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Voltage Sag Mitigation by D-STATCOM Using Voltage Regulation Technique

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***Abstract*— This paper illustrates modeling and simulation of DSTATCOM in compensating voltage sag problem in distribution sector. The method is based upon d-q reference frame. The term power quality is used to describe as the quality of power that is given as input to various electrical load and ability of load to function properly. Without proper power the devices may misoperate or fail. There are many ways in which electric power can be poor quality and many more causes for such poor quality. Among the various power quality problems, voltage sag is most common problem. This paper demonstrates power quality, various causes and effects of voltage sag and its compensating techniques. Since DSTATCOM is a flexible, dynamic load compensation and easy implementing device, it is used as the compensation device in this paper. The test model of 33kV, 50 Hz, the D-STATCOM with inverter and its controller has been designed in Simulink of MATLAB version 7.10.0.499 (R2010a).**

Keywords*— Power Quality, Voltage Sag, D-STATCOM, Custom Power Devices, Simulink.

I. INTRODUCTION

Power quality issues, causes, effects and analysis has become an important aspect of research work in recent days. As the power is generated in power stations which are generally far away from load centers, the huge amount of power generated from a generating station is transported to the consumer through transmission lines. The transmission of power from the generating point to the point of consumption is combined with variations of weather, variations in loads, variations in demands etc. which compromises the quality of power.

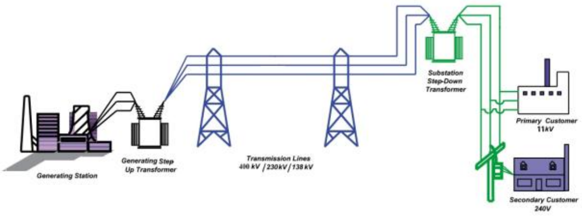

Fig.1. Typical Power System

Industrial and commercial consumers of electrical power are becoming increasingly sensitive to power quality problems [1]. Reliability and quality are two important parameters in the field of power engineering. Combining today's utility power with the ever increasing quantity of electrical sensitive load yields one of the major contributors to downtime in business and industries today. Issues of deregulation, standards and customer awareness (economics and legal) have brought forth a great deal of focus and motivation in these areas. Tremendous dedication from engineers as well as huge amounts of revenue has been spent to enhance the quality and reliability of electricity delivery.

Power quality problem is described as the deviation in voltage, current and frequency from its nominal value in a power system [2]. Various power quality problems such as voltage sag, swell, fluctuation, harmonic distortion, unbalance and transient may have impact on customer devices which will cause malfunctions and loss of production [1].

Out of all the power quality problems voltage sag is the most common disturbance that is faced by a consumer. These problems are arose by many equipment operations, equipment failure or faults. Several compensation devices are used to mitigate this problem, out of which D-STATCOM gives better performance in voltage sag mitigation.

II. PROBLEM IN POWER QUALITY, CAUSES AND EFFECTS

According to Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as "*The concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment*".

In the past the term reliability and quality was same as because there were no power electronic equipments and all the equipments were linear in nature. All the equipments were heating, lighting and motors, which were not very sensitive to voltage variation.

In the last few decade power quality has become an important issue since many equipments are semiconductor based and controlling is done with power electronic equipments.

A. Causes of Power Quality Problem

Some common disturbances which may cause power quality problems are listed below:

- Lightning and natural phenomena,
- Formation of snow on transmission line, storm etc.
- Energization of capacitor banks and transformers,
- Switching or start-up of large loads e.g. Induction motors,

- Operation of non-linear and unbalanced loads,
- Failure of equipment, e.g. transformers and cables,
- Wrong maneuvers in distribution substations and plants.

The main cause of power quality problem is the short circuit fault occurring in the distribution side. This short circuit can cause a huge increase in the system current and consequently a large voltage drop in the impedance of the supply system [3].

In systems where overhead lines are predominant, natural phenomena are responsible for the majority of faults in transmission and distribution systems, especially lightning [4, 5]. In principle, a lightning stroke is a transient increase in the voltage along the line. However, an arc is created between the phase hit by the stroke and ground and consequently the voltage is depressed to zero.

When unbalanced loading is done on a system it causes an unbalance voltage in the phases, which ultimately creates power quality problem. This unbalance voltage increases rotor heating due to negative sequence magnetic flux generated in the stator winding.

B. *Effects of Power Quality Problem*

Poor electric power quality has many harmful effects on power system devices and consumer goods. These effects are so dangerous that it is not visible until failure occurs in the equipments. Even if there is no occurrence of failure of the equipment, there will be losses and heating in the equipment which will ultimately reduce the life span of the equipment.

- When harmonics are added to the supply voltage equipment could receive high value of instantaneous voltage and may be susceptible to failure. This high voltage may also force electronic components of power system to operate in the saturation, producing additional harmonics and disturbances.

- The effects of poor power quality on capacitors, rotating machines, cables and transformers, fuses, and customers' equipment creates heating, noise, poor performance etc.

- Premature failure of distribution transformer due to heating can be caused by harmonics.

- Due to power quality problem there is huge power loss in the transformer, motors and transmission lines, specifically due to harmonics (e.g., inter and sub-harmonics) [6].

- Due to sudden rise in voltage and/or current, failure of power system components and customer loads can occur.

III. VOLTAGE SAG

In the past, equipment used to control industrial process was mechanical in nature, which was rather tolerant of voltage disturbances. But nowadays most of the equipments are electronic controlled such as PLC, automatic speed drive which requires a pure supply voltage without any ripple or disturbance. Typical disturbances that cause problems for electronic equipment are voltage sags [7].

Voltage sag is defined as a sudden drop in the root mean square (r.m.s.) voltage and is usually characterized by the remaining (retained) voltage. Voltage sag is thus, short duration reduction in r.m.s. voltage, caused mainly by short circuits, starting of large motors and equipment failures.

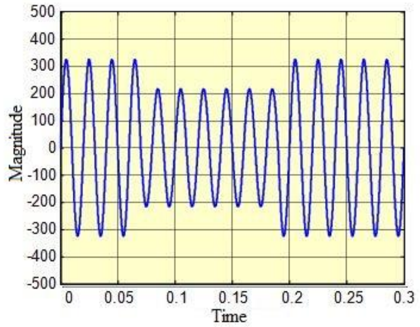

Fig. 2. Voltage Sag

According to IEEE Std. 1159 (1995), sag magnitudes range from 10% to 90% of nominal voltage and sag durations from half- cycle to 1 minute. Furthermore, sags may be classified by their duration as shown in Table-1.

TABLE I. Classification of voltage sag according to IEEE

Type of Sag	**Duration**	**Magnitude**
Instantaneous	0.5 – 30 cycles	0.1 – 0.9 p.u.
Momentary	30 cycles – 3 secs	0.1 – 0.9 p.u.
Temporary	3 secs – 1 min	0.1 – 0.9 p.u.

Voltage sags are the most common power disturbance whose effect is quite severe especially in industrial and large commercial customers such as the damage of the sensitivity equipments and loss of daily productions and finances. The examples of the sensitive equipments are Programmable Logic Controller (PLC), Adjustable Speed Drive (ASD) and Chiller control. Voltage sag at the equipment terminal can be due to a short circuit fault hundreds of kilo meters away in the transmission system.

A. *Causes of Voltage Sag*

There are various causes for which sag is created in system voltage:

1. Closing and Opening of Circuit Breakers: When the circuit breaker of a phase is opened suddenly, then the line which it is feeding will be temporarily disconnected. The other feeder lines from the same substation system will act as a voltage sag.

2. Due to Fault: Voltage sag due to fault can be critical to the operation of a power plant. The magnitude of voltage sag can be equal in each phase or unequal respectively and it depends on the nature of the fault whether it is symmetrical or unsymmetrical.

3. Due to Motor Starting: Voltage sag due to motor starting are symmetrical since the induction motors are balanced three phase loads, this will draw approximately the same high starting current in all the phases.

4. Due to Transformer Energizing: There are mainly two causes of voltage sag due to transformer energizing. One is normal system operations which include manual energizing

of a transformer and another is the reclosing actions. These voltage sags are unsymmetrical in nature.

5. Equipment Failure: Failure of electrical equipment occurs due to insulation breakdown or heating or short circuit etc.

6. Bad Weather: Lightning strikes in the power line cause a significant number of voltage sags. A line to ground fault occurs when lightning strikes the line and continues to ground.

7. Pollution: Flash over takes place when there is storm in the coastal regions, where the power line is covered with salt. This salt formation acts as a good conductor of electricity and faults occur.

8. Construction Activity: Generally all power lines are undergrounded in urban areas, digging for doing foundation work of buildings can cause damage to underground cables and create voltage sags.

IV. STATCOM AND ITS WORKING PRINCIPLE

The STATCOM is basically a shunt connected FACTS controller whose capacitive or inductive output current can be controlled independent of the ac system voltage. The STATCOM that is used at the distribution level is known as Distribution STATCOM (DSTATCOM).

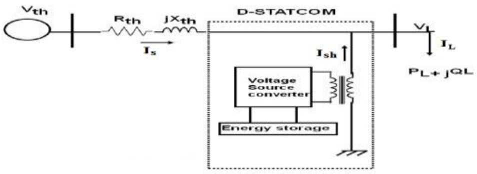

Fig.3. STATCOM working principle

STATCOM is known as shunt voltage controller consists of voltage source converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the network and associated control circuit [8, 9] as shown in the Fig. 3.

The value of the injected shunt current I_{sh} can be written as:

$$I_{sh} = I_L - I_s$$

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

The D-STATCOM's complex power injection can be expressed as:

$$S_{sh} = V_L I_{sh}^{*}$$

A. *Principle of Voltage Regulation*

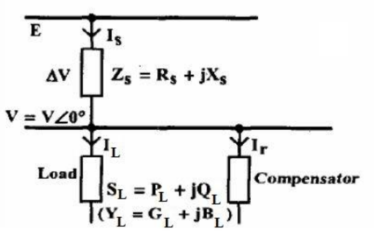

Fig. 4. Circuit for demonstrating the voltage regulation principle

1) Voltage Regulation without DSTATCOM:

A simple circuit as shown in Fig 4 consisting of a source voltage E, voltage at Point of Common Coupling (PCC) is V and a load drawing the current I_L. Without a voltage compensator [10], the PCC voltage drop caused by the load current I_L, shown in fig as ΔV,

$$\Delta V = E - V = Z_s * I_l,$$

$$S = VI^{*} \quad ,so \quad S^{*} = V^{*}I$$

from the above equations,

$$I_l = \frac{P_l - j*Q_l}{V}$$

so that,

$$\Delta V = (R_s + jX_s)(\frac{P_l - jQ_l}{V})$$

$$= \frac{(R_sP_l - X_sQ_l)}{V} + j\frac{(X_sP_l + R_sQ_l)}{V}$$

$$= \Delta V_r + \Delta V_x$$

The voltage change has a component ΔV_r in phase with V and component ΔV_x, which is explained in Fig 5. It can be seen that both magnitude and the phase of V, are functions of the magnitude and phase of the load current. The voltage drop depends upon active and reactive power of load. The component ΔV is rewritten as,

$$\Delta V = I_sR_s + jI_sX_s$$

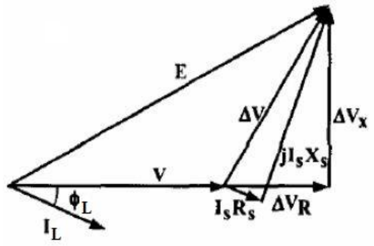

Fig. 5. Phasor diagram for uncompensated system

2) Voltage regulation with DSTATCOM:

Considering a compensator connected to the system which is shown in Fig. 4. Fig. 6 shows vector diagram with voltage compensation. By connecting a shunt compensator i.e. DSTATCOM, it is possible to make the voltage |E| equal to PCC voltage |V| by controlling I_S

$$I_S = I_R + I_L$$

where, I_R is the compensating current.

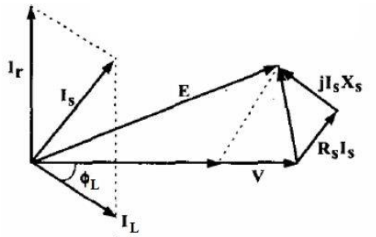

Fig. 6. Phasor diagram for voltage regulation with compensation

B. *Advantages of STATCOM*

1. Out of all FACTS devices, the STATCOM has the potential to be exceptionally reliable with the capability to supply reactive current.
2. Quicker response time (a STATCOM has a response time of 8ms- 30ms). This helps with compensation of negative current & reduce voltage flicker.
3. Active power control is possible with STATCOM with optimal storage of energy on DC circuit. This will further help with system stability control.
4. STATCOM requires a smaller installation space due to use of capacitor to generate MVAR, minimal or no filtering & the availability of high capacity power semiconductor devices.
5. The STATCOM is a shunt connected reactive power compensation equipment, which is capable of generating and/ or absorbing reactive power whose output can be controlled using some parameters.

C. *Park's Transformation and D-STATCOM Modeling*

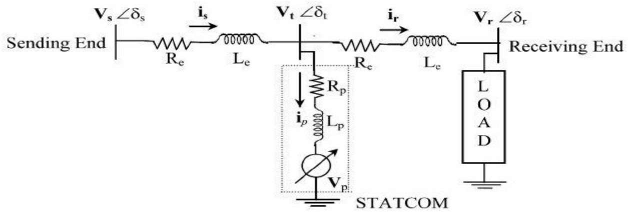

Fig. 7. Equivalent circuit of system with DSTATCOM

From the equivalent circuit the dynamic equations governing the instantaneous values of the three-phase voltages across the two sides of DSTATCOM [11] and the current flowing into it are given by:

$$\left(R_p + L_p \frac{d}{dt}\right) i_p = V_t - V_p$$

where,

$$i_p = (i_a \quad i_b \quad i_c)^T ,$$

$$V_t = (V_{ta} \quad V_{tb} \quad V_{tc})^T \qquad and \qquad V_p = (V_{pa} \quad V_{pb} \quad V_{pc})^T .$$

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

This is known as Park's Transformation. And after transforming to d-q-0 axis the equations in two phases are given by,

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = T \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Thus the dynamic equations after transformations are,

$$\frac{di_{pd}}{dt} = -\frac{R_p}{L_p} i_{pd} + \omega i_{pq} + \frac{1}{L_p}(V_{td} - V_{pd}) \qquad \text{-----------------(1)}$$

and,

$$\frac{di_{pq}}{dt} = -\frac{R_p}{L_p} i_{pq} - \omega i_{pd} + \frac{1}{L_p}(V_{tq} - V_{pq}) \qquad \text{------------(2),}$$

where, $\omega = (d\theta/dt)$, is the angular frequency of the source voltage.

The equation (1) and (2) together describe the dynamic model of DSTATCOM. The voltage regulation control strategy for DSTATCOM is concerned with the control of ac-bus and dc-bus voltage on both sides of DSTATCOM. The dual control objectives are met by generating appropriate current reference (for d and q axis) and then by regulating these currents in the DSTATCOM. Attempting to decouple the d-axis and q-axis current regulators, PI controllers are conventionally employed.

In this project work the voltage controller technique [12] (also called as decouple technique) is used as the control technique for DSTATCOM. The method is already discussed in the previous topic. This control strategy uses the d-q-0 rotating reference frame because it offers higher accuracy than stationary frame-based techniques [13]**.** In this V_{abc} is the three-phase terminal voltages, I_{abc} is the three-phase currents injected by the DSTATCOM into the network, V_{rms} is the root-mean-square (rms) voltage, V_{dc} is the dc voltage of the capacitor. This controller uses a phase-locked loop (PLL) to synchronize the three phase voltages at the converter output with the zero crossings of the fundamental component of the phase-A terminal voltage.

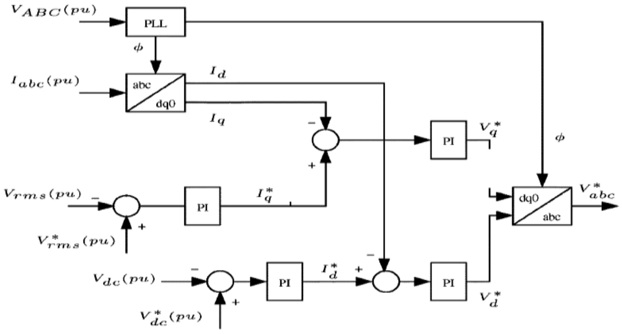

Fig. 8. Controlling Technique

The block diagram of a proposed control technique is shown in Fig. 8. Therefore, the PLL provides the angle φ to the abc-to-dq0 (and dq0-to-abc) transformation which helps in synchronism. There are four PI controllers used:

1st PI controller- It responsible for controlling the terminal voltage through the reactive power exchange with the ac network. This controller provides the reactive current reference I_q^*.

2nd PI controller- responsible for keeping the dc voltage constant through a small active power exchange with the ac network.

3rd and 4th PI controller- determine voltage reference V_d^*, and V_q^*, which are sent to the PWM signal generator of the converter, after a dq0-to-abc transformation. After that V_{abc}^*

are the three-phase voltages sent to the PWM generator and finally modulation is done with a triangular reference wave. This modulated signals are provided to the six gate terminal of the IGBT's.
The controller used in the simulation is shown in Fig. 9.

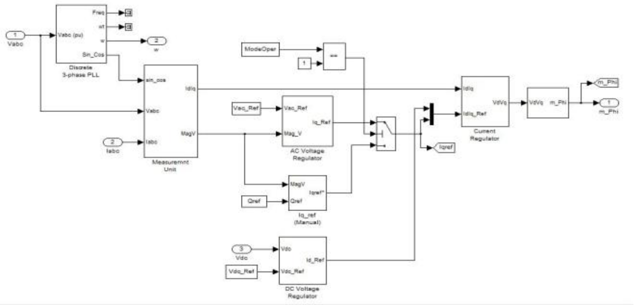

Fig. 9. Controller used in MATLAB Simulink

V. SIMULATION AND TEST RESULT

The model consists of an AC source, source bus, feeder line, distribution transformer, a load bus, a constant load, a variable load (RL). And a D-STATCOM connected to the system through a D-STATCOM bus and a transformer. The single line diagram of the test system is shown in Fig. 10.

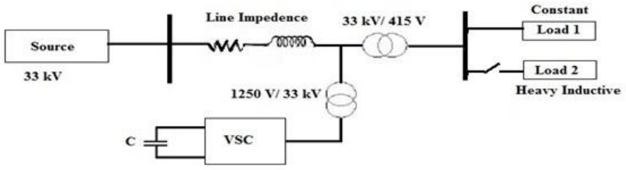

Fig. 10. Single Line Diagram of the Test System

The specification of the test system is shown in Table II.

TABLE II. Specification of Test system

Source	33kVrms, 50 Hz, Y- grounded
Source Impedance	0.8929Ω , 16.58 mH
Feeder Line	25KM
Distribution Transformer	6MVA, 33kV/415V, 50 Hz, Δ-Y connected
Constant Load	415V, 50 Hz, 8.5MW
Heavy Inductive Load	415V, 50 Hz, 1MW, 4MVAR
3-Φ Circuit Breaker Timings	0.1seconds to 0.2seconds and 0.3seconds to 0.4seconds

A. *Simulation Model*

3-φ voltage sag is created by connecting a heavy inductive load of 415 Vr.m.s, 1 MW and 4MVAR. The connection of the inductive load is done by connecting it through a breaker for a period of 0.1 second - 0.2 seconds and 0.3 seconds - 0.4 seconds. The simulation is run for 0.5 seconds. MATLAB model of a test system compensating voltage sag is shown below.

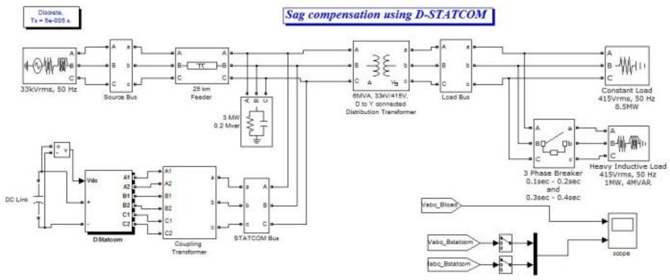

Fig. 11. Model compensating voltage sag using DSTATCOM

B. *Simulated Results*

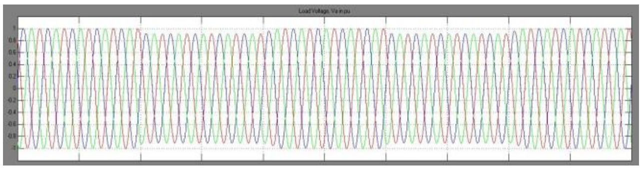

Fig. 12. Voltage sag created by switching heavy inductive load

It is clear from the above wave shape that the phase to phase voltage where inductive load is connected is dipping during this duration in the uncompensated system. The sag during this period is found out to be 0.91 pu.

Now a DSTATCOM is connected in parallel to the system at 33 kV line. Results show that it can compensate the dipped voltage.

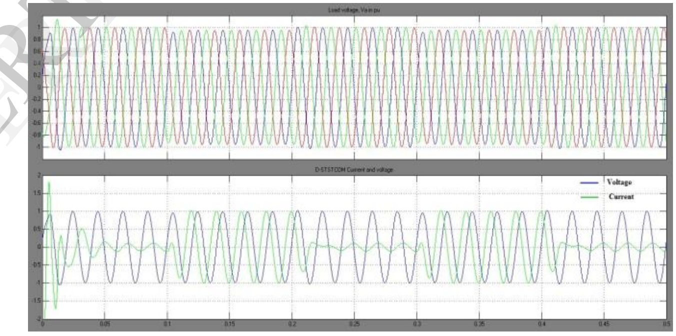

Fig. 13. Sag compensation using DSTATCOM

It is clear from the above wave shape that the voltage in phase where sag has been occurred was eliminated after compensating it with D-STATCOM. The remaining sag after compensation is found out to be 0.95 pu. The 2nd graph shows the DSTATCOM's voltage and current. The green colored wave shows that during heavy inductive loading, DSTATCOM provides a capacitive current to compensate the dipping voltage.

VI. CONCLUSION

It has been discussed that voltage sag problem Is very common and can create problem for consumer good and industrial application. So a DSTATCOM has been modeled using voltage regulation technique and it is found to be good in compensating voltage sag condition. The DSTATCOM can compensate the voltage from 0.91 pu to 0.95 pu for a 33 kV, 50 Hz line.

VII. ACKNOWLEDGMENT

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