DSTATCOM has been shown in the Fig.8. It is observed that the voltage slightly increases after the feeder tripping and regains original values after the reclosing of the feeder.

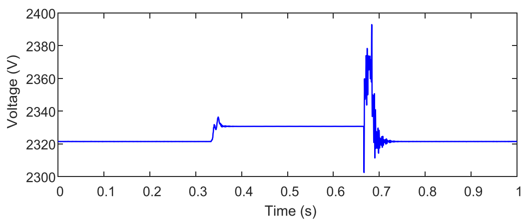

Fig.8. Voltage without DSTATCOM during feeder tripping.

The total harmonic distortions of the voltage and current with and without the DSTATCOM in the presence of solar PV system during the event of feeder tripping are provide in Table 1. It has been observed that the THD of voltage decreases from 0.37% to 0.20% by the use of the DSTATCOM

TABLE.1. Total Harmonic Distortions of Voltage and Current

S.No	Different cases of methodology	With DSTATCOM		Without DSTATCOM	
		THDv (%)	THDi (%)	THDv (%)	THDi (%)
1	Feeder tripping	0.20	4.76	0.37	10.28
2	Feeder Reclosing	0.26	5.23	0.43	12.37
3	Switching ON the Capacitor Bank	0.19	5.01	0.38	10.32
4	Switching OFF the Capacitor Bank	0.16	4.30	0.26	6.75
5	Switching OFF the Inductive Resistive Load	0.11	0.58	0.19	1.17
6	Switching ON the Inductive Restive Load	0.25	4.98	0.40	11.30

3.2 Switching ON the Capacitor Bank

Switching ON of the capacitor bank (connected on bus 675) has been simulated at 0.33 s by opening the circuit breaker. The DSTATCOM has been kept connected on the bus 632 of the test system and solar PV is integrated to the test system on the bus 680 of the test system. The power supplied by the substation transformer (source) is shown in Fig.9. It is observed that the power supplied by the source has been increased just after switching ON the capacitor bank. The capacitor bank has been switched OFF at the time 0.667s. It is observed that the power transients are observed at the time of the switching ON the capacitor bank.

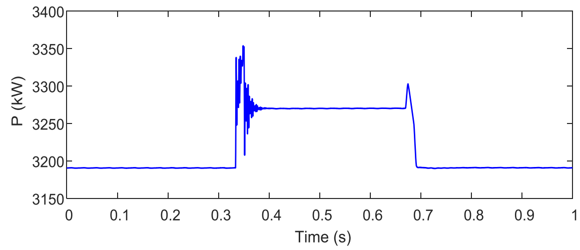

Fig.9. Power supplied by the source (substation transformer) during switching ON the capacitor bank.

The power drawn by the load (IEEE-13 bus test system) during the event of switching ON the capacitor bank is shown in Fig.10. It is observed that the power drawn by the load has also been increased just after switching ON the capacitor bank. This is due to the increased reactive load on the IEEE-13 bus test system. It is also observed that the power transients are observed at the time of switching ON the capacitor bank at 0.333 s but not at the time of switching OFF the load 0.67 s.

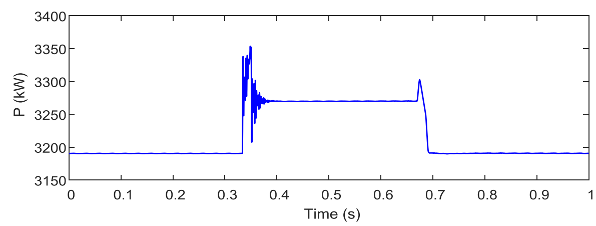

Fig.10. Power taken by the load during switching ON the capacitor bank.

The power supplied drawn by the DSTATCOM during switching ON the capacitor bank is shown in Fig.11. It is observed that power exchange between the IEEE-13 bus test system and DSTATCOM remains almost constant after switching ON the capacitor bank. However, a power transient of high magnitude has been observed at the time of switching ON the capacitor bank and low magnitude transient has been observed at the time of the switching OFF the capacitor bank.

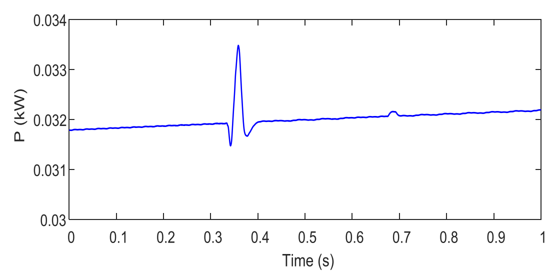

Fig.11. Power supplied by the DSTATCOM during switching ON the capacitor bank.

The power supplied by the solar PV system during switching ON the capacitor bank is shown in Fig.12. It is observed that the power supplied by the solar PV system is almost constant having the value of 980 kW.

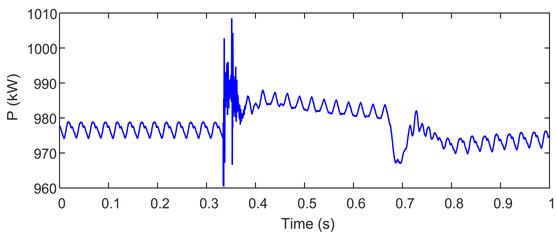

Fig.12. Power supplied by the solar PV system during switching ON the capacitor bank.

The rms values of the voltage on the point of common coupling of the DSTATCOM i.e. the bus 680 of the IEEE-13 bus test system in the presence of the DSTATCOM has been shown in the Fig.13. It is observed that the voltage slightly increases after switching ON the capacitor bank. The high magnitude transient component is available with the voltage at the time of switching ON the capacitor bank.

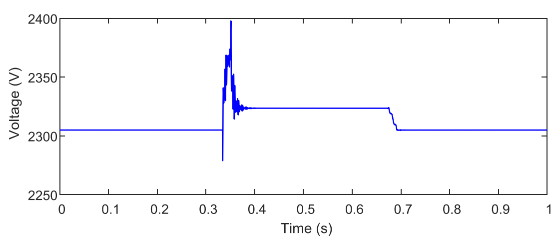

Fig.13. Voltage in the presence of DSTATCOM during switching ON the capacitor bank**.**

The rms values of the voltage on the point of common coupling of the DSTATCOM i.e. the bus 680 of the IEEE-13 bus test system in the absence of the DSTATCOM has been shown in the Fig.14. It is observed that the voltage slightly increases after switching ON the capacitor bank. The low magnitude transient component is available with the voltage at the time of switching ON the capacitor bank. It is concluded that the magnitude of the voltage transient components are high without DSTACOM compared to the presence of the DSTATCOM.

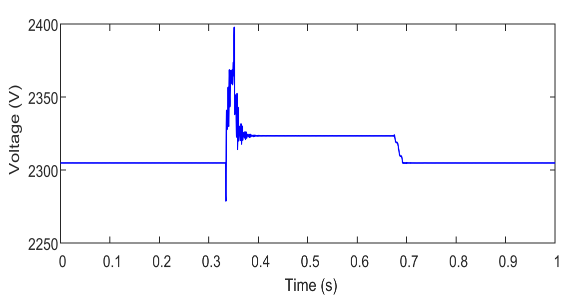

Fig.14. Voltage in the presence of DSTATCOM during switching ON the capacitor bank.

3.3 Switching OFF the Inductive Resistive Load

Switching OFF of the inductive resistive load (connected on bus 680) has been simulated at 0.33 s by opening the circuit breaker. The DSTATCOM has been kept connected on the bus 632 of the test system and solar PV is integrated to the test system on the bus 680 of the test system. The power supplied by the substation transformer (source) is shown in Fig.15. It is observed that the power supplied by the source has been decreased just after switching OFF the inductive-resistive load. The inductive-resistive load has been switched ON at the time 0.667s. It is observed that small magnitude power transient is observed at the time of the switching ON the inductive-resistive load.

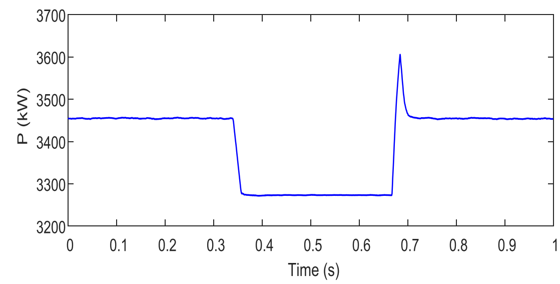

Fig.15. Power supplied by the source (substation transformer) during switching OFF the inductive-resistive load.

The power drawn by the load (IEEE-13 bus test system) during the event of switching OFF the inductive resistive load is shown in Fig.16. It is observed that the power drawn by the load has also been decreased just after switching ON the inductive resistive load. This is due to the decreased load on the IEEE-13 bus test system. It is also observed that power transients have not been observed at the time of switching ON and OFF the inductive resistive load.

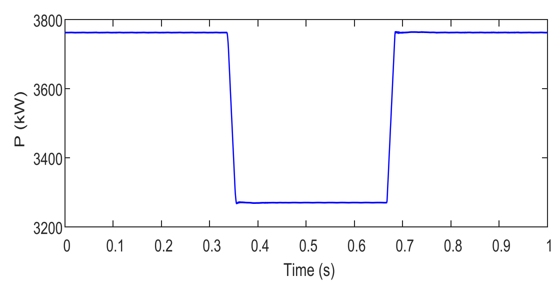

Fig.16. Power taken by the load during switching OFF the inductive-resistive load.

The power supplied drawn by the DSTATCOM during switching OFF the inductive resistive load is shown in Fig.17. It is observed that power exchange between the IEEE-13 bus test system and DSTATCOM decreased after switching OFF the inductive resistive load. Power transient of have not been observed at the time of switching OFF and ON inductive resistive load.

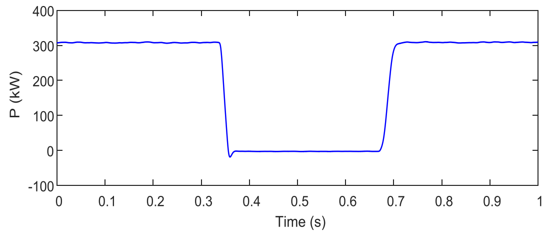

Fig.17. Power supplied by the DSTATCOM during switching OFF the inductive-resistive load.

The power supplied by the solar PV system during switching OFF the inductive resistive load is shown in Fig.18. It is observed that the power supplied by the solar PV system is increased after switching OFF the inductive resistive load. Power transients have not been observed at the time of the switching OFF and ON the inductive resistive load.

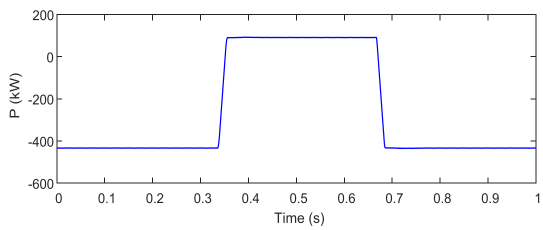

Fig.18. Power supplied by the solar PV system during switching OFF the inductive-resistive load.

The rms values of the voltage on the point of common coupling of the DSTATCOM i.e. the bus 680 of the IEEE-13 bus test system in the presence of the DSTATCOM has been shown in the Fig.19. It is observed that the voltage slightly increases after switching OFF the inductive-resistive load. The high magnitude transient component is not available with the voltage at the time of switching OFF the inductive resistive load.

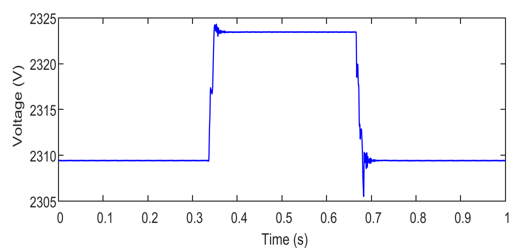

Fig.19. Voltage in the presence of DSTATCOM during switching OFF the inductive-resistive load.

The rms values of the voltage on the point of common coupling of the DSTATCOM i.e. the bus 680 of the IEEE-13 bus test system in the absence of the DSTATCOM has been shown in the Fig.20. It is observed that the voltage increases after switching OFF the inductive resistive load. The low magnitude transient component is available with the voltage at the time of switching ON and OFF the inductive resistive load. It is concluded that magnitude of the voltage transient components are high without DSTATCOM compared to the presence of the DSTATCOM. Hence the voltage transients' components have been reduced in the presence of the DSTATCOM in the distribution network. Hence, the presence of the DSTATCOM improves the overall power quality of the distribution system in the presence of the solar PV energy.

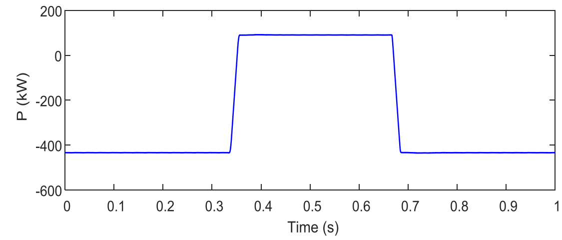

Fig.20. Voltage without DSTATCOM during switching OFF the inductive-resistive load.

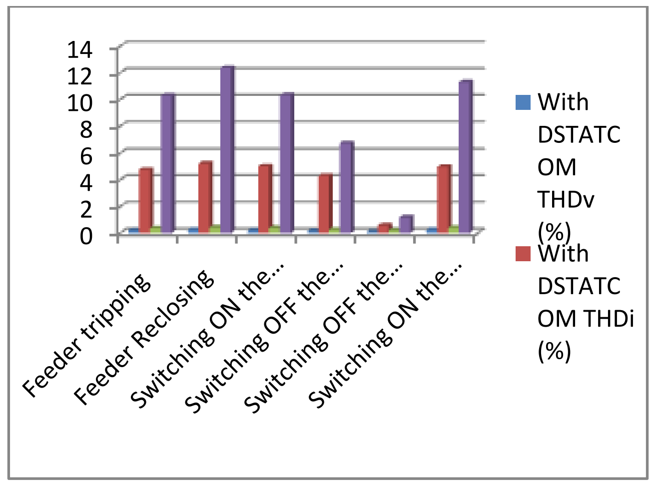

Fig. 21 cumulative analysis of Harmonic Distortion with and without DSTATCOM

Figure 21 shows the analysis of total harmonic distortion in presence and absence of DSTATCOM where it conclude that total harmonic distortion was maximum in absence of DSTATCOM and further it gets reduced upto 50% in presence of DSTATCOM.

IV. CONCLUSION

This work investigates the power quality improvement in the distribution system in the presence of solar PV system using DSTATCOM with battery energy system during the events such as feeder tripping, feeder re-closing, switching on/off the capacitor bank and switching on/off the inductive resistive loads. The synchronous reference frame theory based control has been used for the control of the DSTATCOM for the power quality improvement in distribution system with solar energy penetration. The proposed methodology has been carried out in the MATLAB/simulink environment IEEE-13 bus test system. It has been concluded that the reduction in the power transients have been achieved by the use of the distribution static compensator in the distribution system. Improvement in the total harmonic distortions in the voltage and current has been achieved up to 50% by the use of the DSTATCOM. Improvement in the transients of voltage has also been reduced by the use of the distribution static compensator in the distribution system. Hence, it has been established that the use of DSTATCOM in the distribution system controlled by the synchronous reference frame theory based control can effectively be utilized for the improvement of power quality, reduction of power transient components and voltage transients in the distribution system in the presence of the solar PV system during the operational events such as feeder tripping, feeder re-closing, switching on/off the capacitor bank and switching on/off the inductive resistive loads.

The proposed methodology has been validated on the IEEE-13 bus test system. To generalize the proposed algorithms, the same methodology needs to validate on the large test networks such as IEEE-123 bus system. The proposed methodology may be extended for the use of wind generator in the distribution system. The methodology further may also be extended to the hybrid power system in which both wind and solar PV system are integrated simultaneously.

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