Compensation of Voltage sag magnitude due to symmetrical and unsymmetrical faults in Power Systems using STATCOM.

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ABSTRACT

This work reports study of voltage sag in Power systems due to symmetrical and unsymmetrical faults, and its compensation using STATCOM. The voltage and phase angle after the occurrence of various faults like LLL, LG and LLG faults are determined to find the most affected bus. A procedure to evaluate the rating of the STATCOM connected to the most affected bus is demonstrated. A framework is developed for finding the current injected by the STATCOM for all types of faults considered. A program is developed in MATLAB environment to accomplish the above mentioned objectives. The effectiveness of the program is validated by applying it to a standard 11 bus test system. It is observed that the STATCOM is effective in compensating the most affected bus voltage magnitude for all types of faults considered.

Keywords : Fault calculation, Rating, static compensator (STATCOM), System impedance matrix, Algorithm, Voltage sag compensation.

1 INTRODUCTION

Power frequency disturbance describes events that are slower and longer lasting compared to electrical transient. Power frequency disturbances can last anywhere from one complete cycle to several seconds or even minutes. One of the most common power frequency disturbances is voltage sag. By definition, voltage sag is an event that can last from half of a cycle to several seconds. Most of the voltage sags in power systems are caused due to short circuit faults in the transmission and distribution network [11]. The flexible ac transmission system (FACTS) devices are power-electronic-based devices that can control parameters like current, voltage, and impedance and is effective in compensating voltage sag [8]. Static compensator (STATCOM) is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus. This paper focuses on Voltage Sag mitigation by STATCOM.

The step by step procedure for formation of the bus Impedance matrix and fault current calculation for balanced and unbalanced faults are discussed in [5].

The rating of STATCOM is determined based on the short circuit level of the bus connected to load and sag characteristics of the bus [5]. The voltage sag mitigation by STATCOM by means of an analytical approach using system impedance matrix which incorporates STATCOM and the maximum voltage sag that can be corrected without the injection of active power are discussed in [10].

This paper demonstrates the procedure for determining the rating and the injected current of the STATCOM for voltage sag compensation at the most affected bus due to various short circuit faults mentioned. A detailed structure to obtain the voltage magnitude and phase angle of the most affected bus is also discussed.

This paper comprises of the following sections: Section 2 deals with the basics of Voltage sag. In section 3, the modeling of system components for fault studies and the fault analysis using bus impedance matrix are presented. Section 4 presents voltage sag compensation using STATCOM. Section 5 presents the fault calculation algorithm. Section 6 comprises of the test system, results and discussions. The results include voltages of the test system before and after fault, rating of the STATCOM to compensate voltage of the most affected bus and bus voltage magnitude and angle after compensation. Conclusion is presented in Section 7.

2 VOLTAGE SAG

Voltage sag is decrease in voltage below threshold followed by recovery after a short period. Voltage sag threshold is quite different from interruption threshold and it is assumed to be equal to 90% of the declared voltage by EN 50160 2000 and IEC 61000-2-8-2002.

In IEEE 1159 1995, the under voltages are classified as the voltages characterized by a magnitude between 80% and 90% of the nominal voltage with duration greater than 1 minute. A voltage dip is characterized by a pair of data: the residual voltage, or depth, and the duration. The residual voltage is the lowest value of the voltage during the event. The depth is the difference between the reference voltage and the residual voltage. Duration is the time that the root mean square (RMS) stays below the threshold; generally, the duration of a voltage dip is between 10 ms and 1 minute.

A voltage dip can be caused by short circuits and subsequent fault clearing by protection equipment or by a sudden change of load, such as a motor starting. After a short circuit, the duration of the voltage dip depends on the protection system.

3 SHORT CIRCUIT STUDIES

Short circuit studies are performed to evaluate the bus voltages and current flow during various types of fault. Fault are classified into

i) Symmetrical (or) balanced faults
ii) Unsymmetrical (or) unbalanced faults

3.1 Modeling of System Components for fault calculation studies

3.1.1 Modeling of System Components

The modeling of system components for fault calculation studies is shown in Table 1.

TABLE 1
MODELING OF SYSTEM COMPONENTS

Components	**Modeled as**
Overhead and Underground cables	positive-, negative-, and zero-sequence lumped parameters
Transformers	positive-, negative-, and zero-sequence series impedances
bulk supply point	a fixed sequence resistance and sub-transient reactance.
Loads	static constant impedance loads

3.1.2 System Impedance Matrix

There are generally two methods for forming a system impedance (Z) matrix [5]:

- Inverting the system admittance matrix Y_s
- Direct formation of Z

In this paper, the method of direct formation of a Zmatrix is employed. The Z matrix is assembled by starting with a single element connected to the reference bus and by adding one element at a time and correspondingly modifying the matrix after each addition. Each added element should be connected to at least one other bus of the system. This method is based on the principle of modification of a Z matrix, which can be described as follows:

- Adding a branch between existing buses
- Adding a branch from a new bus to the reference
- Adding a branch from a new bus to an existing bus
- Adding a branch from existing bus to the reference.

Classical fault calculation starts with converting all impedances to per unit value.

3.1.3 Modeling of STATCOM

STATCOM can be employed to compensate voltage. For voltage control purposes, generally, STATCOM can be modeled as a variable current source [8] as shown in Fig.1.

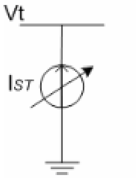

Fig. 1. Model of STATCOM

At reduced voltage, STATCOM can continue to operate with rated leading (lagging) current. Therefore, STATCOM is able to provide better voltage support when the voltage become severely depressed.

3.2 Fault analysis using Z-Bus Matrix

In large networks, the network reduction technique is not applicable. By utilizing the elements of bus impedance matrix, the fault current, bus voltages during the fault can be easily calculated.

3.2.1 Symmetrical Fault analysis using Z-Bus Matrix

The step by step procedure for obtaining the fault current and post fault bus voltages for symmetrical fault are described below.

Step 1: Form the bus impedance matrix using bus building algorithm.
Step 2: Determine the pre fault bus voltage from power flow solution.
Step 3: The short circuit current is

$$I_2=I_0=0 \tag{1}$$

$$I_f=I_1=\frac{V_k}{Z_{kk}+Z_{fault}} \tag{2}$$

Step 4: Compute the post fault bus voltage

$$\begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{pmatrix} = \begin{pmatrix} V_1^{pre} \\ V_2^{pre} \\ \vdots \\ V_n^{pre} \end{pmatrix} + (Z_{bus}) \begin{pmatrix} 0 \\ 0 \\ -I_f \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{3}$$

3.2.2 Un Symmetrical Fault analysis using Z-Bus Matrix

The step by step procedure for obtaining the fault current and post fault bus voltages for unsymmetrical fault are described below.

Step 1: Form the positive, negative and zero sequence bus impedance matrix using bus building algorithm.

Step 2: Determine the pre fault bus voltage from power flow solution.

Step 3: The short circuit current for

(i) LG Fault

$$I_1 = I_2 = I_0 = \frac{V_k^{pre}}{Z_{kk}^1 + Z_{kk}^2 + Z_{kk}^0 + 3 * Z_{fault}} \quad (4)$$

$$I_f = 3 * I_1 \quad (5)$$

(ii) LLG Fault

$$I_1 = \frac{V_k}{Z_{kk}^1 + \frac{Z_{kk}^2 (Z_{kk}^0 + Z_{fault})}{(Z_{kk}^0 + Z_{fault}) + Z_{kk}^2}} \quad (6)$$

$$I_2 = -I_1 \frac{(Z_{kk}^0 + 3Z_{fault})}{Z_{kk}^2 + Z_{kk}^0 + 3Z_{fault}} \quad (7)$$

$$I_0 = -I_1 \frac{Z_{kk}^2}{Z_{kk}^2 + Z_{kk}^0 + 3Z_{fault}} \quad (8)$$

Step 4: Compute the post fault bus voltage

(i) Zero sequence voltage

$$\begin{pmatrix} V_1^0 \\ V_2^0 \\ \vdots \\ V_n^0 \end{pmatrix} = \begin{pmatrix} V_1^{pre} \\ V_2^{pre} \\ \vdots \\ V_n^{pre} \end{pmatrix} + \left(Z_{bus}^0\right) \begin{pmatrix} 0 \\ 0 \\ I_0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (9)$$

(ii) Positive sequence voltage

$$\begin{pmatrix} V_1^1 \\ V_2^1 \\ \vdots \\ V_n^1 \end{pmatrix} = \begin{pmatrix} V_1^{pre} \\ V_2^{pre} \\ \vdots \\ V_n^{pre} \end{pmatrix} + \left(Z_{bus}^1\right) \begin{pmatrix} 0 \\ 0 \\ -I_1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (10)$$

(iii) Negative sequence voltage

$$\begin{pmatrix} V_1^2 \\ V_2^2 \\ \vdots \\ V_n^2 \end{pmatrix} = \begin{pmatrix} V_1^{pre} \\ V_2^{pre} \\ \vdots \\ V_n^{pre} \end{pmatrix} + \left(Z_{bus}^2\right) \begin{pmatrix} 0 \\ 0 \\ -I_2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (11)$$

4 VOLTAGE COMPENSATION USING STATCOM

4.1 Rating of STATCOM

The equivalent network can be viewed from the faulted point of fault as shown in Fig.2. Derivation of the method is demonstrated assuming that the devices is capable of restoring the voltage to nominal from a 50% voltage drop and phase shift ≤ 30 [15] .

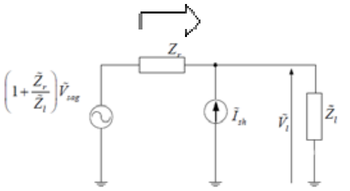

Fig. 2. Single line diagram of STATCOM connected to a bus

Voltage at compensated bus is

$$V_l = V_{sag} + \frac{Z_l * Z_r}{Z_l + Z_r} I_{sh} \quad (12)$$

$$V_{sag} = V_{sag} < \alpha - 30^{\circ} \text{ and} \quad (13)$$

$$V_l = V_l < \alpha$$

$$|V_{sag}| = 0.5 \text{ and } |V_t| = 1 \quad (14)$$

$$Z_r = Z_r < \gamma$$

$$Z_l = Z_l < \beta \quad (15)$$

$$I_{sh} = I_{sh} < \sigma$$

one can derive apparent power of the STATCOM as equation (16) and active and reactive power are as equation (17) and equation (18):

$$S_{STAT} = \frac{Z_r e^{-j\gamma} + Z_l e^{-j\beta}}{Z_r e^{-j\gamma} Z_l e^{-j\beta}} \left(V_l^2 - V_l V_{sag} e^{j30^{\circ}}\right) \quad (16)$$

$$P_{STAT} = \frac{V_l^2}{Z_l} \cos\beta + \frac{V_l^2}{Z_r} \cos\gamma - \frac{V_l V_{sag}}{Z_l} \cos(\beta + 30^{\circ}) - \frac{V_l V_{sag}}{Z_r} \cos(\gamma + 30^{\circ}) \quad (17)$$

$$Q_{STAT} = \frac{V_l^2}{Z_l} \sin\beta + \frac{V_l^2}{Z_r} \sin\gamma - \frac{V_l V_{sag}}{Z_r} \sin(\beta + 30^{\circ}) - \frac{V_l V_{sag}}{Z_r} \sin(\gamma + 30^{\circ}) \quad (18)$$

Taking into account of predefined values for sag magnitude and restored voltage one gets:

$$P_{STAT} = \frac{1}{Z_l} \cos\beta + \frac{1}{Z_r} \cos\gamma - \frac{1}{2Z_l} \cos(\beta + 30^{\circ}) - \frac{1}{2Z_r} \cos(\gamma + 30^{\circ}) \quad (19)$$

$$Q_{STAT} = \frac{1}{Z_l} \sin\beta + \frac{1}{Z_r} \sin\gamma - \frac{1}{Z_r} \sin(\beta + 30^{\circ}) - \frac{1}{2Z_r} \sin(\gamma + 30^{\circ}) \quad (20)$$

4.2 Calculation of Injected Current [4],[10]

4.2.1 LLL fault

Consider voltages at the compensated bus and faulted bus

$$V_t = V_t^{pre} - I_f * Z_{tf} + I_{sh} * Z_{tt} \quad (21)$$

$$V_f = V_f^{pre} - I_f * Z_{ff} + I_{sh} * Z_{ft} \quad (22)$$

$$V_f = Z_{fault} * I_f \quad (23)$$

Expressing previous equations in matrix for:

$$\begin{pmatrix} V_t \\ 0 \end{pmatrix} = \begin{pmatrix} V_t^{pre} \\ V_f^{pre} \end{pmatrix} - \begin{pmatrix} -Z_{tt} & Z_{tf} \\ -Z_{ft} & Z_{ff} + Z_{fault} \end{pmatrix} \begin{pmatrix} I_{sh} \\ I_f \end{pmatrix} \quad (24)$$

Therefore

$$\begin{pmatrix} I_{sh} \\ I_f \end{pmatrix} = \mathrm{inv} \begin{pmatrix} -Z_{tt} & Z_{tf} \\ -Z_{ft} & Z_{ff} + Z_{fault} \end{pmatrix} * \begin{pmatrix} V_t^{pre} - V_t \\ V_f^{pre} \end{pmatrix} =$$

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} * \begin{pmatrix} V_t^{pre} - V_t \\ V_f^{pre} \end{pmatrix} \tag{25}$$

Then

$$I_{sh} = M_{11} * V_t^{pre} + M_{12} * V_f^{pre} - M_{11} * V_t$$

$$V_S < \gamma = M_{11} * V_t^{pre} + M_{12} * V_f^{pre} \tag{26}$$

$$M_{11} = k = k < \beta \tag{27}$$

$$V_t = V_t < \alpha \tag{28}$$

(29)

$$I_{sh} = I_{sh} < (\pi/2 + \alpha) \tag{30}$$

$$I_{sh} = V_s - kV_t \tag{31}$$

Solving (31) gives

$$I_{sh} = -kV_t \sin\beta + \mathrm{sqrt}(V_S^2 - (kV_t \cos\beta)^2) \tag{32}$$

$$V_t = (-I_{sh} \sin\beta) + \mathrm{sqrt}(V_S^2 - (kV_t \cos\beta)^2)/k \tag{33}$$

$$\alpha = \sin^{-1}\left(\frac{(KV_S)^2 - V_s{}^2 - I_{sh}{}^2}{(2 * V_s * I_{sh})}\right) + \gamma\ \gamma \tag{34}$$

Two cases can be considered for the calculation of injected current

Case (i):

$V_s \geq kV_t \cos\beta$ and with $(V_t = V_t^{pre-fault})$ **(35)**

Voltage can be restored to pre fault value.

Case (ii):

$V_s < kV_t \cos\beta$ and with $(V_t = V_t^{pre-fault})$ **(36)**

Voltage magnitude can be restored to

$$V_t = \frac{V_s}{k\cos\beta} \tag{37}$$

The injected current and phase angle are given by equation (32) and (34).

When $I_{sh} > I_{rate}$

$$I_{sh} = I_{rate} = \frac{Q_{rated}}{V_t^{pre-fault}} \tag{38}$$

The voltage magnitude that can be restored as given by (33) and the phase angle by (34).

4.2.2 LG fault

When LG fault occurs, negative and zero sequence networks have to be included in calculation, so

$$\begin{aligned} V_t{}^0 &= V_t^{0pre} - I_f{}^0 * Z_{tf}{}^0 + I_{sh}{}^0 * Z_{tt}{}^0 \\ V_f{}^0 &= V_f^{0pre} - I_f{}^0 * Z_{ff}{}^0 + I_{sh}{}^0 * Z_{ft}{}^0 \end{aligned} \tag{39}$$

$$\begin{aligned} V_t{}^1 &= V_t^{1pre} - I_f{}^1 * Z_{tf}{}^1 + I_{sh}{}^1 * Z_{tt}{}^1 \\ V_f{}^1 &= V_f^{1pre} - I_f{}^1 * Z_{ff}{}^1 + I_{sh}{}^1 * Z_{ft}{}^1 \end{aligned} \tag{40}$$

$$\begin{aligned} V_t{}^2 &= V_t^{2pre} - I_f{}^2 * Z_{tf}{}^2 + I_{sh}{}^2 * Z_{tt}{}^2 \\ V_f{}^2 &= V_f^{2pre} - I_f{}^2 * Z_{ff}{}^2 + I_{sh}{}^2 * Z_{ft}{}^2 \end{aligned} \tag{41}$$

The following equations have to be satisfied:

$$I_f{}^0 = I_f{}^1 = I_f{}^2 = I_f/3 \tag{42}$$

$$V_f{}^0 + V_f{}^1 + V_f{}^2 = V_f = 3I_f * Z_{fault} \tag{43}$$

From equation(39)-(42) yields

$$V_f = V_f^{pre} - I_f{}^1(Z_{ff}{}^0 + Z_{ff}{}^1 + Z_{ff}{}^2) - I_{sh}{}^0 Z_{tf}{}^0 - I_{sh}{}^1 Z_{tf}{}^1 - I_{sh}{}^2 Z_{tf}{}^2 \tag{44}$$

And further:

$$\begin{pmatrix} V_t^0 \\ V_t^1 \\ V_t^2 \\ V_f \end{pmatrix} = \begin{pmatrix} V_t^0 \\ V_t^1 \\ V_t^2 \\ V_f \end{pmatrix}^{pre} - \begin{pmatrix} -Z_{tt}{}^0 & 0 & 0 & Z_{tf}{}^0 \\ 0 & -Z_{tt}{}^1 & 0 & Z_{tf}{}^1 \\ 0 & 0 & -Z_{tt}{}^2 & Z_{tf}{}^2 \\ -Z_{ft}{}^0 & -Z_{ft}{}^1 & -Z_{ft}{}^2 & Z_{ff}{}^{012} \end{pmatrix} \begin{pmatrix} I_{sh}{}^0 \\ I_{sh}{}^1 \\ I_{sh}{}^2 \\ I_f^1 \end{pmatrix} \tag{45}$$

Equation (45) can be modified and equation(46) obtained

$$I_{sh}{}^1 = M_{22} V_t^{pre} + M_{24} V_f^{pre} - M_{21} V_t^0 - M_{22} V_t^1 - M_{23} V_t^2 \tag{46}$$ (42)

$$V = M_{22} V_t^{pre} + M_{24} V_f^{pre} \tag{47}$$

$$I_{sh}{}^1 = 1/3(I_{sh} + a\, I_{sh} + a^2\, I_{sh}) \tag{48}$$

Assume that the compensation starts from phase then V_b, V_c are uncompensated voltages and I_b, I_c are zero.

$$\begin{aligned} V_S < \gamma &= 3V - M_{21}(V_b + V_C) \\ &\quad - M_{22}(aV_b + a^2 V_C) - M_{23}(a^2 V_b + a V_C) \end{aligned} \tag{49}$$

$$k < \beta = M_{21} + M_{22} + M_{23} \tag{50}$$

The equation of the same format as equation (31) obtained. Solving by the previously described method gives $I_a = I_{sh}$, $V_a = V_t$, V_c equal to the uncompensated voltage, and $I_a = 0$.

Then

$$\begin{aligned} V_S < \gamma &= \frac{1}{a} * (3V - M_{21}(V_a + V_C) \\ &\quad - M_{22}(V_a + a^2 V_C) - M_{23}(V_a + a V_C) - I_a) \end{aligned} \tag{51}$$

$$k < \beta = \frac{1}{a}(M_{21} + aM_{22} + a^2 M_{23}) \tag{52}$$

following the same algorithm, gives $I_b = I_{sh}$, $V_b = V_t$

Further,

$$\begin{aligned} V_S < \gamma &= \frac{1}{a^2}(3V - M_{21}(V_a + V_b) \\ &\quad - M_{22}(V_a + a V_b) - M_{23}(V_a + a^2 V_b) - I_a \\ &\quad - a\, I_b) \end{aligned} \tag{53}$$

$$k < \beta = \frac{1}{a^2}(M_{21} + a^2 M_{22} + aM_{23}) \tag{54}$$

gives $I_c = I_{sh}$, $V_c = V_t$

4.2.3 LG fault

The fault current and voltage can be expressed as:

$$V_f{}^1 = V_f{}^2 = V_f{}^0 - 3I_f * Z_{fault} \tag{55}$$

$$I_f{}^2 = -\, I_f{}^1 \frac{(Z_{ff}^0 + 3Z_{fault})}{Z_{ff}^2 + Z_{ff}^0 + 3Z_{fault}} \tag{56}$$

$$I_f{}^0 = -\, I_f{}^1 \frac{Z_{ff}^2}{Z_{ff}^2 + Z_{ff}^0 + 3Z_{fault}} \tag{57}$$

Equation (58) can be derived by combining equations (55), (56) and (57). Following the same steps as those for LG fault, the injected currents in each phase can be calculated.

5 FAULT CALCULATION ALGORITHM

The step by step procedure for voltage compensation using STATCOM is described below.

Step 1: Pre-fault bus voltages in the system are obtained from power flow.

Step 2: The impedance matrix is formed by following the procedure as described in section 3.1.2.

Step 3: Various faults like LLL, LG and LLG fault are applied one after another to a particular bus.

Step 4: Fault current and post fault voltages for are found as described in section 3.2

Step 5: Determine the most affected bus from step 4 and take this as the bus to be compensated.

Step 7: Rating of the STATCOM is determined by following the procedure as explained in section 4.1.

Step 8: Current to be injected by the STATCOM is calculated as explained in section 4.2.

Step 9: Determine the voltage and phase angle at the compensated bus by using equations (33) and (34)

6 RESULTS AND DISCUSSION

Step by step procedure as explained in section 5 is programmed using m coding in a MATLAB platform. The efficiency of the program is tested using a standard 11 test system.

6.1 Test System

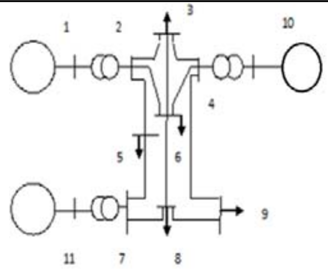

Fig. 3. Single Line diagram of 11 bus system

The single line diagram of the standard 11 bus test system analysis is done on standard 11 bus system is presented in Fig.3. Appendix A provides the Bus data and line data of the test system.

6.2 Results and Discussions

A generalized program is developed in MATLAB to run the load flow on the test system before fault . The results are shown in table 2.

TABLE 2
LOAD FLOW RESULTS BEFORE FAULT

Bus No	**Voltage , in p.u.**	**Angle, in degree**
1	1.06	0.000
2	1.049	-0.76 9
3	1.008	-2.431
4	1.027	-1.445
5	0.982	-7.090
6	1.002	-3.120
7	1.015	-4.296
8	0.986	-4.806
9	0.981	-4.550
10	1.035	-0.583
11	1.020	-3.420

Various faults such as LLL, LG and LLG faults are applied one the other after at bus 8, the post fault bus voltages are found as explained in section 3.2 and the results are tabulated in Table 3. It is observed that bus no 9 is the most affected bus in all three types of faults discussed above. Hence bus no 9 is taken as the bus to be compensated by STATCOM.

TABLE 3
DURING FAULT VOLTAGE FOR 11 BUS SYSTEM

Bus no	**LLL fault Voltage, in p.u.**	**LG faut Voltage, in p.u.**			**LLG fault Voltage, in p.u.**		
	.	**Phase a**	**Phase b**	**Phase c**	**Phase a**	**Phase b**	**Phase c**
1	0.8788	0.8901	0.9737	0.9737	0.9525	0.8440	0.8440
2	0.8268	0.8378	0.9750	0.9750	0.9550	0.7886	0.7886
3	0.7270	0.7502	0.9922	0.9922	0.9863	0.7147	0.7147
4	0.7833	0.7856	0.9994	0.9994	0.9989	0.7627	0.7627
5	0.5153	0.7824	0.9816	0.9816	0.9673	0.7367	0.7367
6	0.5744	0.5979	1.0090	1.0090	1.0154	0.5688	0.5688
7	0.5184	0.6292	0.9987	0.9987	0.9978	0.5907	0.5907
8	0.000	0.000	1.0871	1.0871	1.1357	0.000	0.000
9	0.3147	0.3354	1.0405	1.0405	1.0664	0.3178	0.3178
10	0.8749	0.8565	1.0014	1.0014	1.0024	0.8434	0.8434
11	0.6630	0.8222	0.9586	0.9586	0.9232	0.7507	0.7507

Rating of STATCOM used for compensation is calculated as explained in section 4.1 and results are presented in Table 4.

TABLE 4
RATING OF STATCOM

P_{STAT}, in p.u.	**Q_{STAT}, in p.u.**	**I_{RATE}, in p.u.**
2.6261	3.6362	3.7066

The magnitude of shunt current to be injected by STATCOM are calculated as explained in section 4.2 and results are presented for LLL, LL and LLG faults in Table 5.

TABLE 5
MAGNITUDE OF CURRENT INJECTED BY STATCOM

	LLL fault	**LG fault**		**LLG fault**	
I_{sh}, in p.u.	-0.2980	**Phase a**	-1.984	**Phase a**	-0.1537
		Phase b	0.3585	**Phase b**	-2.3595
		Phase c	3.4044	**Phase c**	3.0216

Injected current as calculated and provided in Table 5 is used to calculate the voltage magnitude and angle at compensated bus (Bus no 9) as explained in section 4.2 and the results are presented in Table 6.

TABLE 6
VOLTAGE MAGNITUDE AND ANGLE AT COMPENSATED BUS

LLL fault		Phases	LG fault		LLG fault	
V_9,	**α,in**		**V_9, in**	**α,in**	**V_9, in**	**α,in**

in p.u.	degre es		p.u.	degree s	p.u.	degree s
0.981	43.7	a	0.981	-26.04	0.981	-8.461
		b	0.981	-204.1	0.981	-110.35
		c	0.981	67.13	0.981	-251.60

From the Table 6, it can be observed that the STATCOM as designed is effective in compensating voltage at the most affected bus in all three types of faults considered.

7 CONCLUSION

In this paper, compensation of voltage sag due to various faults such as LLL, LG and LLG faults by STATCOM are demonstrated. A procedure is developed for finding the rating of STATCOM. A step by step procedure for calculating the current injected by the STATCOM is also presented.

A program is developed in MATLAB environment and the effectiveness of the program is tested using standard 11 bus test system. The results show that the STATCOM is effective in restoring the voltage magnitude of the most affected bus to the pre fault value in all types of faults considered.

LIST OF NOMENCLATURE

Zkk	Fault impedance
Vk	Voltage at faulted bus k
If	Short circuit current
I1,I2 ,I0	Positive, negative and Zero sequence currents
Zfault	Fault impedance
Ish	Injected current
Zl	Load impedance
Zr	Thevenin's impedance of the system observed from faulted point
Vf	Voltage at faulted bus f
Ztf	transfer impedance between bus t and f
Ztt	primary impedance of bus t
Zft	transfer impedance between bus f and t
Zff	Impedance of fault bus f

APPENDIX A

A.1 LINE AND TRANSFORMER DATA

Bus No	Bus No	R, in p.u.	X^1, in p.u.	X^0, in p.u.	½ B, in p.u.
1	2	0.00	0.06	0.06	0.0000
2	3	0.08	0.30	0.60	0.0004
2	5	0.04	0.15	0.30	0.0002
2	6	0.12	0.45	0.90	0.0005
3	4	0.10	0.40	0.80	0.0005
3	6	0.04	0.40	0.80	0.0005
4	6	0.15	0.60	1.00	0.0008
4	9	0.18	0.70	1.10	0.0009
4	10	0.00	0.08	0.08	0.0000
5	7	0.05	0.43	0.80	0.0000
6	8	0.06	0.48	0.95	0.0000
7	8	0.06	0.35	0.70	0.0004
7	11	0.00	0.10	0.10	0.0000
8	9	0.052	0.48	0.90	0.0000

A.2 GENERATOR TRANSIENT IMPEDANCE

Gen.No	R_a , in p.u.	X_d' , in p.u.	X^0, in p.u.	X^1 , in p.u.
1	0	0.20	0.06	0.05
10	0	0.15	0.04	0.05
11	0	0.25	0.08	0.00

A.3 LOAD DATA

Bus No	Real Power, in MW	Reactive Power, in MVAR
3	150	120
5	120	60

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