Int. J. Elec&Electr.Eng&Telecoms. 2014

International Journal of Electrical and Electronic Engineering & Telecommunications

ISSN 2319 – 2518 www.ijeetc.com
Vol. 3, No. 1, January 2014

Research Paper

A NEW DESIGN OF THE DISTRIBUTION CUSTOM POWER CONTROLLERS FOR MITIGATION OF POWER QUALITY PROBLEMS

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This paper deals with A New design of the distribution custom power controllers (D-STATCOM (Distribution Static Compensator) and DVR) is used for Mitigation of Power Quality Problems under unbalance caused by various loads in distribution system. This paper addresses the modeling and analysis of custom power controllers, power electronic-based equipment aimed at enhancing the reliability and quality of power flows in low voltage distribution networks using DSTATCOM and DVR. A new PWM-based control scheme has been proposed that only requires voltage measurements the operation of the proposed control method is presented for D-STATCOM and DVR. Simulations and analysis are carried out in MATLAB/SIMULINK with this control method for two proposed systems.

Keywords: DVR, D-STATCOM, VSC, FACTS devices, PQ, PCC

INRODUCTION

The Dynamic Voltage Restorer (DVR), also known as the Series Voltage Booster (SVB) or the Static Series Compensator (SSC), is a device that utilizes solid state (or static) power electronic components, and is connected in series to the utility primary distribution circuit. The DVR provides three phase controllable voltage, whose vector (magnitude and angle) adds to the source voltage to restore the load voltage to pre-sag conditions (Hingorani, 1995).

Figure 1 is a simplified circuit for the role and location of the DVR in the distribution system. When a fault occurs on the line feeding Load 1, its voltage collapses to zero. Load 2 voltage experiences a sag which magnitude is equal to the voltage at the PCC, and the voltage of the sensitive load protected by the DVR is restored to its prefault value (Ray Arnold, 2001).

From the past few decades, the increase in electrical energy demand for industries and domestic use resulted in the higher production

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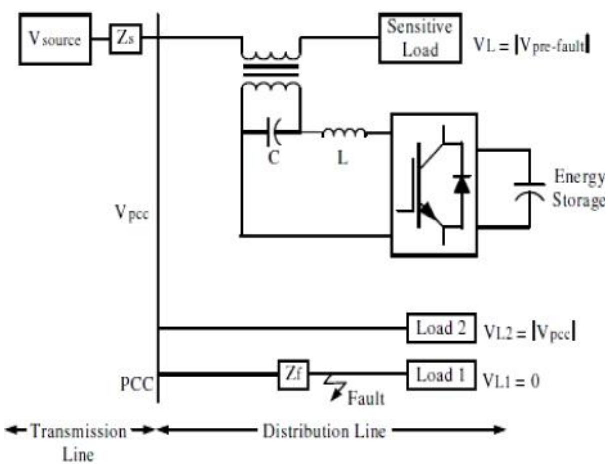
Figure 1: Role and Location of DVR



of electrical energy which has consequently resulted in higher tariff rates, for industrial and domestically usage AC Power is essential, In AC the power factor is described as the ratio of real power to the apparent power (real power + reactive power).

Reactive power is produced when the current and voltage waveforms are out of phase with each other, in a capacitive load current leads voltage whereas in inductive load current lags voltage, reactive power is denoted as var. Reactive power compensation is essential to increase the power factor quality, which obviously results in the decrease of power consumption and tariffs; finally the aim is to decrease the reactive power. Reactive power can be decreased by placing a shunt capacitor in line but it does not fulfill the problem because it gets in resonance when it gets tuned with reactance of the system. In order to overcome the disadvantages caused by placing a shunt capacitor in line, facts devices have been developed to solve the problem effectively examples of FACTS devices are SC, TSC, etc. Though the power electronic devices known as Facts devices are developed for transmission part of the system its model have been changed from past few years to serve better power quality at low and medium voltages.

DSTATCOM is a distribution static compensator network which is placed at the distribution part of the system which works with the FACTS devices which react faster than the shunt capacitors actually.

In recent years, the custom power technology, the low-voltage counterpart of the more widely known Flexible AC Transmission System (FACTS) technology, aimed at high-voltage power transmission applications, has emerged as a credible solution to solve many of the problems relating to continuity of supply at the end-user level. Both the FACTS and custom power concepts are directly credited to EPRI. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator (D-STATCOM) based on the VSC principle (John Stones and Alan Collision, 2001; and Po-Tai Cheng *et al.*, 2003) has been used to perform the Modelling and analysis of such controllers for a wide range of operating conditions based PWM control reported inthis seminar forthe D-STATCOM. It relies only on voltage measurements for its operation, i.e., it does not require reactive power measurements (Soo-Young Jung *et al.*, 2002).A sensitivity analysis is carried out to determine the impact of the dc capacitor size on D-STATCOM performance.

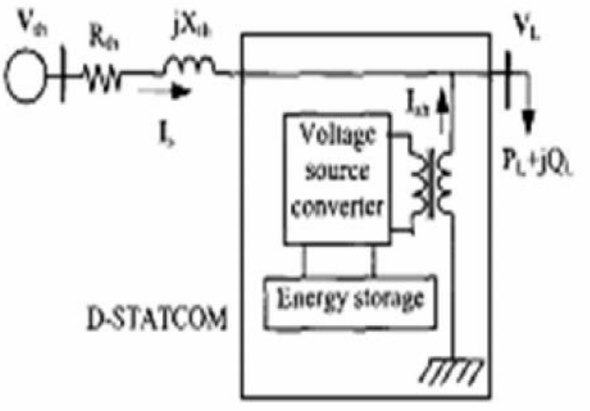
When used in low-voltage distribution systems the STATCOM is normally identified as Distribution STATCOM (D-STATCOM).It operates in a similar manner as the STATCOM (FACTS controller), with the active power flow controlled by the angle between the AC system and VSC voltages and the reactive power flow controlled by the difference between the magnitudes of these voltages. As with the STATCOM, the capacitor acts as the energy storage device and its size is chosen based on power ratings, control and harmonics considerations. The D-STATCOM controller continuously monitors the load voltages and currents and determines the amount of compensation required by the AC system for a variety of disturbances.

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Fig.1consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the DSTATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power. The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes (Bollen, 2001):

- Voltage regulation and compensation of reactive power
- Correction of power factor
- Elimination of current harmonics

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter.

Figure 2: Single Line Diagram of D-STATCOM Connected Distribution System



SYSTEM REPRESENTATION

Distribution Static Compensator (DSTATCOM)

A D-STATCOM (Distribution Static Compensator), which is pictorially depicted in Figure, is accumulated with a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The dc voltage across the storage device into a set of three-phase ac output voltages with the use of VSC. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. The configuration allows the device to absorb or generate controllable active and reactive power.

The ac system in combination with a shunt VSC provides a multifunctional topology results in the following advancements:

- Voltage regulation and compensation of reactive power;
- Correction of power factor; and
- Elimination of current harmonics.

Device is employed to provide continuous voltage regulation using an indirectly controlled converter.

Figure 2 the shunt injected current I_{sh} corrects the voltage sag by adjusting the voltage drop across the system impedance Z_{th}. The value of I_{sh} can be controlled by adjusting the output voltage of the converter.

The shunt injected current Ish can be written as,

$$I_{sh} = I_L - I_S = I_L - \frac{V_{TH} - V_L}{Z_{th}} \qquad ...(1)$$

The complex power injection of the D-STATCOM can be expressed as,

$$S_{sh} = V_L I_{sh}^{*} \qquad ...(2)$$

It may be mentioned that the reliability of the D-STATCOM in correcting voltage sag depends on the value of Z_{th} or fault level of the load bus. When the shunt injected current Ish is kept in quadrature with V_L, the desired voltage correction can be achieved without injecting any active power into the system. When the value of I_{sh} is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system on the other hand. The control scheme for the D-STATCOM. The switching carrier frequency is set at 1075 Hz.

Dynamic Voltage Restorer

The most usual application of a DVR is to protect sensitive loads from the effects voltage dips. A dip is usually taken as an event lasting less than one minute while the voltage decreases to between 0.1 and 0.9 p.u. A DVR consists of a VSC placed in series with the load (via an injection transformer for higher voltages), which is controlled to inject a voltage in series with a depleted supply voltage to maintain the load voltage at a constant value. The DVR is a powerful controller that is commonly used for voltage sags mitigation at the point of connection. The DVR employs the same blocks as the D-STATCOM, but in this application the coupling transformer is connected in series with the ac system The VSC generates a three phase ac output voltage which is controllable in phase and magnitude. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference. The converter generates the reactive power needed while the active power is taken from the energy storage. The energy storage can be different depending on the needs of compensating.

The DVR often has limitations on the depth and duration of the voltage dip that it can compensate. Therefore right sized has to be used in order to achieve the desired protection. Options available for energy storage during voltage dips are conventional capacitors for very short durations but deep, batteries for longer but less severe magnitude drops and super capacitors in between. There are also other combinations and configurations possible.

There are configurations, which can work without any energy storage, and they inject a lagging voltage with the load current. There are also different approaches on what to inject to obtain the most powerful solution. The main advantage with this method is that a single *DVR* can be installed to protect the whole plant (a few MVA) as well as single loads. Because of the fast switches, usually IGBT's, voltage compensation can be achieved in less than half a cycle (Ghosh and Ledwich, 2002). Disadvantages are that it is relatively expensive and it only mitigates voltage dips from outside the site. The cost of a *DVR* mainly depends on the power rating and the energy storage capacity.

The circuit on left hand side of the *DVR* represents the Theven in equivalent circuit of the system. The system impedance Z_{th} depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained (Haque, 2001). The series injected voltage of the *DVR* can be written as,

The schematic diagram of a typical *DVR* is as shown in Figure 3.

$$V_{DVR} = V_L + Z_{th} * I_L - V_{th} \quad ...(3)$$

Z_{th} is the load impedance

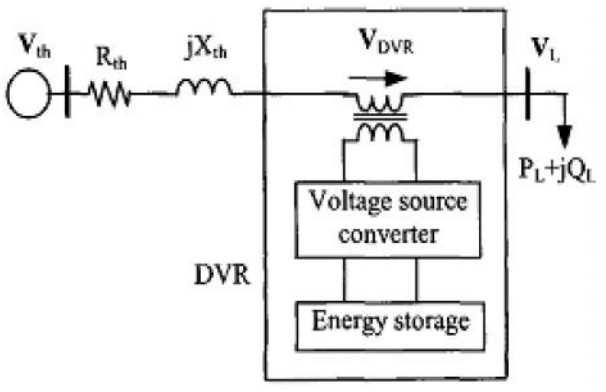
I_L is the load current

V_{th} is the system voltage during fault condition

The load current I_L is given by,

When V_L is considered as a reference, Equation (1) can be rewritten as,

Figure 3: Schematic Diagram of DVR



$$I^*_{sh} = \left(\frac{P_L + JQ_L}{V_L}\right) \quad ...(4)$$

The complex power injection of the DVR can be written as,

$$S_{DVR} = V_{DVR} * I^*_L \quad ...(5)$$

It may be mentioned here that when the injected voltage V_{DVR} is kept in quadrature with I_L, no active power injection by the *DVR* is required to correct the voltage. It requires the injection of only reactive power and the *DVR* itself is capable of generating the reactive power. Note that *DVR* can be kept in quadrature with I_L only up to a certain value of voltage sag and beyond which the quadrature relationship cannot be maintained to correct the voltage sag. For such a case, injection of active power into the system is essential. The injected active power must be provided by the energy storage system of the *DVR*.

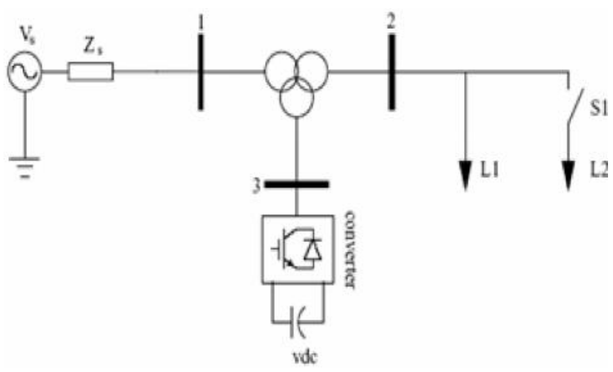
Test System

Figure shows the test system used to carry out the various D-STATCOM simulations.

SWITCHING CONTROL

The aim of the control scheme is to maintain constant voltage magnitude at the point where

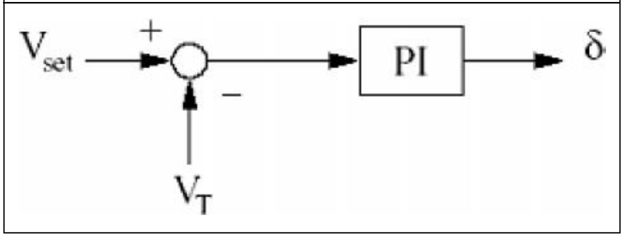
Figure 4: Single Line Diagram of the Test System for D-STATCOM



a sensitive load is connected, under system disturbances. The control system only measures the rms voltage at the load point, i.e., no reactive power measurements are required. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the Fundamental Frequency Switching (FFS) methods favored in FACTS applications. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses.

In Figure 4 shows that the controller input is an error signal obtained from the reference voltage and the value rms of the terminal voltage measured. Such error is processed by a PI controller and the output is the angle d, which is provided to the PWM signal generator. It is important to note that in this case, indirectly controlled converter, there is active and reactive power exchange with the network simultaneously: an error signal is obtained by comparing the reference voltage with the rms voltage measured at the load point. The PI controller process the error signal and generates the required angle to drive the error to zero, i.e., the load rms voltage is brought back to the reference voltage.

Figure 5: Indirect Controller



The sinusoidal signal $V_{CONTROL}$ is phase-modulated by means of the angle ¢.

i.e.,

$$V_A = \sin(\mu t + \text{¢})$$

$$V_B = \sin(\mu t + \text{¢} - 120^o)$$

$$V_C = \sin(\mu t + \text{¢} + 120^o) \quad ...(6)$$

The modulated signal $V_{CONTROL}$ is compared against a triangular signal (carrier) in order to generate the switching signals for the VSC valves. The main parameters of the sinusoidal PWM scheme are the amplitude modulation index of signal, and the frequency modulation index of the triangular signal. The amplitude index is kept fixed at 1 p.u, in order to obtain the highest fundamental voltage component at the controller output.

Figure 6: The Sinusoidal Signal $V_{CONTROL}$

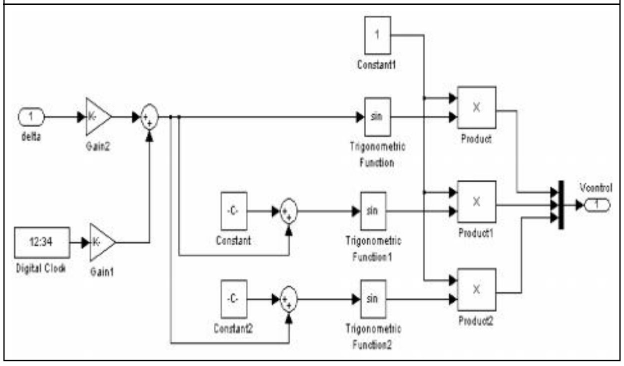
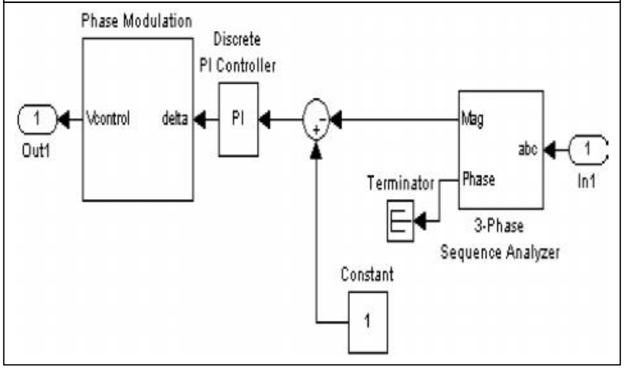


Figure 7: Block Diagram of PWM



where $V_{CONTROL}$ is the peak amplitude of the control signal.

V_{Tri} is the peak amplitude of the triangular signal the switching frequency is set at 1075 Hz. The frequency modulation index is given by;

$$M_a = \frac{V_{CONTROL}}{V_{TRI}} = 1\,p.u \qquad \text{...(7)}$$

$$M_f = \frac{f_x}{f_1} = 25 \qquad \text{...(8)}$$

where f_1 is fundamental frequency

The modulating angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 240° and 120° respectively. It can be seen in that the control implementation is kept very simple by using only voltage measurements as the feedback variable in the control scheme. The speed of response and robustness of the control scheme are clearly shown in the simulation results. The Simulink block diagram of SPWM generator is as shown in Figure 7.

SYSTEM MODELLING

To enhance the performance of distribution system, D-STATCOM was connected to the distribution system. DSTATCOM was

Figure 8: The Simulink Block Diagram of SPWM Generator

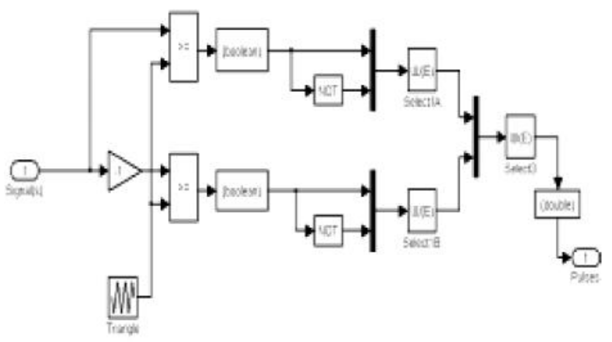


Figure 9: Flow Chart Diagram of Test System

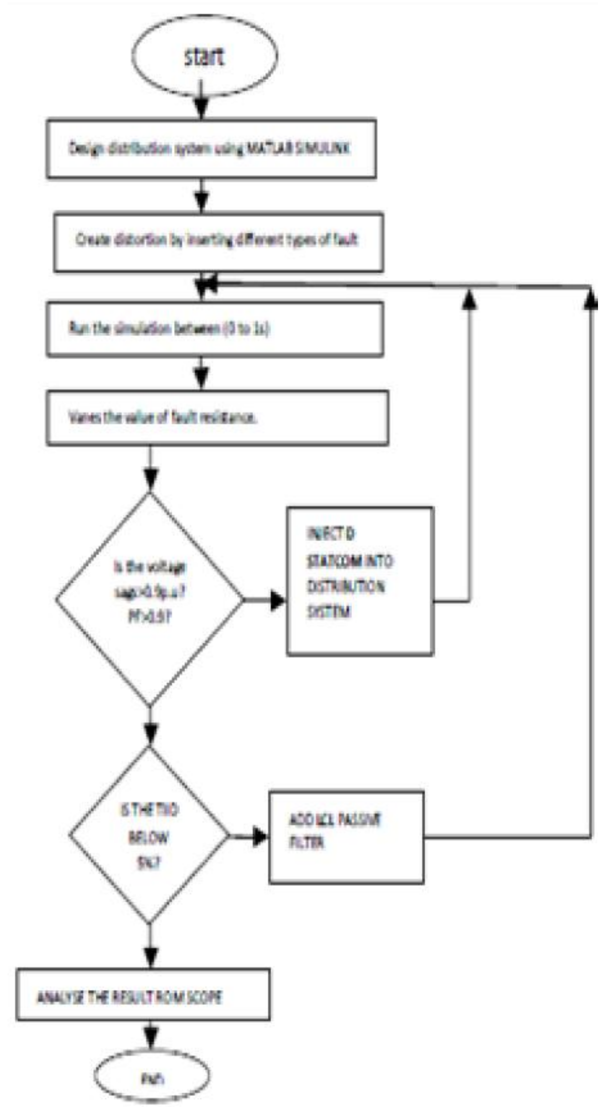
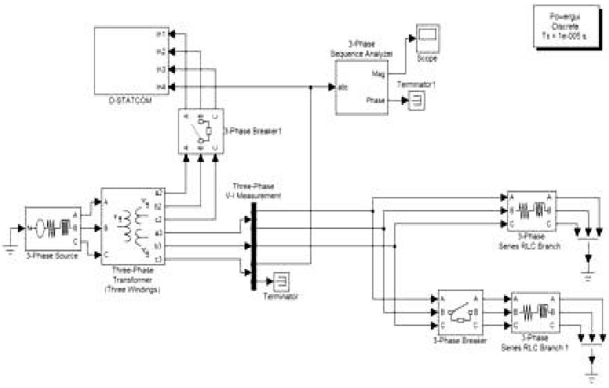


Figure 10: Simulink Model of Test System



designed using MATLAB/SIMULINK version R2007b. Figure 6 below shows the flowchart for the methodology. The test system shown in Figure 7 comprises a 230 kV, 50 Hz transmission system, represented by a Thevenin equivalent, feeding into the primary side of a 3-winding transformer connected in Y/Y/Y, 230/11/11 kV. A varying load is connected to the 11 kV, secondary side of the transformer. A two-level D-STATCOM is connected to the 11 kV tertiary winding to provide instantaneous voltage support at the load point. A 750 µF capacitor on the dc side provides the D-STATCOM energy storage capabilities. Breaker 1 is used to control the period of operation of the D-STATCOM and breaker 2 is used to control the connection of load 1 to the system.

Table 1: Typical Parameters

System Parameters	**Values**
System frequency (f)	50 HZ
Rated voltage	230 KV
Voltage source v_{S1}	230 KV, Phase angle 0°
Voltage source v_{S2}	230 KV, Phase angle 0°
Feeder-1	1 + j0.8 Ω
Load-1	A three-phase diode bridge rectifier with anresistor (500) Ω

Table 2: D-STATCOM / DVR Parameters

System Parameters	**Values**
System frequency (f)	50 HZ
VSC-1 single-phase transformers (T_1)	100 MVA, 230 KV/11 KV, 2% resistance and 8% leakage Reactance
VSC-2 single-phase transformers (T_2)	100 MVA, 230 KV/11 KV, 2% resistance and 8% leakage Reactance

The test system shown in Figure 6 comprises a 230 kV, 50 Hz transmission system, represented by a Thevenin equivalent, feeding into the primary side of a 3-winding transformer connected in Y/Y/Y, 230/11/11 kV. A varying load is connected to the 11 kV, secondary side of the transformer. A two-level D-STATCOM is connected to the 11 kV tertiary winding to provide instantaneous voltage support at the load point. A 750 µF capacitor on the dc side provides the D-STATCOM energy storage capabilities. Breaker 1 is used to control the period of operation of the D-STATCOM and breaker 2 is used to control the connection of load 1 to the system.

Case 1

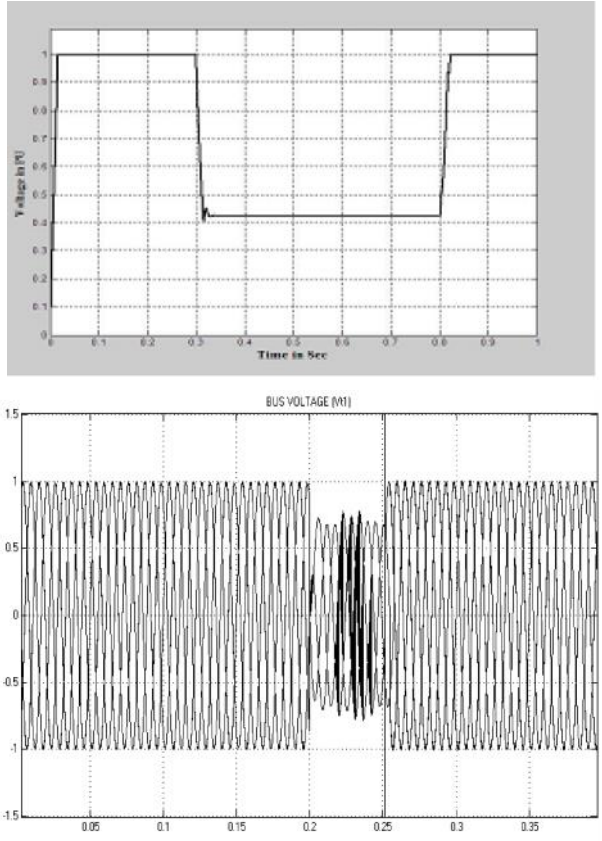
Simulated Results of Sag modeled system with and without D-STATCOM:

The circuit shown is Figure 8, is nothing but a sag generating circuit without the D-STATCOM connected to it is simulated and the magnitude of voltage.

The circuit shown is Figure 11, is nothing but a sag eliminating circuit with the D-STATCOM connected to it is simulated and the magnitude of voltage.

As shown in Figure 11, a very effective voltage regulation which is provided by the

Figure 11: V_{RMS} Voltage at the Load Point of the Sag System Without D-STATCOM



D-STATCOM can be clearly appreciated. The D-STATCOM supplies reactive power to the system to eliminate the voltage sag. In spite of sudden load variations, the regulated RMS voltage shows a reasonably smooth profile, where the transient overshoots is almost non-existent.

Figure 12: V_{RMS} Voltage at the Load Point of the System with D-STATCOM

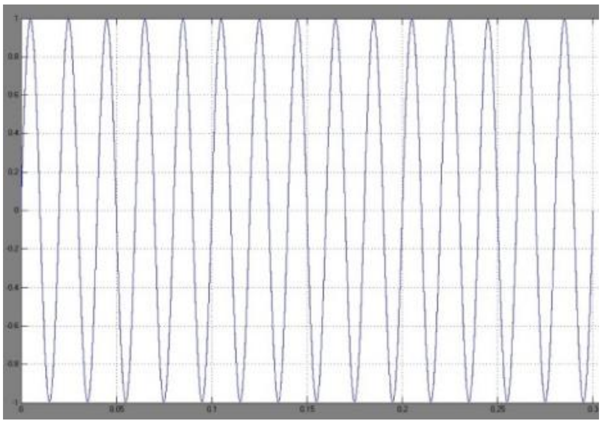
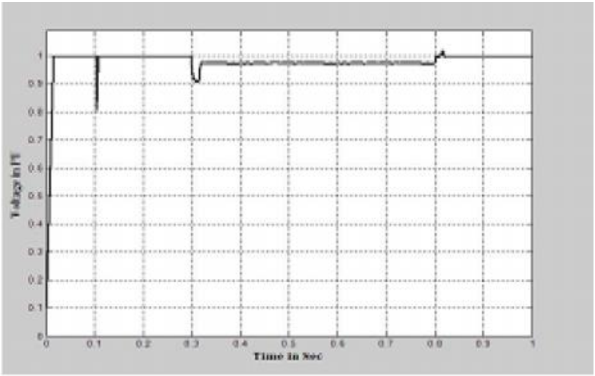


Figure 12 (Cont.)



Case 2

Simulated Results of Swell modeled system with and without D-STATCOM:

The circuit shown is Figure 13, is nothing but a swell generating circuit without the D-STATCOM connected to it is simulated and the magnitude of voltage.

The circuit shown is Figure 14, is nothing but a swell eliminating circuit with the D-STATCOM connected to it is simulated and the magnitude of voltage.

Figure 13: V_{RMS} Voltage at the Load Point of the Swell System Without D-STATCOM

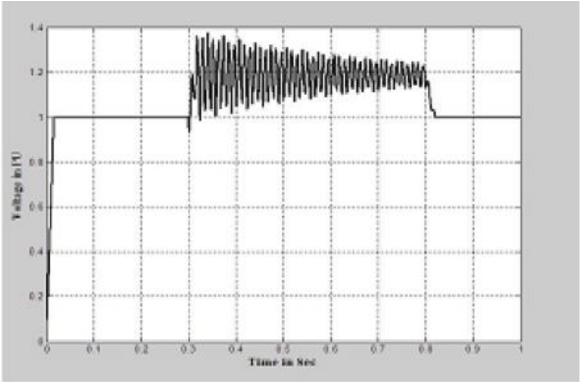
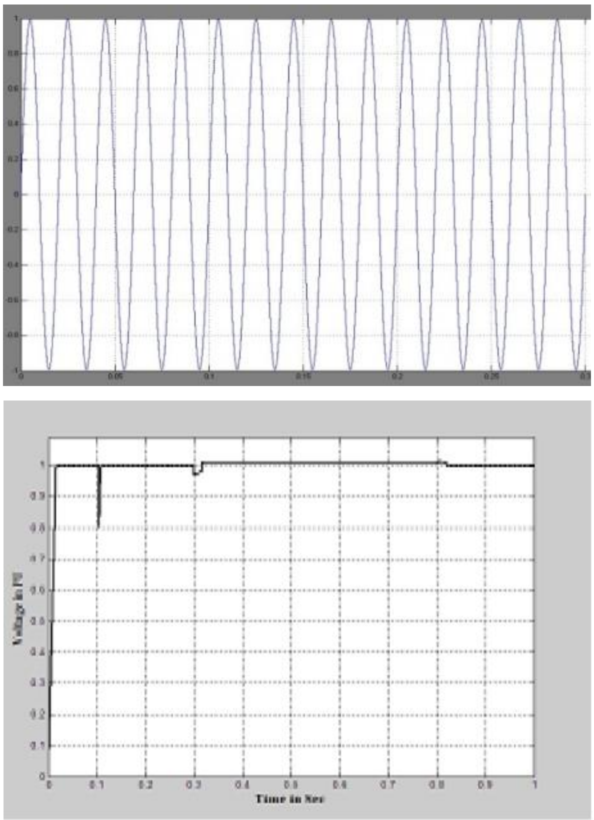


Figure 14: V_{RMS} Voltage at the Load Point of the Swell System with D-STATCOM



As shown in Figure 14, a very effective voltage regulation which is provided by the D-STATCOM can be clearly appreciated. The D-STATCOM eliminates the voltage swell. In spite of sudden load variations, the regulated RMS voltage shows a reasonably smooth profile, where the transient overshoots is almost non-existent.

Case 3

Figure 15 shows the rms voltage at the load point for the case when the system operates with no DVR.

When the DVR is in operation the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 98%, as shown in Figure 15.

Figure 15: Voltage V_{RMS} at the Sensitive Load Point Without DVR

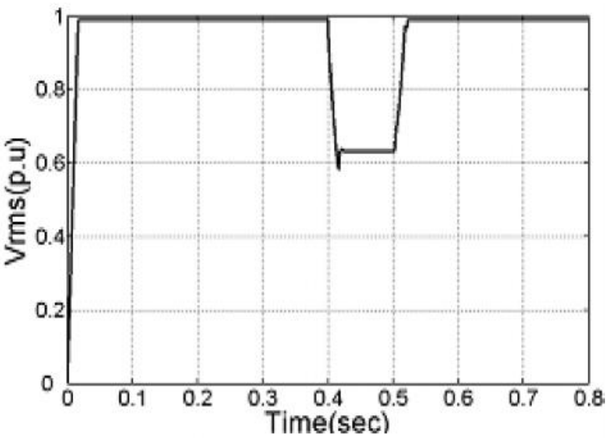
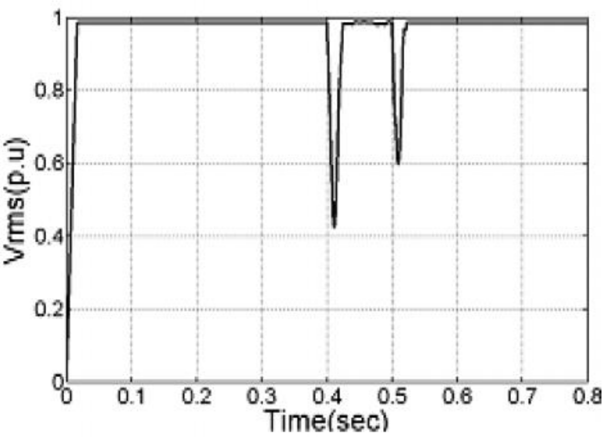


Figure 16: Voltage V_{RMS} at the Load Point with DVR



CONCLUSION

It was also observed that the capacity for power compensation and voltage regulation of DVR and D-STATCOM depends on the rating of the dc storage device. The power quality problems mitigated by using D-STATCOM and DVR is presented in this paper and developed for use in Simulink environment with power system block sets. Here a control system is designed in MATLAB Simulink. A D-STATCOM can control reactive power and also DVR regulate bus voltage. It can improve power quality in power system. Here waveform shows the performance of D-STATCOM and DVR in a distribution system.

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