D-STATCOM based Voltage Sag mitigation in Distribution Feeder under Balanced and Unbalanced Conditions

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Abstract: This paper presents an inclusive study and application of Distribution Static Compensator, D-STATCOM for mitigation of voltage sags in 11-kV Distribution Feeder under balanced, unbalanced and faulty conditions. Voltage sag is an acute power quality issue that generates series of problems for both utilities and consumers equally at the same time. D-STATCOM is a shunt connected technique that is employed to improve the voltages by counterbalancing the reactive power. The basic strategy behind use of D-STATCOM is that; this device dynamically injects a current of desired amplitude, frequency and phase into the line. The proposed technique generates a reference signal that is intended to be penetrated into system, at the point of common connection; PCC-in a way to reduce the voltage sags. This technique offers simple structure and less complex calculation. Through detailed Simulation results, it is found that D-STATCOM maintains required voltages against sags and any other distortion and unbalance in the system caused by external or internal phenomena.

Keywords: D-STATCOM, power quality, reactive power, VSC, PCC.

1. Introduction

Voltage sag is an important power quality problem that generates series of issues for utilities and consumers. These sags disturb all types of users i.e., industrial, commercial, and residential. They result in considerable power and manufacturing losses. These sags leave long lasting effects on certain loads. Voltage sags cause system devices either to fail, or shutdown, or create a large current unbalance that could blow circuit fuses. Voltage sags generate serious power quality issue for the electric power industry. Today, the users are more aware of the issues regarding power; this prompts utilities to assure good power quality to their users. Power quality is basically a term that refers to keep the magnitude of bus voltages and frequency at rated values [1]. It is ultimate goal of research to get energy model that should be clean and free from power distortions. For power quality, voltage sag is an acute issue that can be caused by faults in electrical system, switching of heavy loads and large induction motors [2]. Voltage sag is falling of RMS voltage or current from 0.1 to 0.9 pu at the power frequency durations from 0.5 cycles to 1 minute, IEEE 1159-1995.

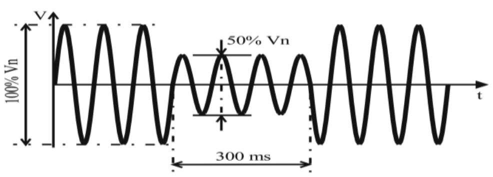

Fig. 1 Voltage Sag illustration

In the present power delivery environment, both end-users and network operators have become increasingly concerned about the power quality [3]. Because of an incredible increase in micro technology and power electronic appliances, the power system is highly relying on swing of the voltages and frequency supplied. Many industrial and commercial customers often have equipment that are sensitive to disturbance of voltage and current, and therefore, it is mandatory to understand the quality of supply being provided to them [4].
The interruption of an industrial process due to a voltage sag results in increased costs to the operation of industry. These costs comprise damaged product and reduced product quantity. The most important is reduced customer satisfaction. The voltage interruptions in medical facilities can cause unbearable loss. Voltage sags are noticed on transmission system, distribution system and on load side of Distribution Feeders. Voltage Sags are caused by Faults on the transmission or distribution network, Faults in consumer's installation, Connection of heavy loads and start-up of large motors. Sometimes, the lightning is causing voltage sags due to faults on overhead transmission and distribution lines during cloudy weather. Voltage sags can be improved by solving a series of important technical issues at source, receiver and transmission lines [5]. Capacitor banks, auto transformers and compensating devices like FACTS devices are used in this regard. The FACTS device such as Dynamic Voltage Restorer (DVR) [6], Unified Power Flow (UPFC) [7], STATCOM/SVCs [8] and others have been used for improving voltage sags since many decades in distribution networks. In this paper, the D-STATCOM is used for overcoming voltage sags. This is a

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very recent technology in power electronics.

H Lei (2017) [1/9]; studied the detection methodology of voltage sag in distribution network. He has not introduced the mitigating technique). L.E Weldemariam and V.Cuk (2017 [10] studied the effects of voltage sag in distribution system on customer side. Weldenmariam, L.E, (2017) [11]; has worked on Monitoring and regulation of voltage sag in the distribution network. Dung Vo Tien and Radomir Gono, (2017) [12]; have analyzed and simulated the voltage sags using EMPT. Lliu Ruihua and Wang Rong (2017) [13] presented the comprehensive evaluating method of power quality problem and their trend in latest energy generation system. Hadi Suyono, Lauhil Mahfudz Hayusman and Moch. Dhofir (2015) [14] have introduced the Dynamic Voltage Restore, DVR for improving voltage sag in distribution feeder. This is a series connected technique hence has more losses compared that of connected in shunt. FACTS devices that are connected in series, like TCSC and SSSC vary the line impedance to regulate the flow of power in the line. TCSC provides series reactance of variable capacitance for compensating power and SSSC changes the overall voltage drop in line, for power flow control. In both light and heavy load conditions, the SSSC is fruitful but drawback is that it contains harmonics content. P. Madhumathi, V. Lavanya, K. Thamaraiselvi, (2018) [15] have used Unified Power Flow Controller, UPFC as voltage sag mitigating technique. This technique is costlier hence finds rare applications. Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) interchange real power between parallel and series parts; these are connected in series with grid. These devices control multiple parameters like bus voltage magnitude, reactance of line and transmitting angle but the limitation is that UPFC is a costlier technique and is rarely used. On the other hand IPFC accompanies an additional parallel converter to supply active power from a desirable line. J.R. Lydia and M.Porkodi (2017) [16] have applied STATCOM for improvement of voltage sag through Artificial Neural Network Algorithm. Parallel connected FACTS devices like SVC and STATCOM counter balance the bus voltage magnitude by absorbing or generating reactive power. These devices regulate voltages within suggested limits hence the power flow is restricted. The limitation of STATCOM is that it will generate voltages if and only if its generated voltage dominates the grid voltage, otherwise it will draw reactive power from grid. This methnique bit complex in calculation and has no satisfactory results. Vijaya Bhaskar and T. Santhosh Kumar (2016) [17] made comparison among FACTS controller for enhancement of qower quality. Rupali D. Burungale and C. R. Lakade (2017) [18] introduced D-STATCOM for improvement voltage sag and swell mitigation. In this method the have used thyristor based D-STATCOM, which don't have sufficient speed against fault events. Norbert Edomah (2009), [19] studied the economic implications of voltage sags, swell on electrical system and on consumer equipments. K Swaroop Paul Kumar and M Mani Susanna, (2016) [20] have used DVR for improvement of voltage profile. Vima P. Mali and R. L. Chakrasali (2017) [21] have conducted a technical investigation for calculation of voltage sag**.** Harshita Batra, Kajol Sharma and Navneet Kumar (2017) [22] have studied the consequences of voltage sag and voltage unbalance on induction motor and drives. Shrikant Mali and Steffy James (2014) [23] have improved the improved the low voltage ride-through capabilities of distribution feeder. Kranthi Kiran Irinjila and Dr Jaya Laxmi Askani (2018) [24] have compared the performance of various FACTS controllers for transmission. Mahela and A. Shaik [25] have used D-STATCOM for quick control of voltage sag and flickers in distribution network. In this method D-STATCOM is used with VSI without battery storage system. G. Gupta and W. Fritz (2017) [26]; this paper elaborates the control strategies to improve dynamic capabilities of D-STATCOM for various applications. This presents stability of voltage by compensating reactive power, suppresses flicker noise and also regulates voltages. But the response of D-STATCOM is not matching with fault events. Gelu Gurguiatu [27] has introduced indirect current technique to get reference signal for Insulated Gate Bipolar Junction Transistor, IGBT. Switching speed of proposed technique is not too much high for IGBTs. Singh (2018) [28] have demonstrated the capability of DSTATCOM wherein design, analysis and comparison of the hysteresis as well as PWM current controllers are described and compared with PI controller and sliding mode controller. Design, implementation and performance of medium-size D-STATCOM for reactive power compensation are described by Cetin in [29]. SHEM (selective harmonic elimination method) is used for eliminating the VSC harmonics and reactive power control is achieved by phase shift angle control method.

2. Distribution Static Compensator, D-STATCOM

The D-STATCOM shown in figure 2, contains three main parts; Coupling transformer, Voltage Source Inverter (VSI), DC capacitor or battery. This is connected to feeder through coupling transformer at PCC. Distribution STATCOM or D-STATCOM is a parallel connected device. This is devised to regulate the voltages by counterbalancing the reactive power. The D-STATCOM is flexible compensator that can operate in both current and voltage control modes. This compensates voltage variation during current control mode and reactive power during voltage control mode [10]. The D-STATCOM generates compensating current corresponding to the reference signal obtained from extraction technique. The D-STATCOM will be connected to distribution network at the point of common connection (PCC) [11]. The D-STATCOM is also helpful in flicker suppression, voltage stabilization, power factor correction and harmonic control. Comparing with SVCs, the D-STATCOM has fast response time and compact design [30].

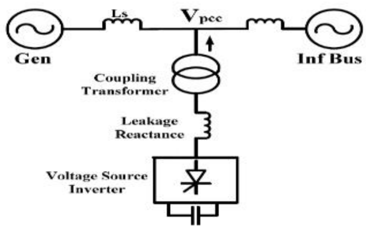


Fig. 2 Basic Structure of D-STATCOM

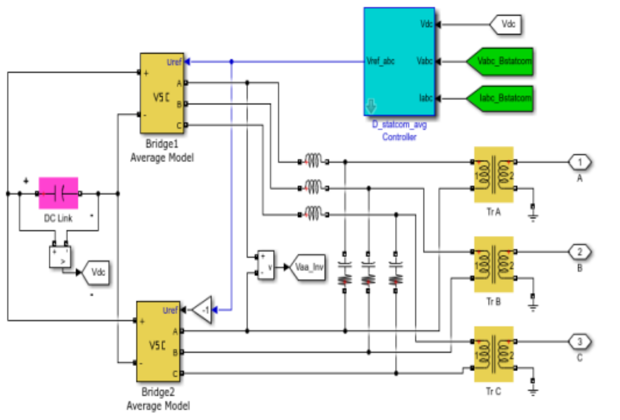


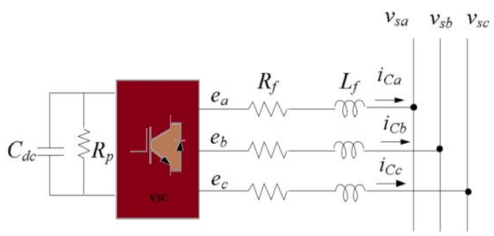
Fig. 3 Internal Structure of D-STATCOM

2.1 Working Principle of D-STATCOM

The working of D-STATCOM is quite simple and requires fewer calculations. D-STATCOM generates controlled ac voltages by voltage source inverter connected to dc battery. This work appears behind leakage reactance which generate reference signal with the help of PI Controller. This reactance causes interchange of active and reactive powers in the system. When voltages at PCC are lower than required voltages, the DSTATCOM generates capacitive reactive power and when the voltages are high, it generates inductive reactive power. All required values of voltages and current are pre-described into controller. The controller compares the generated values with actual values and acts accordingly. The controller performs close loop control with VSI.

2.2 Mathematical Modeling of DSTATCOM

In the fig. below, D-STATCOM equivalent circuit is connected to Distribution Network at PCC. The VSI based DSTATCOM is connected to distribution network via coupling transformer.



Here, e_a, e_b, e_c are output voltages of DSTATCOM,

I_a, i_b, i_c are output of DSTATCOM,

V_a, V_b, V_c are phase voltages at PCC,

R_f, L_f is reactance of interfacing inductor,

V_{dc}, I_{dc} are dc voltages and current of capacitor respectively,

C is capacitance of dc capacitor.

The relationship between phase voltages and battery voltages is given by,

$$v_a = \frac{1}{2} m_a V_{dc}, \qquad v_b = \frac{1}{2} m_b V_{dc}, \qquad v_c = \frac{1}{2} m_c V_{dc},$$

Here m_a, m_b, m_c are modulation signals of phase *a*, *b*, *c*.

The power consumed on battery side is,

$$P_{dc} = V_{dc} C_{dc} \frac{d}{dt} V_{dc} + \frac{Vdc^2}{R_{dc}}, \quad (1)$$

Here,

$$\frac{d}{dt} V_{dc} = -\frac{1}{R_{dc} C_{dc}} V_{dc} + \frac{3}{2C_{dc}} M_d I_d, \quad (2)$$

$$\frac{d}{dt} I_d = -\frac{R}{L} I_d + \omega I_q - \frac{1}{2L} M_d V_{dc} + \frac{1}{L} E_d \quad (3)$$

$$\frac{d}{dt} I_q = -\omega I_d - \frac{R}{L} I_q - \frac{1}{2L} M_q V_{dc}, \quad (4)$$

Here V_{dc}, I_d, and I_q are system variables, M_d, and M_q are the inputs, and V_{dc} and I_q are outputs, and E_d is a constant.

Now, the power delivered to system from DSTATCOM is,

$$P_{ac} = \frac{3}{2} E_d I_d, \quad (5)$$

The net voltages injected by DSTATCOM at PCC is

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix},$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = (R_s + sL_s) \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \quad (6)$$

Here,

$$s = \frac{d}{dt}, R_s = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}, L_s = \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix}$$

The above matrices of voltages and currents can be expressed to d-q reference form as,

$$\begin{bmatrix} e_d - v_d \\ e_q - v_q \\ e_0 - v_0 \end{bmatrix} = K_s \begin{bmatrix} e_a - v_a \\ e_b - v_b \\ e_c - v_c \end{bmatrix}, \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = K_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \quad (7)$$

Here, K_s is Park's transformation and is expressed as,

$$K_s = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (8)$$

When there is no neutral in the system, there will be no zero sequence components, hence above matrices are expressed as,

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} - \begin{bmatrix} v_d \\ v_q \end{bmatrix} = (R_s + sL_s)\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\omega & 0 \\ 0 & \omega \end{bmatrix} L'_s \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

Here,

$$R_s = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}, Ls' = \begin{bmatrix} Ls' & 0 \\ 0 & Ls' \end{bmatrix} = \begin{bmatrix} L_s - M & 0 \\ 0 & L_s - M \end{bmatrix}$$

2.3 D-STATCOM Control Strategy

Figure 3, represents the simplified sketch of D-STATCOM control. The D-STATCOM is connected to system at that place, where, the quality of voltages is concerned. All required values of voltages, current and frequency are pre-set into controller to compare actual and required values.

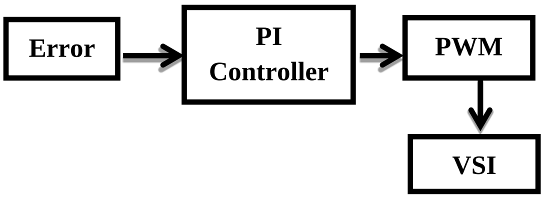


Fig. 4 Control Scheme of D-STATCOM

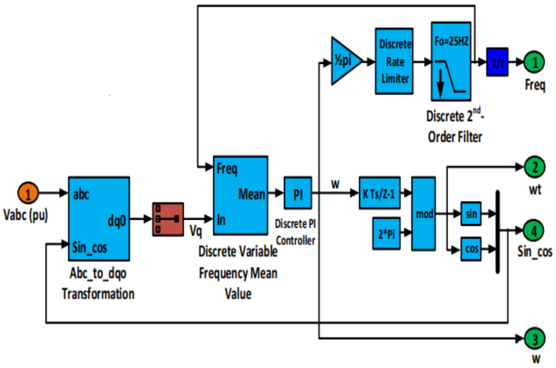


Fig. 5 Interior of Control Scheme

The error signal, which is actually a difference of required value and calculated value at PCC is regulated through PI controller to get reference signal. These reference signals/values are compared with triangular wave to generate PWM signal. Then this PWM signal is derived into VSI to generate signal of required frequency.

3. Results and Discussions

In this research, the performance of VSC based D-STATCOM working as voltage regulator is thoroughly examined using MATLAB software. The proposed model is shown in fig.5. The complete configuration of test model is detailed in table.1. In this work, three phase-three wires system is assumed. This paper shows that D-STATCOM is working safe in the distribution network and removes voltage sags developed under abnormal conditions. The performance results of DSTATCOM are divided into two sections; Sect-1 and Sect-2. Section-1 shows the behavior of DSTATCOM during balanced condition and Section-2 shows behavior during unbalance and fault conditions.

Table.1 configuration of proposed system

Source	11kV, 50Hz
Feeder	11kV, 3-phase 3-wire,12km length, 50Hz
Transformer	11kV / 440V, 50Hz, Delta-Star (with secondary grounded)
Load-1	1MW, 0.5 kVAR, 50Hz
Load-2	1MW, 0.5 kVAR, 50Hz
Breaker-1	Switching times 0.1sec, 0.2 sec
Breaker-2	Switching times 0.1sec, 0.2 sec
D-STATCOM	11kV, 50 Hz, +/- 3VAR Average model

Section-1 (Balanced load condition)

The section-1 is categorized into two cases. Case-I shows performance of system without D-STATCOM during and case-II shows performance of system with DSTATCOM during variable load.

Case-I, without D-STATCOM

In this model, D-STATCOM is electrically disconnected from system.

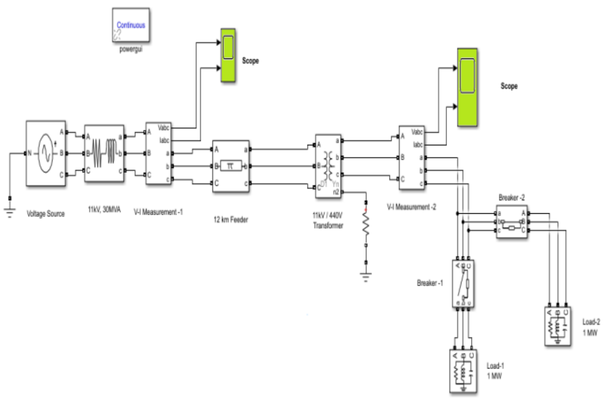


Fig. 6 Model without D-STATCOM

Figure 6, shows the response of Distribution Feeder with a dynamic induction load of 2MW. Initially there is a fixed load of 1MW connected to the Feeder via Circuit Breaker-2. After 0.1 second the circuit breaker-1 is closed and switching on extra 1MW load on the system. Hence the load voltages are decreased, creating voltage sag for 5 cycles. This simulation is shown in Figure above and results are shown in Figure 7.

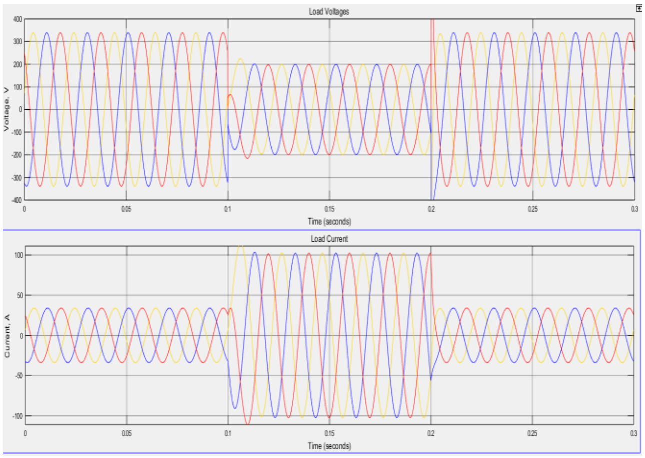


Fig. 7 Simulation Results without D-STATCOM

Fig 7, clearly elaborates that there is reduction in load voltages due to switching of extra 1MW for the period of 0.1 second (5 cycles) through Circuit Breaker-1. Correspondingly, there is swelling in current due to decrease in voltage during above mentioned period.

Case-II, with D-STATCOM

In this model, D-STATCOM is electrically connected to system at PCC.

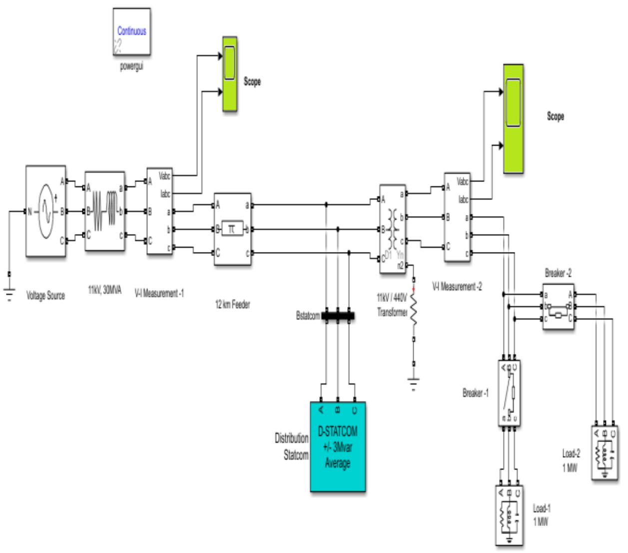


Fig. 8 Model with D-STATCOM

Figure 8, shows the response of ac Distribution Feeder with a dynamic induction load of 2MW with D-STATCOM. The simulation results are shown in figure below.

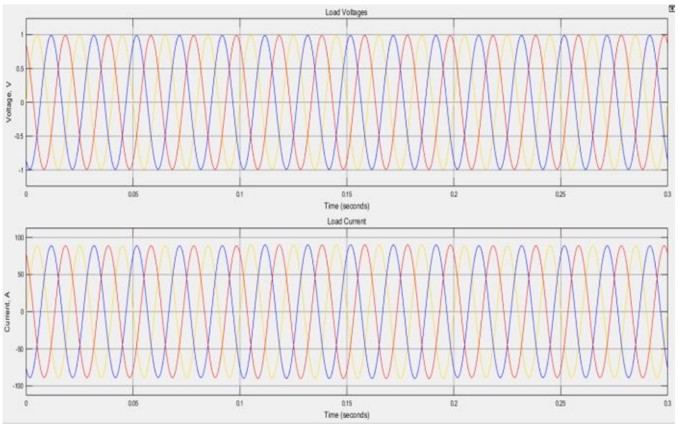


Fig. 9 Simulation Results with D-STATCOM

The performance analysis of a D-STATCOM in mitigating voltage sag is demonstrated using MATLAB Simulation. The modeling and simulation results of both cases with and without D-STATCOM are described in detail. During ordinary conditions, D-STATCOM continues to regulate the load voltages without contributing. When there is a power quality problem like voltage sag that is created by load switching in this study, the D-STATCOM operates its control panel and acts accordingly. Fig. 7 and Fig. 9 clearly differentiate the role of D-STATCOM.

Section-2 (Unbalance load condition)

Case-I

Model with fault

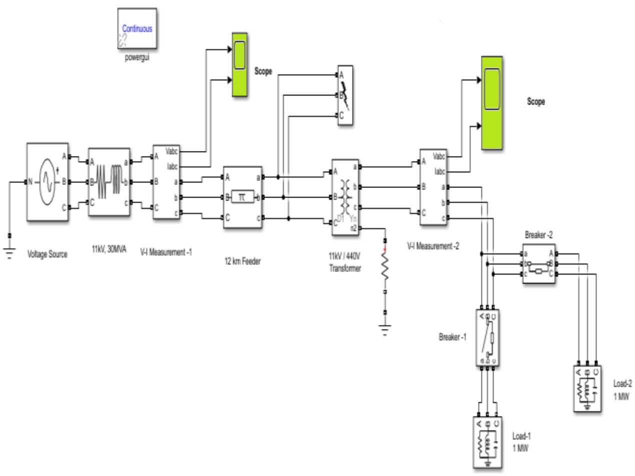


Fig. 10 Model with three phase fault

In this model a three phase fault is applied at PCC with fault resistance of 0.1 ohm. The duration of fault is set as 0.1 to 0.2 second. The corresponding results are depicted in figure below.

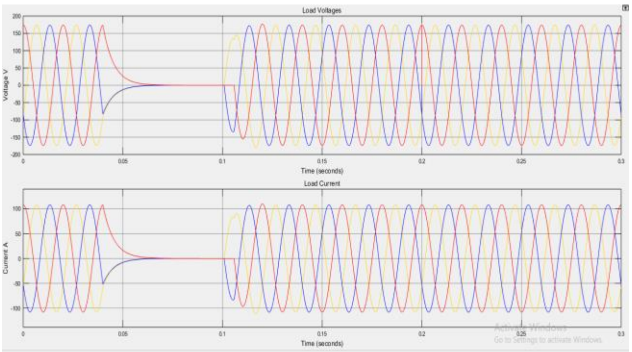


Fig. 11 Simulation results with symmetrical fault

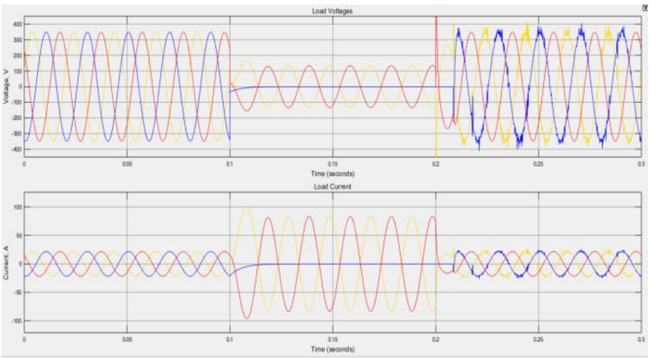


Fig. 12 Simulation results with asymmetrical fault

Case-II Model with fault and DSTATCOM

In this model, DSTATCOM is connected to system with fault. The corresponding results are given in below fig.

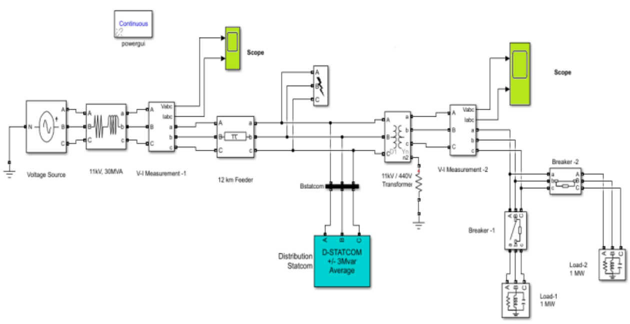


Fig. 13 Model with fault and DSTATCOM

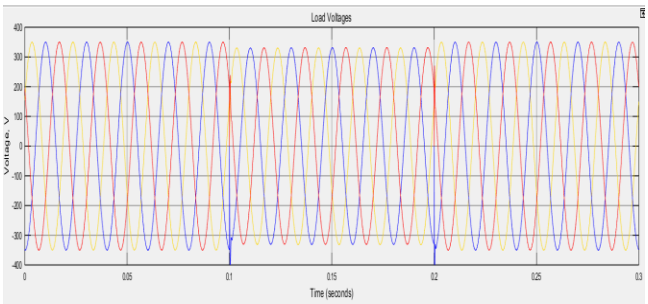


Fig. 14 Simulation results of Model with fault and DSTATCOM

The fig.12 clearly elaborates the performance of DSTATCOM during service. It has regulated the terminal voltages at considerable level. DSTATCOM has recovered 91% sag voltages.

4. Conclusion

This research work presents performance and application of D-STATCOM in distribution Networks. The performance of DSTATCOM is thoroughly investigated during different power quality issues. The D-STATCOM regulated the voltages at PCC using instantaneous PQ theory. In Section-1, it regulated the voltages near to required terminal voltages. In Section-2, it regulated the voltages from 0 to considerable level of 97% of rated voltages. Control strategy of D-STATCOM is quite simple and requires less calculation. PWM control just requires the measurement of voltages. This characteristic makes it ideally suitable for low-voltage systems and applications. The response of D-STATCOM is thoroughly examined under severe cases and it is found that D-STATCOM is robust in each case. D-STATCOM is similar to STATCOM in concept, but its control strategy makes it suitable for power quality improvement in low voltage level. Beside voltage sag mitigation, D-STATCOM is found beneficial for correction of other quality issues as well, like reactive power unbalance, low power factor and elimination of harmonics. This makes D-STATCOM superior to other custom power devices.

5. Future recommendation

The transient response of D-STATCOM is bit complex when connected to grid. So the transient stability of D-STATCOM may be the future work.

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