Power line Voltage Sag Mitigation by DynamicVoltage Restorer using ANN optimization Technique Approach

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Abstract:
Voltage sag is one of the most severe power quality disturbances to be dealt with by the industrial sector, as it can cause severe process disruptions and results in substantial economic loss. A short-term decreasein voltage lasting anywhere from milliseconds up to a few seconds is called voltage sag. 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) and the dynamic voltage restorer (DVR) are most effective devices for mitigation of voltage sag, both of them based on the voltage source converter (VSC) principle. A DVR injects a voltage in series with the system voltage and a D-STATCOM injects a current into the system to correct the voltage sag. Control unit is the heart of DVR and D-STATCOM where the main function of it is to detect the presence of voltage sag in the system and calculating the required compensating voltage for the above compensating devices. Due to approximation in the process of the control design the existing control schemes used for DVR and D-STATCOM have some tracking error. This work evaluates the performance of the above compensating devices with a novel algorithm called two neuron control algorithm for simultaneous sag compensation and replenishing dc bus energy. This algorithm uses the simplest pre-sag supply voltage boosting technique. Besides, a self-charging technique is used which maintains the dc capacitor voltage at the desired level. The salient advantages of this method are compensating long duration deeper voltage sags, reduction in size of dc-link capacitor and simplicity of algorithm for digital implementation. Comprehensive results are presented to assess the performance of the two neuron control algorithm for each device as a potential custom power solution.

Keywords: Voltage sag, DVR, D-STATCOM, FACTS Devices, Power quality

1. Introduction

Power quality is the term used to define how closely electrical power delivered to consumers matches with appropriate standards in terms of voltage and frequency. A Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a mal- 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. In developing countries like India, where the variation of power frequency and many such other determinants of power quality are themselves a serious question, it is very vital to take positive steps inthis direction .The present work is to identify the prominent concerns in this area and hence the measures that can enhance the quality of the power are recommended. Electronic devices function properly as long as the voltage (or driving force) of the supply system feeding the device stays within aconsistent range. There are several types of voltage fluctuations that can cause problems, including surges and spikes, sags, harmonic distortions, and momentary disruptions. Voltage sags are common events on the electric power network. It is one of the most severe power quality disturbances to be dealt with by the industrial sector, as it can cause severe process disruptions and result in substantial economic loss. Voltage sag is not a complete interruption of power; it is a temporary drop below 90 percent of the nominal voltage level. Most voltage sags do not go below 50 percent of the nominal voltage and they normally last from 3 to 10 cycles or 50 to 170 milliseconds.

Even short duration voltage sag could cause a malfunction or a failure of a continuous process, therebyincurring heavy financial loss. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications explained by Lara, Acha (2002) and Bollen (2001). Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices, both of them based on the VSC principle. A new PWM-based control scheme has been implemented to control the electronic valves in the two-level VSC used in the D-STATCOM and DVR proposed by Madrigal, Acha (2000) and Mienski, et al. (2004). A series connected converter based mitigation device, the dynamic voltage restorer (DVR) proposed by Woodley.N.H, et al.,(1999), is the most economical and technically advanced mitigation device proposed to protect sensitive loads from voltage sags shown in figure-1. The amount of energy storage within the DVR becomes one of the main limiting factors in mitigating long duration voltage sags. Therefore, researchers presently pay greater attention to the DVR energy storage and its optimumuse. A progressive phase advance technique where all the three phase voltages are progressively advanced by a certain angle to minimize the amount of real power supplied by the DVR has been proposed by Vilathgamuwa.D.M, et al., (1999) and Li.B.H, et al., (2000).

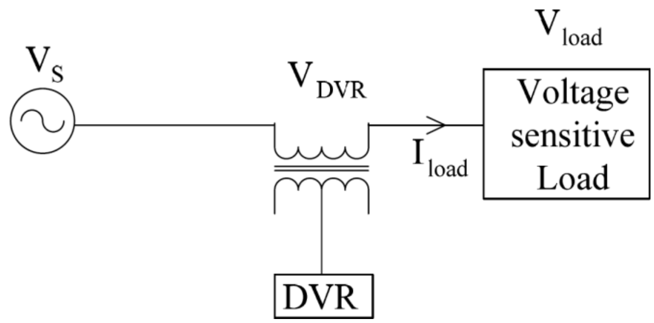

Figure 1 Dynamic voltage restorers

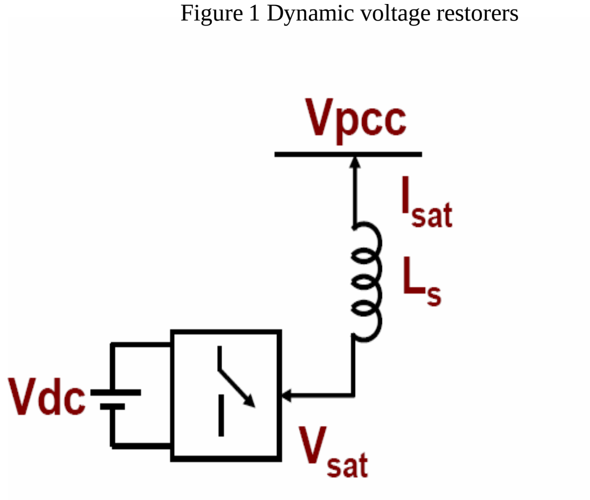

Figure 2. Distribution Static Compensator

The control strategy adopted for generating reference signal plays a key role in deciding the dynamic behavior of a system. Usually, the control voltage for mitigating voltage sag is derived by comparing the supply voltage against a reference waveform as explained by Nielsen.J.G, etal. (2001). although thesystem stability is guaranteed in this type of control, the stability margin can be inadequate and the damping of output voltage would be poor. Because of these reasons, the current mode feedback controlproposed by Vilathgamuwa.D.M, et al., (2002) is gaining acceptance for voltage sag mitigation. Efficiency of DC Energy Storage Schemes for DVR Voltage Sag Mitigation System is evaluated by H.P.Thiwari, et al., (2010). But they are not economical. The simulation and experimental verification of a DVR using PSCAD/EMTDC software based on SVPWM technique is performed by Rosli Omar and Gupta (2010). The techniques of correcting the supply voltage sag swell and interruption in a distributed system using DVR and D-STATCOM is described by Kumar and Nagaraju (2011). A D- STATCOM (Distribution Static Compensator), which is schematically depicted in Figure-2, consists 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. Due to approximation in the process of the control design the control schemes used for DVR and D-STATCOM explained above have some tracking error. Hence there is a need to implement new control schemes for voltage sag compensation and self charging technique for maintaining dc bus voltage of DVR and D- STATCOM. The performances of both the devices are evaluated after implementing two neuron control algorithm.

2. Series voltage controller (DVR)

The series voltage controller is connected in series with the protected load as shown in Figure-1. Usually the connection is made via a transformer, but configurations with direct connection via power electronics also exist. The resulting voltage at the load bus bar equals the sum of the grid voltage and the injected voltage from the DVR. 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. The circuit on left hand side of the DVR represents the Thevenin 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. The series injected voltage of the DVR can be written as,

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \quad (1)$$

Where

V_L is the desired load voltage magnitudeZ_{Th} is the load impedance

I_L is the load current

V_{th} is the system voltage during fault conditionThe load current I_L is given by,

$$I_L = \left(\frac{(P_L + J * Q_L)}{V_L} \right)^* \quad (2)$$

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

$$V_{DVR} \angle \alpha = V_L \angle 0 + Z_{th} I_L \angle (\beta - \theta) - V_{th} \angle \delta \quad (3)$$

Here α, β and δ are the angle of V_{DVR}, Z_{th} and V_{th}, respectively, and θ is the load power factor angle, $\theta = \tan^{-1}(Q_L/P_L)$.

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

$$S_{DVR} = V_{DVR} I_L^* \quad (4)$$

It may be mentioned here that when the injected voltage V_{DVR} is kept in quadrature with I_L, no activepower 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.

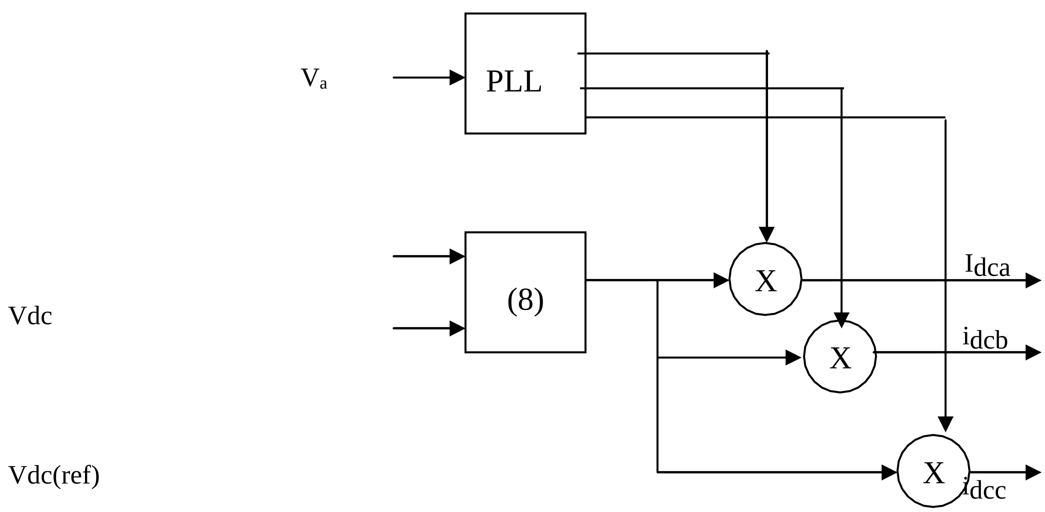

Figure 3 Three-phase self charging circuit

3. Shunt Voltage Controller (D-STATCOM)

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Figure-2, consists 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 D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM 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 beused for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive power;
2. Correction of power factor and
3. Elimination of current harmonics.

Here, such a device is employed to provide continuous voltage regulation using an indirectly controlled converter. In 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 I_{sh} can be written as,

$$I_{sh}\angle\eta = I_L\angle-\theta-\frac{V_{th}}{Z_{th}}\angle(\delta-\beta)+\frac{V_L}{Z_{th}}\angle-\beta \quad (5)$$

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

$$S_{sh} = V_L I_{sh}^{*} \quad (6)$$

It may be mentioned that the effectiveness 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 I_{sh} is kept in quadrature with $V_{L,}$ the desired voltage correction can be achieved without injecting any active power into the system. On the other hand, when the value of I_{sh} is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system.

4. Control Strategy

To regulate the dc link capacitor voltage at the desired level, real power has to be drawn by the DVRor D-STATCOM from the supply side to charge the capacitor. The configuration of three-phase self charging current is shown in Figure 3.

The PLL synchronizes itself with the supply voltage of phase 'a' and outputs three sine waves which are 120° out of phase from each other. Three phase i_{dc} is obtained by multiplying these sine waves with the current I_{dc} which is calculated by the control algorithm. Thus, the three phase injection currents canbe calculated as

$$i_{inj,a} = -I_{dc}\sin\omega t$$

$$i_{inj,b} = -I_{dc}\sin(\omega t-120)$$

$$i_{inj,c} = -I_{dc}\sin(\omega t+120)$$

Where I_{dc} is given as,

$$I_{dc} = 2C\frac{\{[V_{dc}(ref)]^2-[V_{dc}]^2\}}{3VT} \quad (7)$$

(8)

The minus sign indicates that the charging current i_{dc} flows into the DVR or D-STATCOM. An adjustable carrier PWM controller is used to control the switching of the DVR or D-STATCOM.The simplest pre-sag supply voltage boosting technique is considered for developing a new two neuroncontrol algorithm. The pre-sag voltage boosting technique can be explained by vector diagram shown in Figure 4.

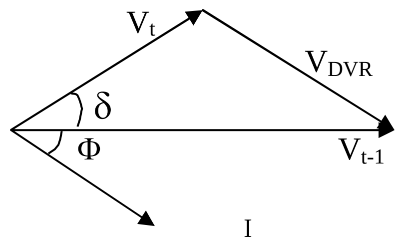

Figure 4 Pre-sag supply voltage boosting technique

Current is taken as reference vector throughout this section. Under pre-sag condition, the system voltage is V_{t-1} which leads current by an angle φ. At time'‘t’, sag occurs in supply voltage and is shiftedin phase by an angle δ called phase angle jump. The ratio of voltage during sag to voltage before sag isreferred as sag factor ‘a’. That is, a $=V_t/V_{t-1}$. The series converter of DVR has to inject a voltage ‘V_{DVR}’ such a way to bring voltage during sag V_t to its pre-sag value V_{t-1}. The control algorithm developed for generating the reference signal to compensate voltage sag is named as two-neuron control technology.

$$|V|_{ref} = \sqrt{V_{\alpha ref}^2 + V_{\beta ref}^2}$$

$$\theta_{ref} = \tan^{-1}\left(\frac{V_{\beta ref}}{V_{\alpha ref}}\right) \quad (9)$$

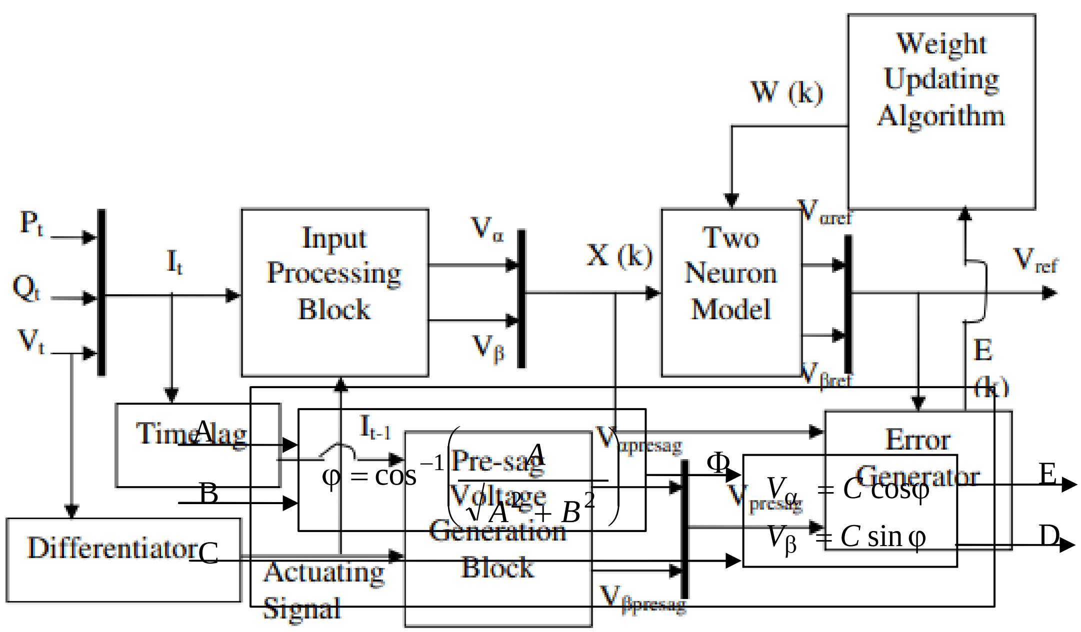

Figure 5 Basic block diagram of controller

Figure 6 Input processing / Pre-sag voltage generation

The same principle is used for D-STATCOM in which current reference has to be calculated instead ofvoltage reference in DVR. The shunt converter of the D-STATCOM has to inject the reference current I_{ref} to the system. Thus due to change in voltage drop in the Thevenin's impedance of system, the terminal voltage at the sensitive load is brought back to orginal value. But the voltage terms should be replaced by current and the same algorithm can be used for D-STATCOM. That is, $I_{\alpha ref} = \gamma_1 V_\alpha$ and $I\beta ref = \gamma_2 V_\beta$.

The basic block diagram of the control algorithm for DVR is shown in Figure-5. The same control algorithm can be used for D-STATCOM. But the only difference is the output of two neuron model block should be treated as $I_{\alpha ref}$ and $I_{\beta ref}$ instead of $V_{\alpha ref}$ and $V_{\beta ref}$. Also the input to error generator block is calculated as $V_{\alpha ref} = I_{\alpha ref} Z_{th}$ and $V_{\beta ref} = I_{\beta ref} Z_{th}$ for D-STATCOM.

The input processing block and pre-sag voltage generation block shown in figure-6 performs the same function of calculating the in-phase and phase-quadrature components of voltage, but for different input quantities. Figure-6 shows the input processing/pre-sag voltage generation block. In case of input processing function, the inputs and outputs are $A=P_t$; $B=Q_t$; $C=V_T$; $D=V_\alpha$ and $E=V_\beta$. On the other hand, for pre-sag voltage generation the inputs and outputs are $A=P_{t-1}$; $B=Q_{t-1}$; $C=V_{t-1}$; $D=V_{\alpha presag}$ and $E=V_{\beta presag}$. The time lag block in Figure 5 is used for obtaining inputs P_{t-1}, Q_{t-1} and V_{t-1} from P_t, Q_t and V_t respectively. The inputs are denoted in figure as

$$I_t = [P_t, Q_t, |V_t|] \quad and \quad I_{t-1} = [P_{t-1}, Q_{t-1}, |V_{t-1}|] \tag{10}$$

Both input processing block and pre-sag voltage generation block responds to input only when activating signal is generated by the differentiator (Figure 5). Under normal condition without voltage sag, the differentiator output is zero and the blocks are not activated.

The error generator block is shown in Figure 7. The line voltage is added with reference voltage generated by the control algorithm and compared with the pre-sag voltage generated by pre-sag voltage generation block. In the case of D-STATCOM, the error generator block input is calculated as $V_{\alpha ref} = I_{\alpha ref} Z_{th}$ and $V_{\beta ref} = I_{\beta ref} Z_{th}$. The error signal is given as input to weight updating algorithm.

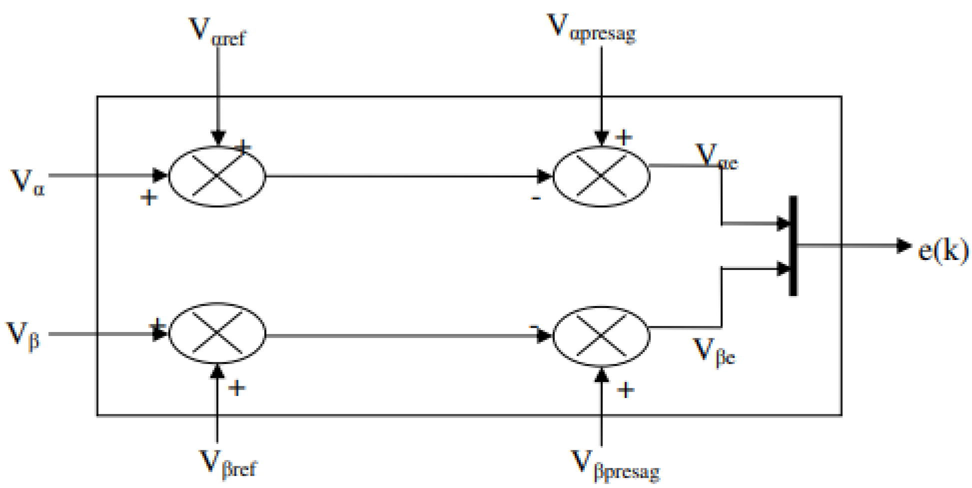

Figure7 Error generator

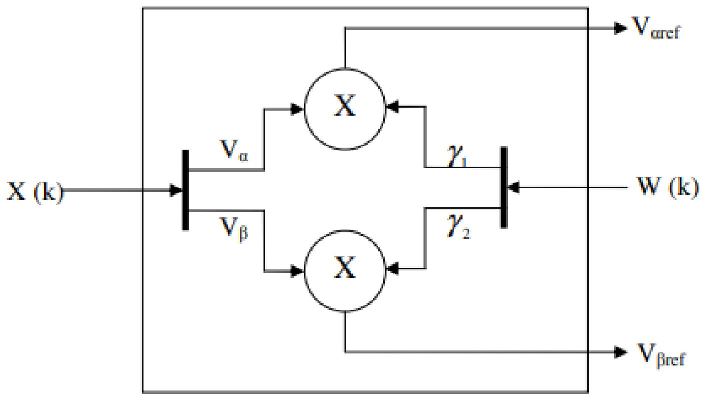

Figure 8 Two-Neuron models

5. Simulation of DVR Using Two Neuron Control Algorithms

Single line diagram of the test system for DVR is shown in Figure-9 and the test system employed to carry out the simulations for DVR is shown in Figure-10. Such system is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/15 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 15/11 kV.To verify the working of a DVR employed to avoid voltage sags during short-circuit, a fault is applied at point X via a resistance of 0.4 Ω. Such fault is applied for 100msec. The capacity of the dc storage device is 5 kV.

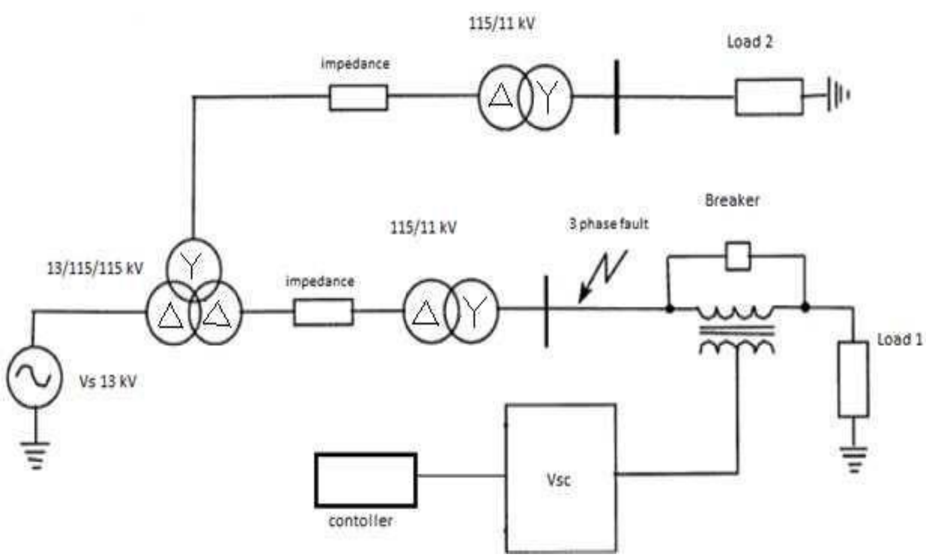

Figure-9. Single line diagram of the test system for DVR

Using the facilities available in MATLAB SIMULINK, the DVR is simulated to be in operation only for the duration of the fault, as it is expected to be the case in a practical situation. Power System Block set for use with Matlab/Simulink is based on state-variable analysis and employs either variable or fixed integration-step algorithms. Figure-11 shows the simulink model of DVR and Figure-8 shows the Simulink model of the test system for DVR.

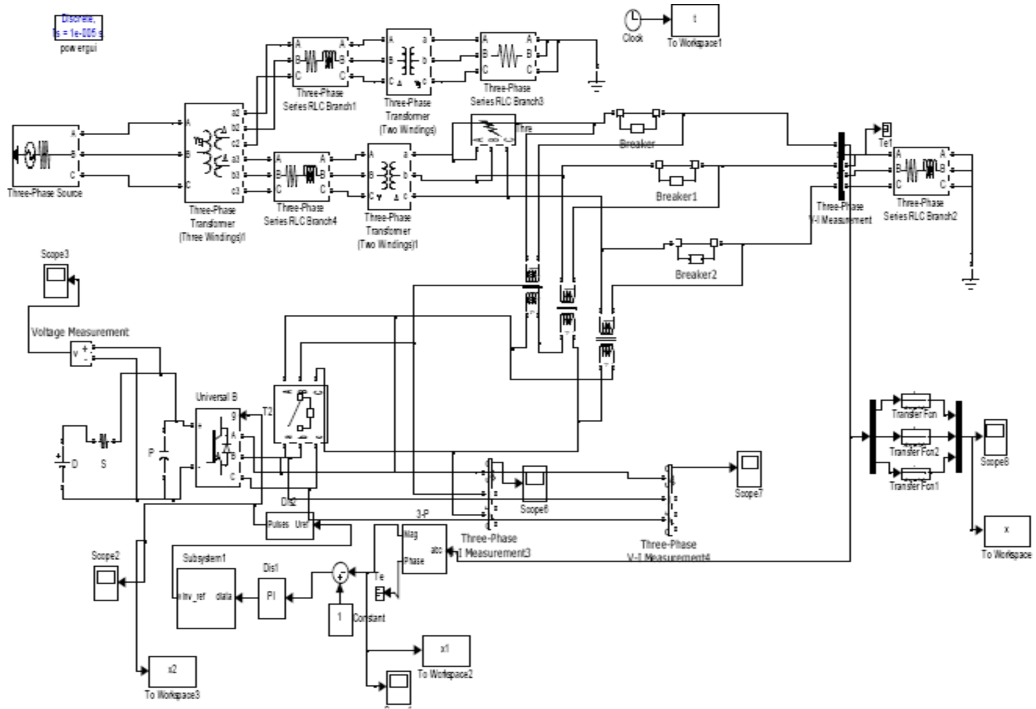

Figure-10. Simulink model of DVR test system for voltage sag

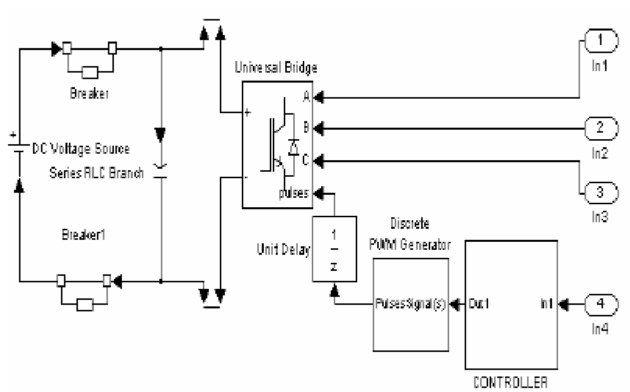

Figure 11. Simulink model of DVR.

The first simulation contains no DVR and a single line to ground fault is applied, via a fault resistance of 0.2 Ω, during the period 500–900 ms and the result is shown in figure-12. The voltage sag at the load point is 30% with respect to the reference voltage. The second simulation is carried out using the same scenario as above but now with the DVR in operation. The total simulation period is 1400 ms.

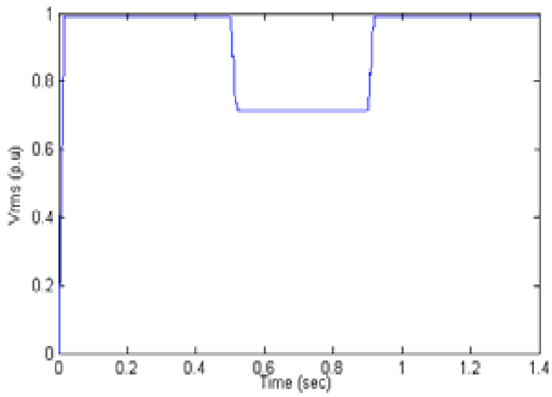

Figure 12 RMS Voltage without DVR

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-13.

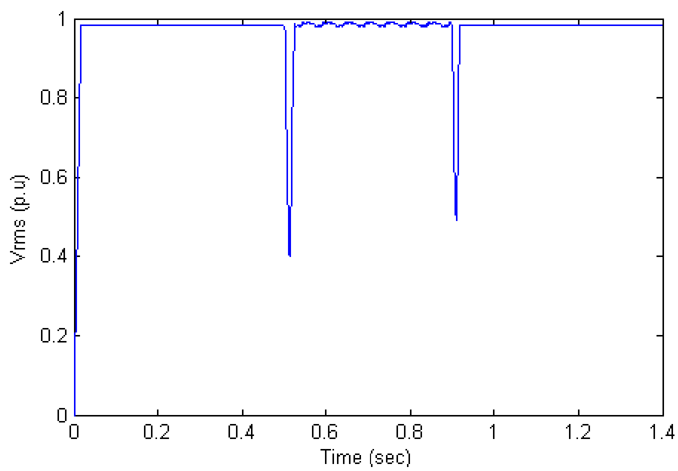

Figure 13 RMS Voltage with DVR

6. Simulation of D-STATCOM Using Two Neuron Control Algorithms

Figure-14 shows the test system used to carry out the various D-STATCOM simulations.

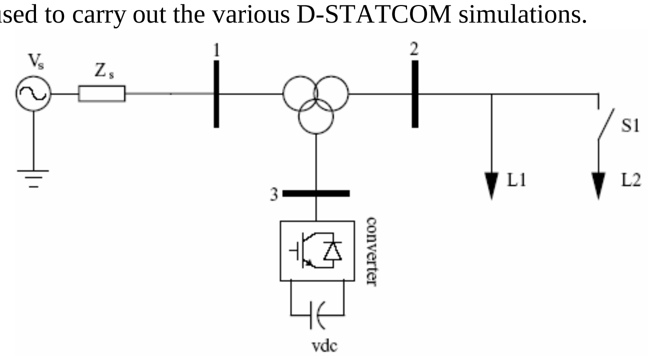

Figure-14. Single line diagram of the test system for D-STATCOM

Figure-15 shows the test system implemented in MATLAB SIMULINK. The test system comprises a 230kV, 50Hz 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 kVA 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. To show the effectiveness of this controller in providing continuous voltage regulation, simulations were carried out with and with no D-STATCOM connected to the system.

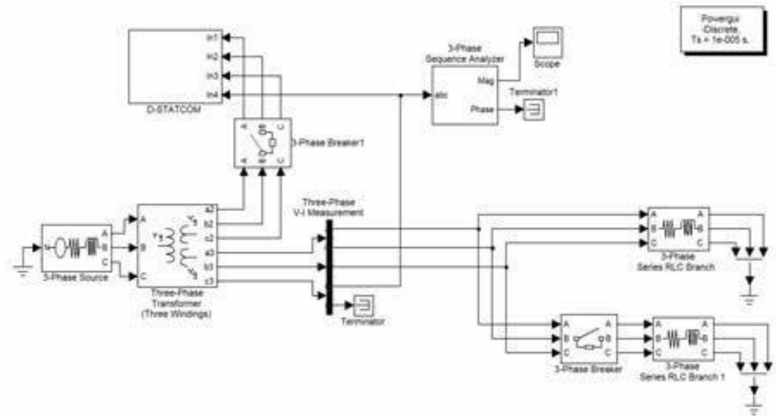

Figure-15. Simulink model of D-STATCOM test system

The D-STATCOM model which is incorporated in the transmission system for voltage regulation is asshown in Figure-16.

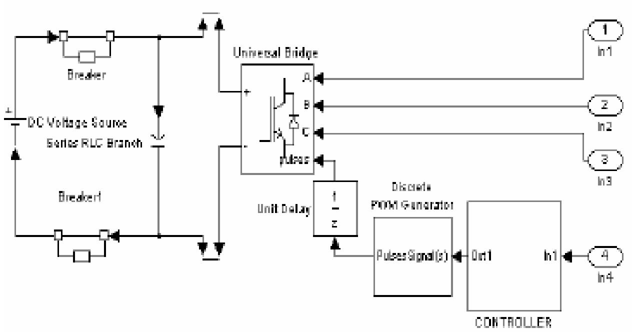

Figure-16. Simulink model of D-STATCOM

The first simulation contains no D-STATCOM and single line to ground fault is applied and result isshown in figure-17, via a fault resistance of 0.2 Ω, during the period 500–900 ms. the voltage sag at the load point is 45% with respect to the reference voltage.

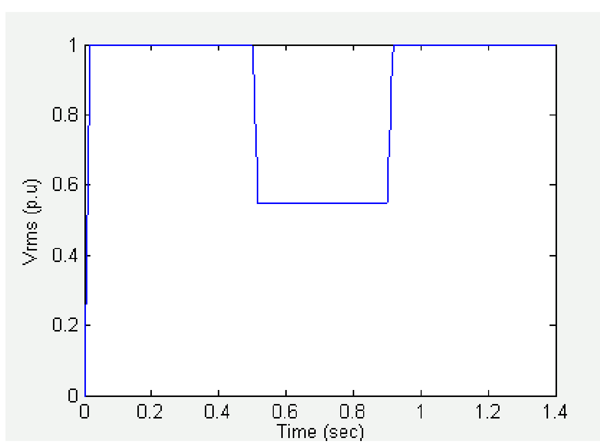

Figure 17 RMS Voltage without D-TATCOM

Similarly, a new set of simulations was carried out but now with the D-STATCOM connected to thesystem as shown in Figure-18 where the very effective voltage regulation provided by the D- STATCOM can be clearly appreciated.

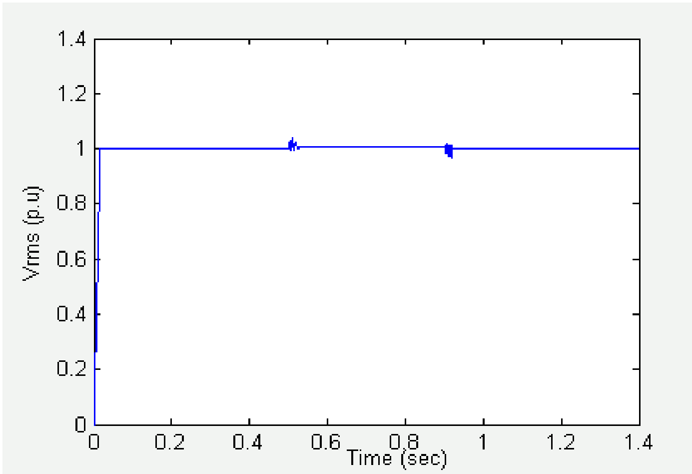

Figure 18 RMS Voltage with D-STATCOM

7. Conclusion

This paper has presented the power quality problem caused by voltage sag and mitigation techniques of custom power electronic devices DVR and D-STATCOM. The design and applications of DVR and D-STATCOM for voltage sags and comprehensive results are presented. A new two neuron control scheme has been implemented to control the electronic valves in the two-level VSC used in the D- STATCOM and DVR. As opposed to fundamental frequency switching schemes already available in the MATLAB/ SIMULINK, this control scheme only requires voltage measurements. This characteristic makes it ideally suitable for low-voltage custom power applications. The simulations carried out showed that the DVR provides relatively better voltage regulation capabilities. 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 capability of any device used to compensate long duration voltage sag mainly depends on the amount of energy stored within the device. This work has applied a new control algorithm for DVR and D-STATCOM in voltage sag mitigation which can minimize the dc link energy storage. Besides, a self-charging technique is used which maintains the dc capacitor voltage at the desired level. Simulation results proved the efficiency of the proposed method. The salient advantages of the proposed method are compensating long duration deeper voltage sags, reduction in size of dc-link capacitor and simplicity of algorithm. Thus this approach is a valuable contribution to the supply system in maintaining power quality.

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