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d-q approach in Mitigating Voltage Sag, Swell and Fluctuation using D-STATCOM

Manish Paul
Assistant Professor, Electrical Engineering Department
Girijananda Chowdhury Institute of Management and Technology

Mahua Chanda
PG Scholar, Electrical Engineering Department
National Institute of Technology, Agartala
Tripura, India

***Abstract*— This paper illustrates the modeling of D-STATCOM based on d-q-0 reference frame in compensating voltage sag, swell and fluctuation. Among the various PQ problem, voltage sag, voltage swell and voltage fluctuations are the most important power quality problems faced by many industries and utilities. They contribute more than 80% of power quality problems that exist in power systems.**

This paper work is based upon estimation and mitigation of voltage sag, voltage swell and voltage fluctuation using one of the Custom Power Devices that is D-STATCOM. Since, a D-STATCOM is known for its flexibleness, easy implementation, dynamic load compensation & multifunctional operation, it is chosen to be compensating device in this project work.

The model of DSTATCOM connected in shunt configuration to a 3-φ source feeding a constant and a variable load, which is developed using Simulink of MATLAB version 7.10.0.499 (R2010a). Simulated result demonstrates that DSTATCOM can be considered as a viable solution for solving voltage sag, swell and fluctuation problems.

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

I. INTRODUCTION

Our electrical power industry mainly consist of electrical generation, transmission and distribution to the customer or consumer. The transfer of electric energy from the point of production to the point of consumption is combined with variations in weather, generation, demand and other factors including faults and heavy loading which is very complex. Industrial and commercial consumers of electrical power are becoming increasingly sensitive to power quality problems [1].

Power quality has become a very important issue recently due to the impact on electricity suppliers, equipment manufacturers and customers [1]. Due to the advent of sensitive equipment based on semiconductor devices, the quality of power has become an important factor for smooth operation of the equipment. 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 these, momentary voltage sag, voltage swell and fluctuations are the most common disturbances that greatly affect electric customer process operations in large distribution systems. For mitigating the impacts of momentary voltage sag, swell and fluctuation several compensation devices are available. Several devices such as SVC, STATCOM, UPFC, SSSC etc. have been designed to minimize or reduce the impact of these variations.

II. POWER QUALITY ISSUES

- In the past the concept of power quality and reliability of power was same, as there was less power electronic equipment and all the loads were generally linear.
- 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*".
- When all the electrical devices are exposed to power quality problem, they are vulnerable to damage or malfunction. The electrical device might be a computer, an electric motor, communication equipment, a generator, a transformer, a printer, or a household appliance. Depending upon the severity of problem, all these equipments react adversely to any of the power quality issues.
- A power quality problem can be defined as:
- *"Any power problem manifested in voltage/current or leading to frequency deviations that results in failure or misoperation of customer equipment"* [3]. The classification is done on the basis of the duration of fault occurrence. The classification takes the voltage into account, as the quality of the voltage is the addressed issue in most of the cases. However, it is well known that there is always a close relationship between voltages and currents in a power system.
- **Long duration voltage variations**- Deviations in the operating r.m.s. values during longer time than one minute are usually considered long-duration variations. According to the amplitude variation, they can be related to permanent faults, variations in load, and switching operations in the system. As an example, switching a capacitor bank or a large load can cause noticeable changes in the voltage.

- **Short duration voltage variations-** This type of voltage variation is mainly caused by either fault conditions that is associated with fault currents or energization of large loads that require high starting currents for a period ranging from a half cycle to a minute. In this case, the impact on the voltage during the disturbance is of short-period, until protective devices start operating.
- Some of the major power power quality problems are:
- Voltage Sag- A *Voltage Sag* as defined as a decrease in r.m.s value of voltage upto 0.1 pu to 0.9 pu at the power frequency for durations from one half cycles to one minute.
- Voltage Swell- A *Voltage Swell* is defined as an increase in the r.m.s value of the voltage up to a level between 1.1 pu to 1.8 pu at power frequency for periods ranging from a half cycle to a minute.
- Voltage fluctuations- *Voltage fluctuations* are defined as repetitive or random variations in the magnitude of the supply voltage. Its magnitude cannot exceed 10% of the nominal value.
- Voltage Imbalance- *Voltage Imbalance (unbalance)* is defined as the ratio of a negative or zero sequence component to a positive sequence component. The voltage imbalance in a power system is due to single-phase loads.
- Transients- There are two type of transients :- (a) Impulsive Transients**-** An *impulsive transient* is a sudden non-power frequency change in the steady-state condition of voltage or current, or both. Impulsive transients are normally characterized by their rise and decay times. (b) Oscillatory Transients- An *oscillatory transient* consists of a voltage or current whose instantaneous value changes polarity rapidly.
- Noise- The unwanted electrical signals that produce undesirable effects in the circuits of control systems in which they occur are known as electrical *noise*.
- Harmonics- A harmonic of a wave is the component frequency of the signal that is an integer multiple of the fundamental frequency.
- Interharmonics- *Interharmonics* are defined as frequency components of voltages or currents that are not an integer multiple of the normal system frequency (e.g. 50 Hz).
- Power Frequency Variations- These are the frequency variations that may cause a motor to run faster or slower to match the frequency of the input power.
- Some common disturbances which may cause power quality problems are listed below:
  - Lightning and natural phenomena,
  - 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.

III. Overview of Voltage Sag, Swell and Fluctuation

A. Voltage Sag

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 as shown in Fig. 1.

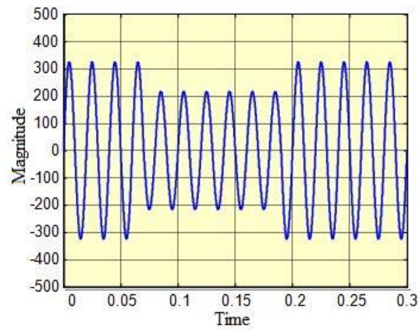

Fig. 2: Voltage Sag

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.

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.

Table 1: Classification of voltage sag according to IEEE 1159

Voltage sag is an important power quality problem as compared to harmonics, flicker, electro-magnetic interference, noise etc. Loads can suffer detrimental effect from voltage sag resulting in economic loss. The most severe sag is caused by faults in the power system at transmission and distribution level. The characteristic of sag will depend on type and location of fault in the system. 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.

Causes of voltage sag:

- operations of circuit breakers,
- due to fault,
- due to heavy inductive motor starting,
- due to transformer energizing,
- equipment failure,
- bad weather,
- snowfall,
- pollution,
- vehicle accident in distribution sector,
- construction activity in urban region.

B. Voltage Swell:

A Voltage Swell is defined as an increase in the r.m.s. value of the voltage up to a level between 1.1 pu to 1.8 pu at power frequency for periods ranging from a half cycle to a minute as shown in fig. 3.

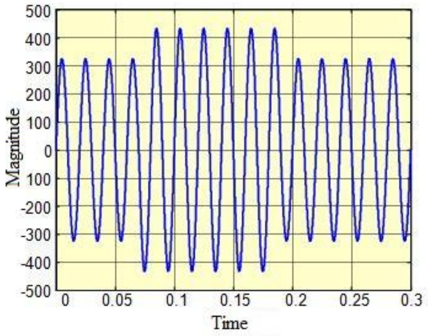

Fig. 3: Voltage Swell

Voltage swell are less common than voltage sag but they also arise due to system faults. Swell can occur due to single line to ground fault, which in turn will raise the voltage of the other phases. It can also cause due to disconnection of heavy industrial loads or switching on the capacitor banks [4]. This is generally due to ungrounded or floating ground delta systems, where a change in ground reference would give voltage rise to the ungrounded system.

Type of Swell	Duration	Magnitude
Instantaneous	0.5 – 30 cycles	1.1 – 1.8 p.u.
Momentary	30 cycles – 3 secs	1.1 – 1.4 p.u.
Temporary	3 secs – 1 min	1.1 – 1.2 p.u.

Table 1: Classification of voltage swell according to IEEE 1159

Causes of voltage swell are mainly due to energization of capacitor bank. It can also be generated by sudden load deduction. Due to the disconnection of load there is a sudden reduction of current, which will give rise the voltage,

$v = L\frac{di}{dt}$, where L is the inductance of the line.

The effects of voltage sag are more severe and destructive. It may cause the electrical equipment to fail, due to overheating caused by high voltage. Also electronic and other sensitive equipment are prone to malfunction.

C. Voltage Fluctuation:

It is defined as the repetitive and random variation of supply voltage from its nominal value for a certain period of time. The magnitude of the voltage variation is not more than 10%. Small magnitude of variation in a supply can give rise to voltage flicker which can be seen with naked eyes [5] as shown in fig. 4.

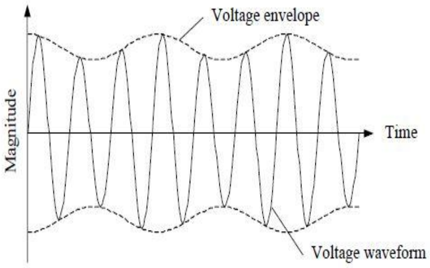

Fig. 4: Voltage Fluctuation

The characteristics of voltage fluctuations depend on the load type and size and the power system capacity. The two important parameters of voltage fluctuations are, the frequency of fluctuation and the magnitude of fluctuation. Both of these components are significant in the adverse effects of voltage fluctuations.

These are caused when loads draw current with sudden or periodic variation. Examples of equipment that creates voltage fluctuations are arc welding, arc furnace, motor drives with cyclic operations etc.

IV. FACTS CONTROLLERS

Flexible AC Transmission System (FACTS) is defined as "*Alternating current transmission systems incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability*" [6, 7].

The development and use of FACTS controllers in power transmission systems has led to many applications of these controllers to improve the stability of power networks.

Classification of FACTS controllers:

- Series connected controllers,
- Shunt connected controllers,
- Combined series- series controllers,
- Combined series- shunt controllers.

V. STATCOM

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). The key component of the STATCOM is a power VSC that is based on high power electronics technologies.

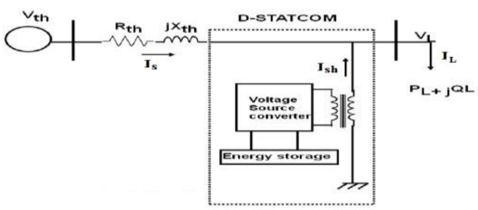

Fig. 5: Operating principle of STATCOM

STATCOM is also known as shunt voltage controller consists of a two level 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. 5. The VSC converts the dc voltage across the storage device into a set of three phase ac output voltages. This 3 phase voltage is coupled with the ac system through the reactance of the coupling transformer. Effective control of active and reactive power exchanges between the STATCOM and ac system is done by suitable adjustment of the phase and magnitude of the STATCOM output voltages. Such configuration allows the device to absorb or generate controllable active and reactive power.

The value of the shunt current I_{sh} can be controlled by adjusting the output voltage of the converter. The shunt injected current I_{sh} can be written as:

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

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

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

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

A. V-I Characteristics

When the STATCOM is operated in voltage regulation mode, it implements the following V-I characteristic:

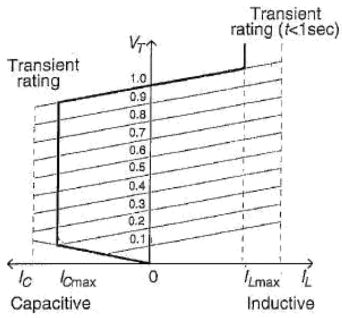

Fig. 6: V-I Characteristics of STATCOM

V-I characteristic has a slope indicated in the fig. and a voltage droop is normally used between 1%- 4% at maximum reactive power output.

$V = V_{ref} + X_s I$

B. Principle of Voltage Regulation

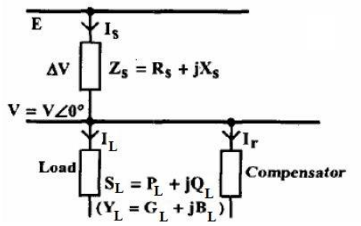

Fig. 7: Circuit for demonstrating the voltage regulation principle

1) Voltage Regulation without Compensator:

Consider a simple circuit as shown in fig. 7. It consists of a source voltage E, V is the voltage at a PCC 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,

$\Delta V = E - V = Z_S * I_L$, (1)

$S = VI^*$, so $S^* = V^*I$ (2)

from the above equations,

$$I_L = \frac{P_L - j^* Q_L}{V}$$

so that,

$$\Delta V = (R_S + jX_S)\left(\frac{P_L - jQ_L}{V}\right)$$

$$= \frac{(R_S - X_S Q_L)}{V} + j\frac{(X_S P_L + R_S Q_L)}{V}$$

$= \Delta V_r + \Delta V_x$

The voltage change has a component ΔV_r in phase with V and component ΔV_x, which are illustrated in fig. 8. It is clear that both magnitude and the phase of V, relative to the supply voltage E, are functions of the magnitude and phase of the load current namely the voltage drop depends on both the real and reactive power of the load. The component ΔV is rewritten as,

$$\Delta V = I_S R_S + jI_S X_S$$

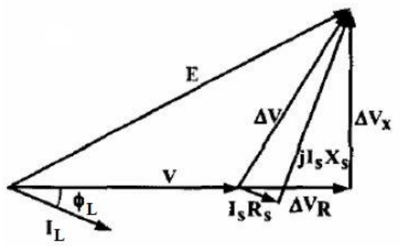

Fig. 8: Phasor diagram for uncompensated system

2) Voltage regulation with DSTATCOM:

Now consider a compensator connected to the system. It is as shown in Fig 5.5 shows vector diagram with voltage compensation. By adding a compensator in parallel with the load, it is possible to make | E | =| V | by controlling the current of the compensator.

$I_S = I_R + I_L$

where, I_R is the compensating current.

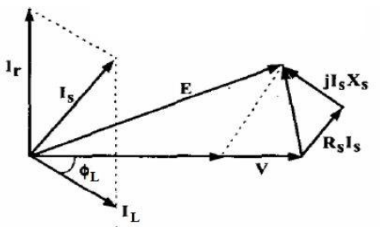

Fig. 9: Phasor diagram for voltage regulation with compensation

VI. MODELLING OF DSTATCOM AND ITS CONTROL STRATEGY

1) d-q Reference Frame

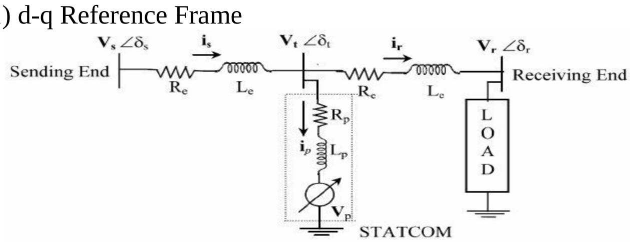

Fig. 10: Equivalent circuit of system with DSTATCOM

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

$V_t = (V_{ta} \quad V_{tb} \quad V_{tc})^T$ and $V_t = (V_{ta} \quad V_{tb} \quad V_{tc})^T$

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

This transformation is called 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 transformed dynamic equations are,

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

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

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

2) Control Strategy

The block diagram of a proposed control technique is shown in fig. 11. Therefore, the PLL provides the angle φ to the abc-to-dq0 (and dq0-to-abc) transformation. There are also four proportional-integral (PI) regulators.

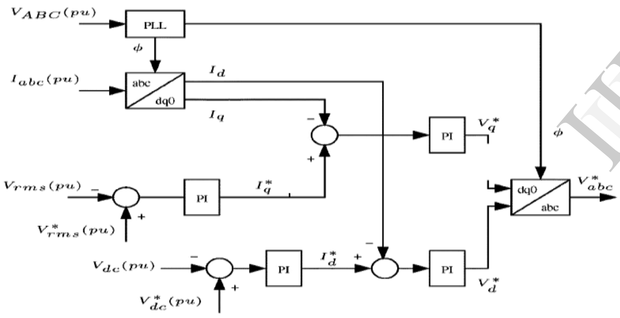

Fig. 11: Proposed control strategy

The first one is responsible for controlling the terminal voltage through the reactive power exchange with the ac network. This PI regulator provides the reactive current reference I_q^*, which is limited between +1 p.u. capacitive and -1 p.u. inductive. Another PI regulator is responsible for keeping the dc voltage constant through a small active power exchange with the ac network, compensating the active power losses in the transformer and inverter. This PI regulator provides the active current reference I_d^*. The other two PI regulators 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. Finally, V_{abc}^* are the three-phase voltages desired at the converter output.

The controller that is employed in this simulation work is shown below in fig. 12.

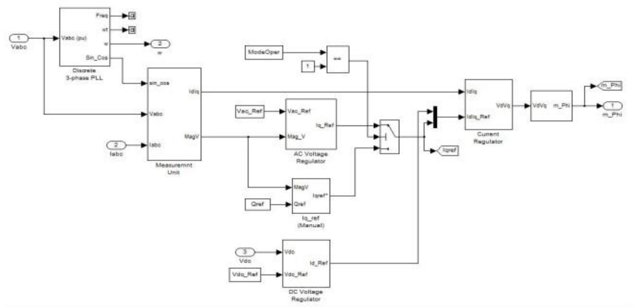

Fig. 12: Controller employed in MATLAB Simulink

VII. TEST MODEL AND DSTATCOM

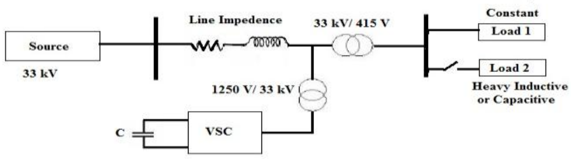

Fig. 13: Test model

Table 3: Specification of the test model

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, 3MVAR
Heavy Capacitive Load	415V, 50 Hz, 1MW, 3MVAR
3-φ Circuit Breaker Timings	0.1seconds to 0.2seconds and 0.3seconds to 0.4seconds

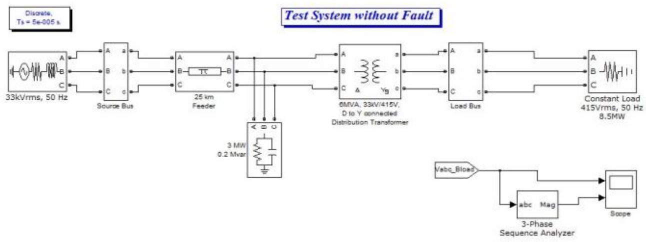

Fig. 14: Simulation model of the test system

VIII. SIMULATION RESULT

1) Sag and its Compensation

The result of the test system creating voltage sag is shown below. A heavy inductive load of 1 MW, 3MVAR is connected to the system for a period of 0.1 second to 0.2 seconds and 0.3 seconds to 0.4 seconds using a 3-φ circuit breaker. The 3-φ voltage waveform and the magnitude are shown in the fig. 15.

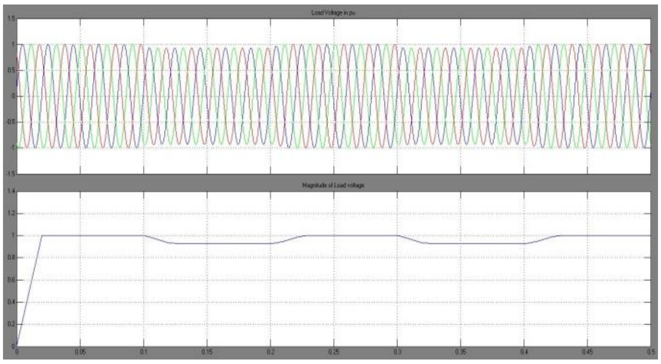

Fig. 15: Results for voltage sag created by heavy inductive load

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 0.9293 pu.

A DSTATCOM is connected in parallel with the line where sag has been created. The voltage waveform, its magnitude, STATCOM current and modulation is shown in fig below.

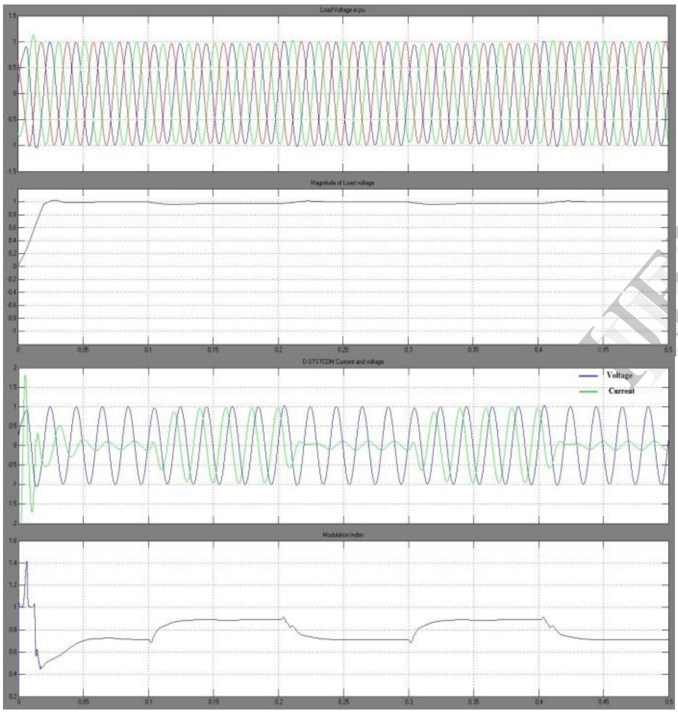

Fig. 16: Results of voltage waveform, its magnitude, STATCOM current and modulation after connecting DSTATCOM

The remaining sag after compensation is found out to be 0.9787 pu.

2) Swell and its Compensation

A heavy capacitive load of 1 MW, 3MVAR is connected to the system for a period of 0.1 second to 0.2 seconds and 0.3 seconds to 0.4 seconds using a 3-φ circuit breaker to create voltage swell. The 3-φ voltage waveform and the magnitude are shown in the fig. 17.

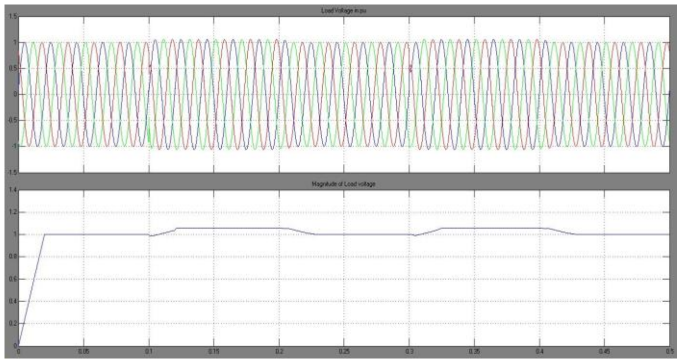

Fig. 17: Results for voltage swell created by heavy capacitive load

The swell during this period is found out to be 1.058 pu.
The swell mitigation using DSTATCOM is shown below.

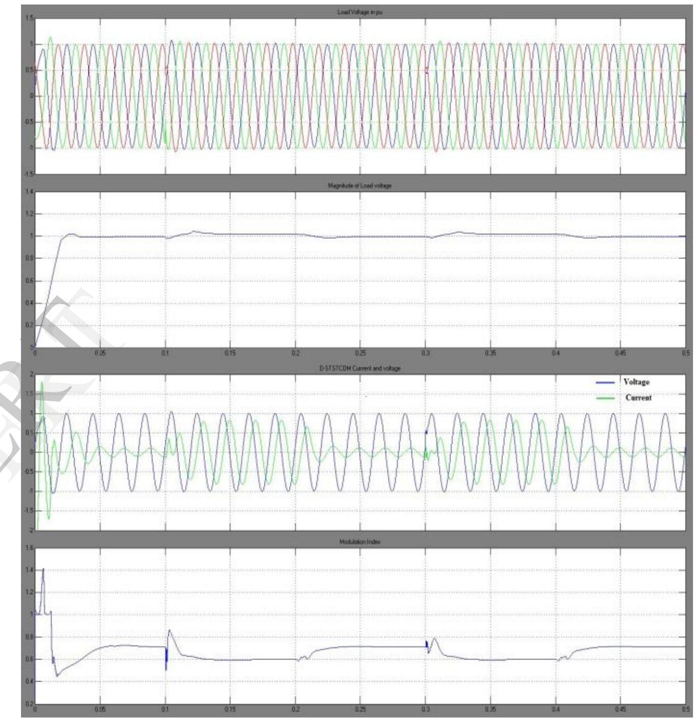

Fig. 18: Results of voltage waveform, its magnitude, STATCOM current and modulation after connecting DSTATCOM

The remaining swell after mitigation is found out to be 1.019 pu.

3) Fluctuation and its Compensation

A heavy inductive load of 1 MW, 3MVAR is connected to the system for a period of 0.1 second to 0.2 seconds and 0.3 second to 0.4 seconds and a heavy capacitive load of 1 MW, 3MVAR is connected to the system for a period of 0.2 second to 0.3 seconds and 0.4 seconds to 0.45 seconds using a 3-φ circuit breaker. The 3-φ voltage waveform and the magnitude are shown in the fig 19.

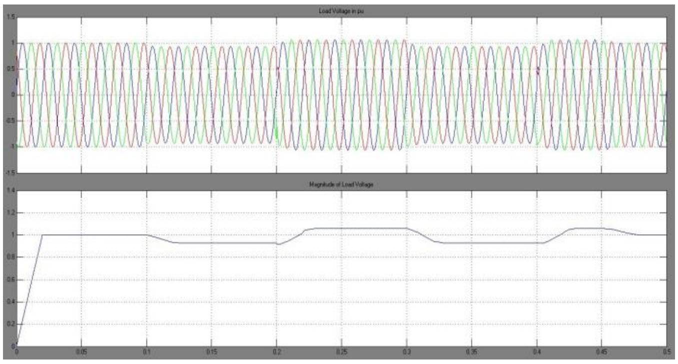

Fig. 19: Results for voltage fluctuation created by heavy inductive and capacitive load

The range of fluctuation during this period is found out to be 0.9293 to 1.058 pu

The fluctuation mitigation using DSTATCOM is shown below.

Fig. 20: Results of voltage waveform, its magnitude, STATCOM current and modulation after connecting DSTATCOM

The remaining range of fluctuation after mitigation is found out to be 0.971 to 1.003 pu.

IX. Conclusion

In this work, the investigation on the role of D-STATCOM is carried out to improve the voltage profile in distribution network with static linear load. Test systems having voltage sag, swell and fluctuation are analyzed and results have been presented in the previous chapter. The Simulation results shows that the DSTATCOM can compensate the voltage sag, swell and fluctuation conditions caused due to sudden switching of loads.

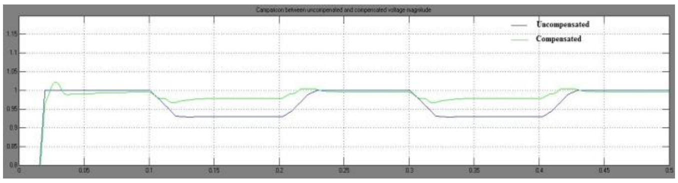

Fig. 21: Comparison of voltage magnitude for uncompensated and compensated sag

The above fig. 21 shows that the sag which was produced by switching a heavy inductive load of 0.9323 pu has been compensated by using a DSATCOM up to 0.9787 pu.

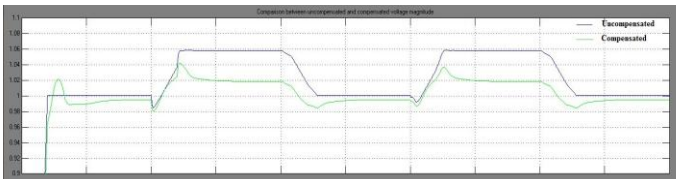

Fig. 22: Comparison of voltage magnitude for uncompensated and compensated swell

The above fig. 22 shows that the swell which was produced by switching a heavy capacitive load of 1.058 pu has been mitigated by using a DSATCOM up to 1.019 pu.

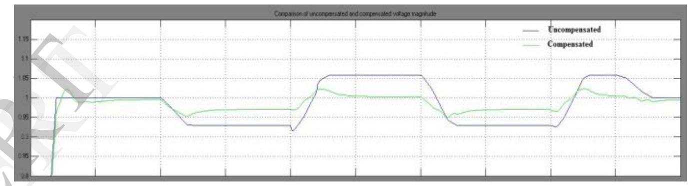

Fig. 23: Comparison of voltage magnitude for uncompensated and compensated fluctuation

The above fig. 23 shows that the fluctuation range of 0.9293 to 1.058 pu which was produced by switching a heavy inductive and capacitive load has been mitigated by using a DSATCOM up to a range of 0.971 to 1.003 pu.

X. Acknowledgment

I would like to thank my parents and my supervisor who has helped me in all possible ways towards successful completion of this work.

XI. References

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