Abstract—The increased demands on transmission, absence of long term planning and need to provide open access to generating companies and customers have created tendency towards reduced quality of supply. FACTS opens up new opportunities for controlling power and enhancing the usable capacity. The Static Synchronous Compensator (STATCOM), based on voltage source inverter is a widely used FACTS device. In this paper a 5-bus system is analyzed in term of voltage level and then optimum bus location is calculated to connect STATCOM to increase voltage level. STATCOM is also connected to the mid-point of a line to investigate its effects on enhancing transient stability.

Index Terms—FACTS, STATCOM, Reactive Power, CPF, Fault analysis, Transient stability, Voltage stability.

I. INTRODUCTION

Increased use of transmission facilities due to higher industrial output and deregulation of the power supply industry have provided the momentum for exploring new ways of maximizing power transfer in existing transmission facilities while, at the same time, maintaining acceptable limits of network reliability and stability. In this environment high performance control of power network is mandatory. The possibility of controlling power flow in an electric power system without generation rescheduling or topology changes can improve the power system performance [1]. The AC power transmission system has diverse limits, classified as static limits and dynamic limits [2]-[4]. These inherent limits restrict the power transaction, which lead to the underutilization of the existing transmission resources. Traditionally, fixed or mechanically switched shunt and series capacitors, reactors and synchronous generators were being used to solve much of these problems. However, there are some restrictions as to the use of these conventional devices. Desired performance was being unable to achieve effectively. Wear and tear in the mechanical components and slow response were the major problems. As a result, it was needed for the alternative technology made of solid state electronic devices with fast response characteristics. The requirement was further fuelled by worldwide restructuring of electric utilities, increasing environmental and efficiency regulations and difficulty in getting permit and right of way for the construction of overhead power transmission lines. This, together with the invention of semiconductor thyristor switch, opened the door for the development of FACTS controllers [5]. The use of FACTS devices in a power system can potentially overcome limitations of the present mechanically controlled transmission systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the voltage stability, and steady state and transient stabilities of a complex power system [6].

In this study, a 5-bus, 2-machine power system has been considered for describing the impact of STATCOM in enhancing the voltage level and transient stability of the system. The simulation has been done using the MATLAB/SIMULINK and Power System Analysis Toolbox (by F. Milano)

II. STATCOM OVERVIEW

Static var generators generate or absorb controllable reactive power by synchronously switching capacitor and reactor banks ‘in’ and ‘out’ of the network. The aim of this approach is to produce variable shunt impedance that can be adjusted to meet the compensation requirements of the transmission network. The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors, by various switching power converters was disclosed by N.G. Hingorani and L. Gyugyi [2]. These converters are operated as voltage and current sources and they produce reactive power essentially without reactive energy source components by circulating alternating current among the phases of the system. Functionally, from the
standpoint of reactive compensation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied with excitation control. Like the mechanically powered machine, they can also exchange real power with the ac system if supplied from an appropriate, usually dc source. Because of these similarities with a rotating synchronous generator, they are termed Static Synchronous Generator (SSG) [1].

Static synchronous compensator (STATCOM) is a FACTS controller based on voltage-sourced converters. This device is shunt connected to a power system. Through injecting or absorbing reactive current, STATCOM can regulate the voltage [2]. Consequently the voltage stability, transient stability or loadability can be greatly improved. If a storage device such as a battery source is provided, a STATCOM can compensate real power too.

The basic voltage-sourced converter scheme for reactive power generation is shown schematically, in the form of a single-line diagram, in Figure 1. From a dc input voltage source, provided by the charged capacitor $C_s$, the converter produces a set of controllable three-phase output voltages with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small tie reactance (which in practice is provided by the per phase leakage inductance of the coupling transformer). By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine.

$$Q = \frac{V(V - V_0 \sin \delta)}{X}$$

Where,

- $V =$ System voltage to be controlled.
- $V_0 =$ Voltage generated by the voltage source converter.
- $X =$ Reactance of interconnecting transformers and filters.
- $\delta = $ Angle of $V$ with respect to $V_0$

That is, if the amplitude of the output voltage is increased above that of the ac system voltage, then the current flows through the tie reactance from the converter to the ac system and the converter generates reactive (capacitive) power for the ac system. If the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power. If the amplitude of the output voltage is equal to that of the ac system voltage, the reactive power exchange is zero [2].

III. STATCOM V-I CHARACTERISTICS

All A V-I characteristic of a STATCOM is depicted in Fig. 2. As can be seen, the STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage. That is, the STATCOM can provide full capacitive-reactive power at any system voltage even as low as 0.15 pu.

![Fig. 2: Typical V-I characteristic of STATCOM [2].](image)

The characteristic of a STATCOM reveals strength of this technology: that it is capable of yielding the full output of capacitive generation almost independently of the system voltage (constant-current output at lower voltages). This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.
IV. ADVANTAGES OF STATCOM

With STATCOM, a number of valuable benefits can be attained in power systems:

- Dynamic voltage control, to enable limiting of over-voltages over long, lightly loaded lines and cable systems, as well as prevent voltage depressions or even collapses in heavily loaded or faulty systems
- Do increased power transmission capability and stability of long power corridors, without any need to build new lines. This is a highly attractive option, costing less than new lines, with less time expenditure as well as impact on the environment.
- Facilitating connection of renewable generation by maintaining grid stability and fulfilling grid codes, as well as making room for the additional power in existing grids.
- Facilitating the building of high speed rail by supporting the feeding grid and maintaining power quality in the point of common connection.
- Maintaining power quality in grids dominated by heavy industrial loads such as steel plants and large mining complexes.
- Enabling the implementation of Smart Grids.[7]

V. MODELLING OF STATCOM

Based on the operating principle of the STATCOM, the equivalent circuit can be derived, which is given in Fig. 3. Then the STATCOM can be equivalently represented by a controllable fundamental frequency positive sequence voltage source $V_{sh}$. In principle, the STATCOM output voltage can be regulated such that the reactive power of the STATCOM can be changed [8].

\[ V_{sh} = V_{sh} \angle \theta_{sh}, \quad V_i = V_i \angle \theta_i \]

then the power flow constraints of the STATCOM are:

\[ P_{sh} = V_i^2 g_{sh} - V_i V_{sh} (g_{sh} \cos(\theta_i - \theta_{sh}) + b_{sh} \sin(\theta_i - \theta_{sh})) \]

\[ Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh} (g_{sh} \sin(\theta_i - \theta_{sh}) - b_{sh} \cos(\theta_i - \theta_{sh})) \]

(4)

Where, $g_{sh} + jb_{sh} = 1/Z_{sh}$

The operating constraint of the STATCOM is the active power exchange via the DC-link as described by:

\[ PE = Re(V_{sh}I_{sh}) = 0 \]

(5)

VI. CASE STUDY

A. The Test System:

Sample test system consists of 5 buses, 2 generators, 6 transmission lines and 5 loads. The single line diagram of 5-bus test system is shown in Figure 5[2]. The IEEE common format data of this system can be seen in Appendix.

B. Voltage Level Enhancement:

Power flow study results of the test system are shown in following graphs:
The best location for reactive power compensation as far as the improvement of static voltage stability margin is concerned, is the ‘weakest bus’ of the system. The weakest bus of the system can be identified using the continuation power flow (CPF) analysis of the test system. Buses (2, 4 and 5) respective voltage performance index have been calculated. Voltage performance index of the bus 4 \( (\Delta V_{\text{m4}}) = V_2 - V_{20} + V_4 - V_{40} + V_5 - V_{50} \)

Where,

- \( V_2 \) = voltage magnitude of bus 2;
- \( V_{20} \) = voltage magnitude of bus 2 before statcom installation = 0.96141 p.u.
- \( V_4 \) = voltage magnitude of bus 4;
- \( V_{40} \) = voltage magnitude of bus 4 before statcom installation = 0.92031 p.u.
- \( V_5 \) = voltage magnitude of bus 5;
- \( V_{50} \) = voltage magnitude of bus 5 before statcom installation = 0.96831 p.u.

Voltage performance indexes of different buses after installing STATCOM at buses 2, 4 and 5 and their comparison are depicted in the following figure.

Thus, bus 4 is the weakest bus in the system.

To measure the effect of installing STATCOM at weak
C. Enhancement of Transient Stability with STATCOM:

The ability of the STATCOM to maintain full capacitive output current at low system voltage makes it effective in improving the transient (first swing) stability. The increase in stability margin obtainable with a STATCOM is clearly illustrated with the use of the equal-area criterion in Figure 9.

![Fig. 9: Improvement of transient stability obtained with a midpoint STATCOM [2].](image)

The system transmitting steady-state electric power \( P_1 \), at angle \( \delta_1 \), is subjected to a fault for a period of time during which \( P_1 \) becomes zero. During the fault, the sending-end machine accelerates (due to the constant mechanical input power), absorbing the kinetic energy represented by the shaded area below the constant \( P_1 \) line, and increasing \( \delta_1 \) to \( \delta \) (\( \delta > \delta_1 \)) Thus, when the original system is restored after fault clearing, the transmitted power becomes much higher than \( P_1 \) due to the larger transmission angle \( \delta \). As a result, the sending-end machine starts to decelerate, but \( \delta \) increases further until the machine loses all the kinetic energy it gained during the fault. The recovered kinetic energy is represented by the shaded area between the \( P \) versus \( \delta \) curve and the constant power line \( P_1 \). The remaining unshaded area below the \( P \) versus \( \delta \) curve and above the constant power line \( P_1 \), provides the transient stability margin. As can be observed, the transient stability margin obtained with the STATCOM, due to the better support of the midpoint voltage.

The test system in Figure 4 is used to observe the transient stability enhancement after installing STATCOM. A three phase fault is simulated near bus Oak (bus 4) at the end of the line 3-4. Simulation of the faulted condition continues until the line is disconnected from the buses at both of the ends of the faulted line after a fault clearing time \( t_c \) s. Then the post-fault system is simulated for a longer time (say, 10 s) to observe the nature of the transients. This fault condition is simulated considering \( t_c = 0.1 \) s (which is five cycles for a 50-Hz system. Now the STATCOM (+/-100 MVAR) is connected to the midpoint of the line 3-4. Resulting graphs are plotted below

![Fig. 10: Relative angular position \( \delta_{21} \) (\( t_c = 0.1s \))](image)

![Fig. 11: Speed of generator 2 (\( t_c = 0.1s \))](image)

VII. CONCLUSION

Here, the effect of STATCOM for improving voltage stability in a five bus system is carried out. Bus 4 is found as the weakest bus and suitable for connecting STATCOM. The transient stability of the system is also investigated incorporating STATCOM at mid-point of the faulted line. The system is simulated by initiating a 3-phase fault near the second machine in the absence of STATCOM. In this case, the difference between the rotor angles of the two machines is increased tremendously and ultimately loses its synchronism. But, when the same fault is simulated in the presence of STATCOM, the system becomes stable as the STATCOM provides voltage support. Thus, it is concluded that, using STATCOM, voltage level and transient stability limit can be enhanced.
APPENDIX

Table 2: 5 bus system generation and load data.

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Generation, MW</th>
<th>Load, MVAR</th>
<th>V, per unit</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>P</td>
<td>Q</td>
<td>P</td>
<td>Q</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>...</td>
<td>65</td>
<td>30</td>
<td>1.04z0</td>
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<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.00z0</td>
</tr>
<tr>
<td>3</td>
<td>180</td>
<td>...</td>
<td>70</td>
<td>1.02z0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>1.00z0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>85</td>
<td>40</td>
<td>1.00z0</td>
</tr>
</tbody>
</table>

Table 3: Line data

<table>
<thead>
<tr>
<th>Lines bus to bus</th>
<th>Length km</th>
<th>R (p.u.)</th>
<th>X (p.u.)</th>
<th>Chargig Mvar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>64.4</td>
<td>0.042</td>
<td>0.168</td>
<td>4.1</td>
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<tr>
<td>1-5</td>
<td>48.3</td>
<td>0.031</td>
<td>0.126</td>
<td>3.1</td>
</tr>
<tr>
<td>2-3</td>
<td>48.3</td>
<td>0.031</td>
<td>0.126</td>
<td>3.1</td>
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<tr>
<td>3-4</td>
<td>128.7</td>
<td>0.084</td>
<td>0.336</td>
<td>8.2</td>
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<tr>
<td>3-5</td>
<td>80.5</td>
<td>0.053</td>
<td>0.210</td>
<td>5.1</td>
</tr>
<tr>
<td>4-5</td>
<td>96.5</td>
<td>0.063</td>
<td>0.22</td>
<td>6.1</td>
</tr>
</tbody>
</table>

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REFERENCES


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