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# Steady State Power Flow Calculations with STATCOM under Load Increase Scenario and Line Contingencies

A. S. Telang, P. P. Bedekar

***Abstract*****—**Flexible AC transmission system controllers play an important role in controlling the line power flow and in improving voltage profiles of the power system network. They can be used to increase the reliability and efficiency of transmission and distribution system. The modeling of these FACTS controllers in power flow calculations have become a challenging research problem. This paper presents a simple and systematic approach for a steady state power flow calculations of power system with STATCOM (Static Synchronous Compensator). It shows how systematically STATCOM can be implemented in conventional power flow calculations. The main contribution of this paper is to investigate this approach for two special conditions i.e. consideration of load increase pattern incorporating load change (active, reactive and both active and reactive) at all load buses simultaneously and the line contingencies under such load change. Such investigation proves to be relevant for determination of strategy for the optimal placement of STATCOM to enhance the voltage stability. The performance has been evaluated on many standard IEEE test systems. The results for standard IEEE-30 bus test system are presented here.

***Keywords*****—**Load flow analysis, Newton-Raphson (N-R) power flow, Flexible AC transmission system, FACTS, Static synchronous compensator, STATCOM, voltage profile.

## I. Introduction

MODERN power systems are largely interconnected to meet the ever increasing demand of the load. Large interconnections make the power system more complicated and more stressed. Voltage collapse typically occurs on such heavily stressed power systems. This phenomenon is mainly due to the inability of the power system to meet the reactive power demands of the loads. This is usually because of the limitations on the production and transmission of reactive power [1]. Traditionally, the reactive power flow has been controlled through compensators and other equipment such as shunt reactors, shunt condensers and rotating synchronous condensers. Introducing fast acting devices like the Flexible Alternating Current Transmission System (FACTS) controllers have proved a reliable technical solution for reactive power flow control. These controllers are widely used for number applications viz. to enhance the power transfer capability, to increase the loadability of transmission lines, to improve voltage stability and also for reducing losses occurred in the system, to damp out power oscillations etc. [2]-[5]. Among the various FACTS controllers, STATCOM is one of the key controllers [2]-[4]. It is a shunt connected device and is most widely used to improve voltage regulation and to increase loadability margin.

The term “power flow” refers to the flows of real and reactive power that occurs during steady state conditions in power system. These power flow calculations are essential for continuous evaluation and analysis of the power system to meet the increased load demand. In fact these power flow studies are routinely used in power system planning and operations for system security assessment and stability analysis [6]. But traditional power flows do not include these newly developed FACTS controllers. Very few researchers have addressed the issue of how to model FACTS devices for load flow calculations [7]. In general, the modeling of FACTS in power flow calculations has become important and a challenging research problem. It emerges as the fundamental requirement of power system analysis, planning, designing and control operations. In recent years, numerous models have been developed for FACTS devices which are to be implemented in power flow calculations, mostly using the Newton-Raphson method since this method has excellent quadratic convergence properties [8], [9]. Several researchers have reported the development of steady state models for FACTS controllers, specifically STATCOM. A new and appropriate STATCOM model for power flow analysis has been proposed in [10], [11]. This model considers the impact of the high frequency effects and the switching characteristics of the power electronic devices on the active power loss and the reactive power injection. The procedure to extend conventional power flow calculations based on Newton-Raphson method to include multiple FACTS controllers viz. STATCOM, SSSC, UPFC and IPFC is nicely presented in [12]-[16]. FACTS model (shunt and series) and algorithm for power flow calculations have been well discussed in [17]. The steady state modeling of STATCOM for voltage stability analysis and power flow is presented in [18], [19]. A new generalized current injection model of the modified power system using Newton-Raphson power flow algorithm has been proposed in [20] for desired power transfer with FACTS devices viz. TCSC, UPFC and GUPFC. A two bus integrated equivalent system is used to predict the voltage collapse point of power system incorporating two major FACTS devices i.e. SVC and STATCOM in [21]. The modeling of STATCOM for power system applications with its linear behavior is

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presented in [22] where three types of state feedback controllers are developed and compared. Reference [23] presents an elegant approach based on current source converter based STATCOM. It shows excellent results in current and voltage waveforms using PSCAD/EMTDC package. Reference [24] proposes flexible and realistic model of STATCOM for effective power flow solution. In [25], the direct implementation of STATCOM model in Newton-Raphson power flow based on power and current mismatches have been described in detail. The multi-control functions of STATCOM in power system steady state operation are presented in [26].

This paper describes the systematic and easy approach to incorporate steady state model of voltage source converter based STATCOM in Newton-Raphson load flow algorithm. Although this approach utilizes existing techniques, the novelty of the work lies in the investigation of power flow model of STATCOM for two special conditions. Those are- consideration of load increase pattern incorporating load change (active, reactive and both active and reactive) at all load buses simultaneously and consideration of the line contingencies under such load change scenario. Such investigation proves to be useful for determination of strategy for the optimal placement of STATCOM to enhance the voltage stability. The performance of the STATCOM during steady state and in response to load increase pattern and line contingencies are evaluated on many standard IEEE test systems and the results for standard IEEE-30 bus test system have been presented here. The programs developed in MATLAB environment are efficiently used for this evaluation. The results obtained show encouragement in terms of voltage stability improvement.

## II. The STATCOM- Structure and Operation

A STATCOM has been one of the most comprehensive and versatile FACTS devices. It has number of applications in power systems with the advent of a new generation of power electronics equipment– high power gate turn-off thyristors and transistor devices (GTO, IGBT…). The voltage source converter (VSC) is the basic electronic part of a STATCOM, which converts the dc voltage into a three phase set of output voltages with desired amplitude, frequency and phase. Fig. 1 shows a simple diagram of the STATCOM based on a VSC. It consists of a shunt transformer, a VSC, a dc capacitor, a magnetic circuit and a controller. The STATCOM has the ability to either generate or absorb reactive power by controlling the output voltage amplitude of VSC with respect to bus voltage. When VSC voltage leads the bus voltage, the STATCOM generates reactive power and when VSC voltage lags the bus voltage, it absorbs reactive power [3], [4].

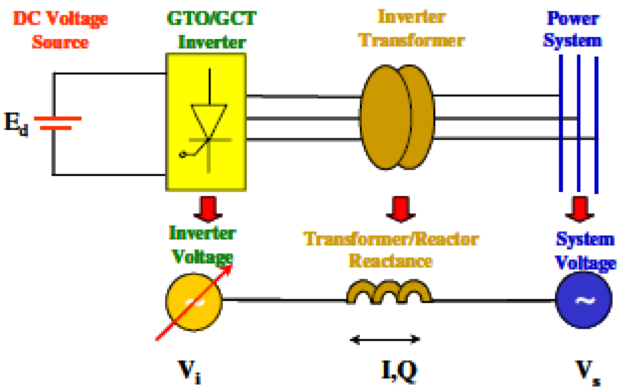


Fig. 1 Circuit for STATCOM

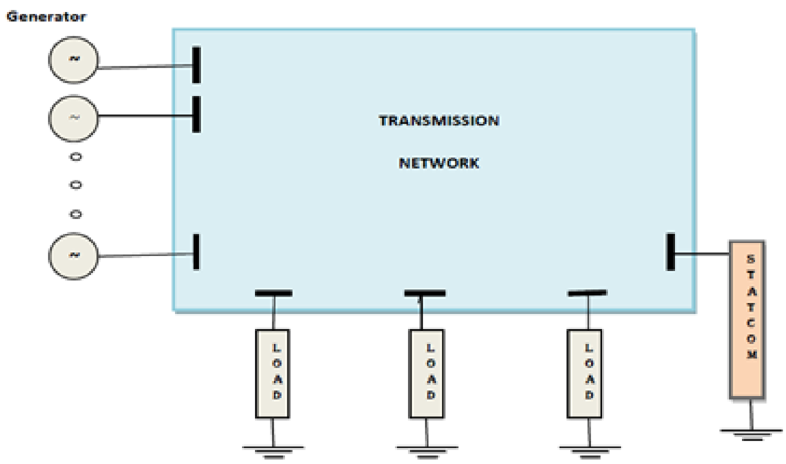


Fig. 2 Symbolic representation of a power system

## III. Modeling of Power Systems with FACTS Controllers

Power flow calculations are necessary for investigating problems in power system operation and control [6]. These calculations can provide a balanced steady state operation state. With regard to the power flow study with STATCOM, specific objectives are-

- To determine appropriate locations and ratings of STATCOM.
- To provide information on the effects on the system active and reactive power flows under normal and abnormal

system conditions.

- To provide initial conditions for transient stability studies.
- To identify critical system conditions, contingencies and power transfer constraints.

The symbolic representation of a power system that includes several generators, several loads and a STATCOM is shown in the block diagram given in Fig. 2.

The interconnection of different components through transmission network can be modeled by its admittance matrix (Y matrix). It should be noted that the power flow model of the system relates the net injected active/reactive power at each bus to all other bus voltages (both magnitude and angles). Furthermore, such model can be easily incorporated in any power flow algorithm, specifically Newton-Raphson power flow algorithm. The conventional power flow equations for a generic bus (bus i) of the power system without FACTS controller can be expressed as:

$$P_i = P_{Gi} - P_{Li} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij})$$
$$Qi = Q_{Gi} - Q_{Li} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (1)$$

where i = 2, 3…N with bus no.1 as slack bus and N is total no. of buses. Referred to Fig. 2 with presence of FACTS devices at buses, say k and t respectively, (1) is modified as:

$$P_k = P_{Gk} - P_{Lk} + P_{kinject} = \sum_{j=1}^{N} |V_k||V_j||Y_{jk}| \cos(\delta_k - \delta_j - \theta_{jk})$$
$$Q_k = Q_{GK} - Q_{Lk} + Q_{kinject} = \sum_{j=1}^{N} |V_k||V_j||Y_{jk}| \sin(\delta_k - \delta_j - \theta_{jk}) \quad (2)$$

$$P_t = P_{Gt} - P_{Lt} + P_{tinject} = \sum_{j=1}^{N} |V_t||V_j||Y_{jt}| \cos(\delta_t - \delta_j - \theta_{jt})$$
$$Q_t = Q_{Gt} - Q_{Lt} + Q_{tinject} = \sum_{j=1}^{N} |V_t||V_j||Y_{jt}| \sin(\delta_t - \delta_j - \theta_{jt}) \quad (3)$$

The buses t and k, as other buses of the network, can be introduced as PV or PQ buses. The power flow equations shown in (1) are iteratively solved using the linearized Jacobian equation given in [6]. This equation is as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (4)$$

where the sub-Jacobian matrices are defined as- $J_1=\partial P/\partial\delta$, $J_2==\partial P/\partial|V|$, $J_3=\partial Q/\partial\delta$, and $J_4=\partial Q/\partial|V|$.

The main objective of this paper is to solve the power flow problem for the system with the FACTS controllers-STATCOM, under load increase scenario and the line contingencies. The presence of FACTS controllers is accommodated in (2) and (3). The Jacobian equation (4) is extended and /modified accordingly.

### *A. Power Flow Model of STATCOM*

To realize the benefits of STATCOM in terms of improvement of system voltage profile and power transfer capability, it becomes necessary to study the power flow model of STATCOM. This requires the correct representation of STATCOM in steady state. A schematic representation of STATCOM and its equivalent circuit is shown in Figs. 3 (a) and (b), respectively [3].

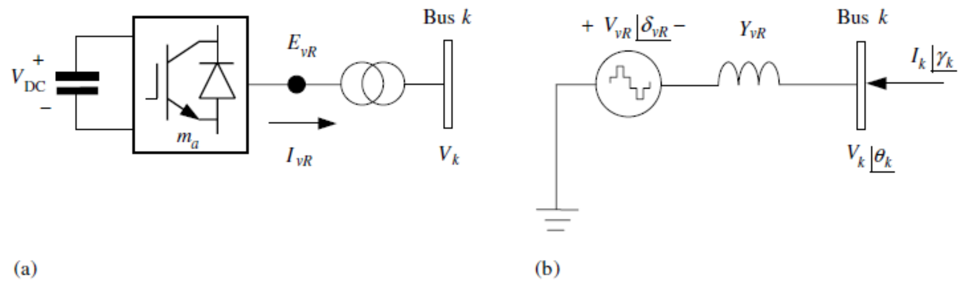


Fig. 3 Equivalent circuit of STATCOM

The bus at which STATCOM is connected is represented as PV bus, which may change to a PQ bus in the event of the limits being violated. In such a case, the generated or absorbed reactive power would correspond to the violated limit [4]. According to the equivalent circuit of the STATCOM shown in Fig. 3, the power flow equations for the converter and bus k can be derived as shown in [3]:

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR}V_k[G_{vR}\cos(\delta_{vR} - \theta_k) + B_{vR}\sin(\delta_{vR} - \theta_k)] \quad (5)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR}V_k[G_{vR}\sin(\delta_{vR} - \theta_k) - B_{vR}\cos(\delta_{vR} - \theta_k)] \quad (6)$$

$$P_k = V_k^2 G_{vR} + V_k V_{vR}[G_{vR}\cos(\theta_k - \delta_{vR}) + B_{vR}\sin(\theta_k - \delta_{vR})] \quad (7)$$

$$Q_k = -V_k^2 B_{vR} + V_k V_{vR}[G_{vR}\sin(\theta_k - \delta_{vR}) - B_{vR}\cos(\theta_k - \delta_{vR})] \quad (8)$$

### *B. Constraints of STATCOM*

Power flow constraints of the STATCOM are:

$$P_{sh} + jQ_{sh} = V_{sh}\angle\theta_{sh}\left(\frac{V_i\angle\theta_i - V_{sh}\angle\theta_{sh}}{Z_{sh}}\right) \quad (9)$$

where $V_{sh}$ is controllable voltage source of the STATCOM. It can be regulated to control local bus voltage. The operating constraint of the STATCOM is active power exchange via the DC link described by:

$$PE = Re\,(V_{sh}\, I_{sh}^{*}) = 0 \tag{10}$$

Also, the bus control constraint is presented in (11):

$$V_i - V_i^{\,spec} = 0 \tag{11}$$

where $V_i\angle\theta_i$ is the $i^{th}$ bus complex voltage, $V_{sh}\angle\theta_{sh}$ is STATCOM complex voltage, $Z_{sh}$ is shunt transformer impedance, $P_{sh} + jQ_{sh}$ is the apparent power through STATCOM and $V_i^{spec}$ is the bus voltage control [13], [26].

### *C. Implementation of STATCOM in Newton-Raphson Power Flow Solution.*

Since the active power exchange with the DC link should be zero at any time, a STATCOM has only one degree of freedom of control. A compact Newton- Raphson power flow algorithm with STATCOM is presented as follows:

$$F(X) = J\,\Delta X \tag{12}$$

where X is the solution vector and **J** is the matrix of partial derivatives of $F(\mathbf{X})$ with respect to **X**, (i.e. the Jacobian matrix), and they can be calculated as:

$$F(X) = \begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix}, \qquad \Delta X = \begin{bmatrix} \Delta\theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta\delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} \tag{13}$$

$$J = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k}V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}}V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k}V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}}V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k}V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial \delta_{vR}}V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k}V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial \delta_{vR}}V_{vR} \end{bmatrix} \tag{14}$$

where $\Delta P_k, \Delta Q_k, \Delta P_{vR}$, and $\Delta Q_{vR}$ are the active and reactive power mismatches at the bus K and at the converter. $P_k, Q_k, P_{vR}$ and $Q_{vR}$ are the sum of active and reactive power flows leaving the bus K and the converter, respectively. Here Jacobian matrix gets modified in comparison to (4) due to presence of STATCOM and hence is called as "augmented Jacobian matrix". The increased size of the augmented matrix depends on types of controllers. The dimensions of such matrix are given as [7]:

$$\begin{gathered} J1\ (n_{pq} + n_{pv} + n_c)\ \text{by}\ (n_{pq} + n_{pv} + n_c) \\ J2\ (n_{pq} + n_{pv} + n_c)\ \text{by}\ (n_{pq}) \\ J3\ (n_{pq})\ \text{by}\ (n_{pq} + n_{pv} + n_c) \\ J4\ (n_{pq})\ \text{by}\ (n_{pq}) \end{gathered} \tag{15}$$

where $n_c$ is the number of STATCOM's installed at a bus.

## IV. Algorithm for NR-Power Flow with STATCOM

The algorithm for solving NR-power flow with STATCOM is described step by step as follows-

1. Read data of the power system and STATCOM. Suppose that the STATCOM is connected at bus k.
2. Form the $Y_{bus}$ of the system using the power system data.
3. Initialize $\delta_{vR}\, and\ V_{vR}$ for the STATCOM.
4. Calculate $P_{VR}$ and $Q_{VR}$ for the STATCOM using (5) & (6).
5. Check the reactive power limits of the voltage controlled buses.
6. Compute the active and reactive power mismatch constraints.
7. Calculate and modify the elements of the Jacobian matrix associated with the STATCOM to produce a complete augmented Jacobian matrix using (14).
8. Update the state variable by matrix inversion.
9. Check the limits on magnitude and angle of STATCOM voltage. If any of them exceeds its upper or lower limit, then set it to the limit violated.
10. Repeat steps 3-9 until all the mismatch vectors are less than a pre-specified tolerance.

## V. Implementation And Results

In order to demonstrate the performance of the Newton-Raphson power flow with FACTS devices, STATCOM, various standard IEEE test systems were considered. The results for standard IEEE 30 bus system (as shown in Fig. 4) are presented in this paper. The system has 6 generation, 4 LTC transformer, and 41 transmission lines [26].

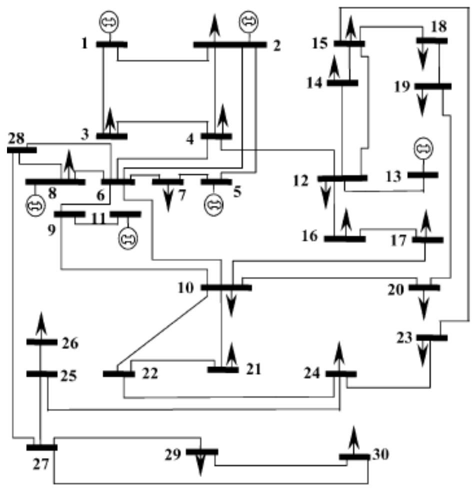


Fig. 4 Single line circuit diagram of the IEEE-30 bus system

The STATCOM power flow model described here is implemented in Newton-Raphson power flow algorithm using a program written in MATLAB. Multiple STATCOM placements (specifically at bus no.24 and 30 for most of the loading cases) have been considered to study different cases as discussed below, with main focus on maintaining the flat voltage profile.

*Case1: Stressed Load Condition*

Here the load flow studies with and without STATCOM is carried out under stressed conditions. These conditions are created on the system considering following sets of load increase pattern at all load buses simultaneously as follows-

- Set a: Active load change
- Set b: Reactive load change
- Set c: Both Active and Reactive load change

From the results of load flow solution, STATCOM has been assumed to be placed at those particular buses with relatively low voltage magnitude. It has been found that multiple STATCOM placement improves the voltage profile of the concerned buses better than single STATCOM. It is observed that effect of active load increment on voltage magnitude is less in comparison with the reactive load increment since active power is weakly coupled with voltage magnitude. The results thus obtained are encouraging and have been presented in Tables I-III.

TABLE I
VOLTAGE MAGNITUDE PROFILE FOR ACTIVE LOAD INCREMENT (SET A)

| Load Increment (1.8 p.u. to 2 p.u.) | Control Parameters (p.u.) | | | |
|---|---|---|---|---|
| | $Vm_{24}$ | $Vm_{26}$ | $Vm_{29}$ | $Vm_{30}$ |
| Without STATCOM | 0.9125 | 0.8871 | 0.8939 | 0.8720 |
| | 0.9067 | 0.8798 | 0.8860 | 0.8627 |
| | 0.8958 | 0.8677 | 0.8737 | 0.8489 |
| With STATCOM (multiple placement at bus no.24 &30) | 1.0000 | 0.9648 | 0.9831 | 1.0000 |
| | 1.0000 | 0.9600 | 0.9868 | 1.0000 |
| | 1.0000 | 0.9560 | 0.9841 | 1.0000 |

TABLE II
VOLTAGE MAGNITUDE PROFILE FOR RECTIVE LOAD INCREMENT (SET B)

| Load Increment (3.6 p.u. to 4p.u.) | Control Parameters (p.u.) | | | |
|---|---|---|---|---|
| | $Vm_{24}$ | $Vm_{26}$ | $Vm_{29}$ | $Vm_{30}$ |
| Without STATCOM | 0.7836 | 0.7532 | 0.8051 | 0.7826 |
| | 0.7620 | 0.7273 | 0.7833 | 0.7594 |
| | 0.7415 | 0.7035 | 0.7644 | 0.7391 |
| With STATCOM | 1.0000 | 0.9461 | 0.9918 | 1.0000 |
| | 1.0000 | 1.0000 | 0.9463 | 0.9268 |
| | 1.0000 | 1.0000 | 0.9398 | 0.9197 |

TABLE III
VOLTAGE MAGNITUDE PROFILE FOR BOTH ACTIVE AND REACTIVE LOAD INCREMENT (SET C)

| Line considered for outage | | Without STATCOM | | | | With STATCOM | | | |
|---|---|---|---|---|---|---|---|---|---|
| Line No. | Lines from and to | $Vm_{24}$ (p.u.) | $Vm_{26}$ (p.u.) | $Vm_{29}$ (p.u.) | $Vm_{30}$ (p.u.) | $Vm_{24}$ (p.u.) | $Vm_{26}$ (p.u.) | $Vm_{29}$ (p.u.) | $Vm_{30}$ (p.u.) |
| 1 | 22-24 | 0.8187 | 0.8004 | 0.8275 | 0.8002 | 1.0000 | 0.9474 | 0.9827 | 1.0000 |
| 2 | 23-24 | 0.8356 | 0.8118 | 0.8349 | 0.8088 | 1.0000 | 0.9471 | 0.9824 | 1.0000 |
| 3 | 24-25 | 0.8482 | 0.8426 | 0.8551 | 0.8298 | 1.0000 | 0.9275 | 0.9787 | 1.0000 |
| 4 | 27-29 | 0.8470 | 0.8668 | 0.6667 | 0.6936 | 1.0000 | 0.9379 | 1.0000 | 0.9411 |
| 5 | 27-30 | 0.8387 | 0.7892 | 0.6885 | 0.5663 | 1.000 | 0.9467 | 0.9742 | 1.0000 |
| 6 | 29-30 | 0.8528 | 0.8206 | 0.8637 | 0.7654 | 1.0000 | 0.9475 | 0.9692 | 1.0000 |

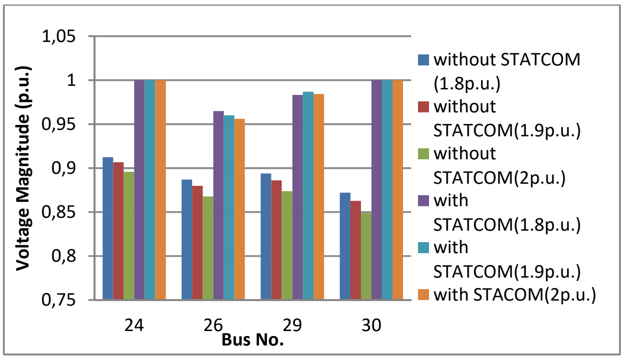


Fig. 5 Voltage magnitude profile with and without STATCOM for active load change

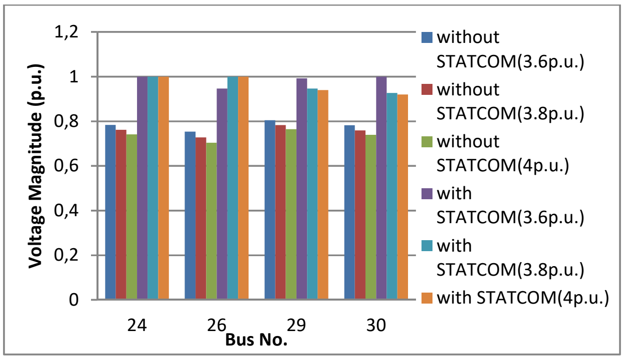


Fig. 6 Voltage magnitude profile with and without STATCOM for reactive load change

Figs. 5-7 reveal that the STATCOM connected in the system is able to maintain the system voltage profile under the load increased pattern.

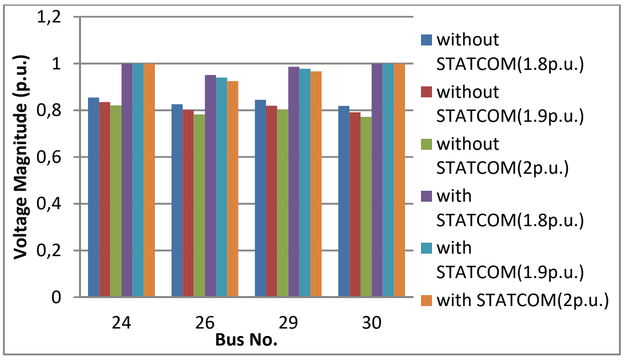


Fig. 7 Voltage magnitude profile with and without STATCOM for both active and reactive load change simultaneously

*Case 2: Contingencies Analysis (Line outage)*

The relatively high cost of STATCOM requires considerable justification. Contingencies like line outages have the greatest effect on the cost to benefit ratio. In general, there is potential for improvements in voltage stability under this type of contingency through the use of STATCOM. The analysis has been carried under novel load increase pattern as mentioned in case 1 (set a, b, and c). The results of set b only are presented in Tables IV-VI. Such analysis shows that the installation of STATCOM in single line outage contingency may significantly improves the voltage stability. While carrying out load flow analysis, it is found that the load buses 24, 26, 29 and 30 need to be analyzed during line outage contingencies and hence only the lines connected to these buses are considered.

TABLE IV
CONTINGENCY ANALYSIS UNDER STRESSED CONDITIONS (SET A)

| Line considered for outage | | Without STATCOM | | | | With STATCOM | | | |
|---|---|---|---|---|---|---|---|---|---|
| Line No. | Lines from and to | $Vm_{24}$ (p.u.) | $Vm_{26}$ (p.u.) | $Vm_{29}$ (p.u.) | $Vm_{30}$ (p.u.) | $Vm_{24}$ (p.u.) | $Vm_{26}$ (p.u.) | $Vm_{29}$ (p.u.) | $Vm_{30}$ (p.u.) |
| 1 | 22-24 | 0.6625 | 0.6374 | 0.7168 | 0.6897 | 1.0000 | 1.0000 | 0.9310 | 0.9106 |
| 2 | 23-24 | 0.7043 | 0.6737 | 0.7437 | 0.7177 | 1.0000 | 1.0000 | 0.9211 | 0.9096 |
| 3 | 24-25 | 0.7178 | 0.7664 | 0.8067 | 0.7829 | 1.0000 | 0.9072 | 1.0000 | 0.9556 |
| 4 | 27-29 | 0.7279 | 0.6785 | 0.5582 | 0.5978 | 1.0000 | 0.9330 | 1.0000 | 0.9587 |
| 5 | 27-30 | 0.7239 | 0.6698 | 0.6327 | 0.5133 | 1.0000 | 0.9375 | 0.9864 | 1.0000 |
| 6 | 29-30 | 0.7400 | 0.7003 | 0.7848 | 0.6936 | 1.0000 | 0.9352 | 0.9747 | 1.0000 |

TABLE V
CONTINGENCY ANALYSIS UNDER STRESSED CONDITIONS (SET B)

| Load Increment (1.8 p.u. to 2p.u.) | Control Parameters (p.u.) | | | |
|---|---|---|---|---|
| | $Vm_{24}$ | $Vm_{26}$ | $Vm_{29}$ | $Vm_{30}$ |
| Without STATCOM | 0.8552 | 0.8258 | 0.8445 | 0.8189 |
| | 0.8352 | 0.8010 | 0.8197 | 0.7915 |
| | 0.8205 | 0.7830 | 0.8023 | 0.7717 |
| With STATCOM | 1.0000 | 0.9515 | 0.9859 | 1.0000 |
| | 1.0000 | 0.9398 | 0.9777 | 1.0000 |
| | 1.0000 | 0.9251 | 0.9672 | 1.0000 |

Fig. 8 shows that the STATCOM connected to the critical lines (lines with low voltage magnitude) is able to maintain the system voltage profile under the novel load increased pattern.

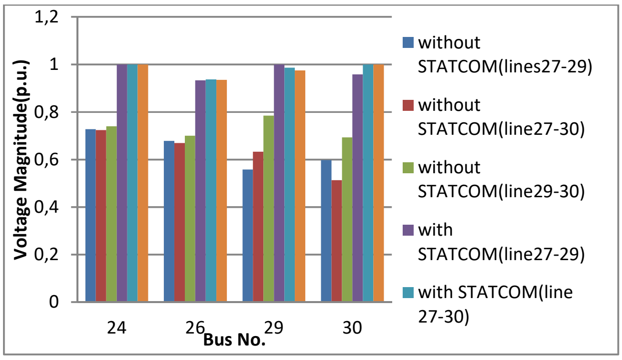


Fig. 8 Voltage magnitude profile with and without STATCOM for critical lines under stressed condition.

TABLE VI
CONTINGENCY ANALYSIS UNDER STRESSED CONDITIONS (SET C)

| Line considered for outage | | Without STATCOM | | | | With STATCOM | | | |
|---|---|---|---|---|---|---|---|---|---|
| Line No. | Lines from and to | $Vm_{24}$ (p.u.) | $Vm_{26}$ (p.u.) | $Vm_{29}$ (p.u.) | $Vm_{30}$ (p.u.) | $Vm_{24}$ (p.u.) | $Vm_{26}$ (p.u.) | $Vm_{29}$ (p.u.) | $Vm_{30}$ (p.u.) |
| 1 | 22-24 | 0.8676 | 0.8487 | 0.8617 | 0.8359 | 1.0000 | 0.9518 | 0.9808 | 1.0000 |
| 2 | 23-24 | 0.8799 | 0.8566 | 0.8661 | 0.8410 | 1.0000 | 0.9516 | 0.9805 | 1.0000 |
| 3 | 24-25 | 0.8942 | 0.8694 | 0.8737 | 0.8489 | 1.0000 | 0.9319 | 0.9769 | 1.0000 |
| 4 | 27-29 | 0.8878 | 0.8498 | 0.7072 | 0.7298 | 1.0000 | 0.9374 | 1.0000 | 0.9331 |
| 5 | 27-30 | 0.8804 | 0.8334 | 0.7256 | 0.6131 | 1.0000 | 0.9440 | 0.9633 | 1.0000 |
| 6 | 29-30 | 0.8934 | 0.8622 | 0.8919 | 0.7955 | 1.0000 | 0.9516 | 0.9657 | 1.0000 |

*A. Impact of Initialization of STATCOM Parameters*

Proper initialization of STATCOM parameters is very much important to achieve a strong and quicker convergence of the Newton-Raphson load flow algorithm. Without proper initialization, the Newton-Raphson algorithm may sometimes diverge or take more iterations and time to converge. Table VII illustrates the impact of STATCOM initialization on the number of iterations and voltage magnitude.

TABLE VII
EFFECT OF INITIALIZATION OF STATCOM PARAMETERS

| Initial value of STATCOM parameters | | No. of iterations required | Remark |
|---|---|---|---|
| Vsh (p.u.) | θsh (deg.) | | |
| 1 | 0 | 5 | Satisfactory voltage magnitude for flat voltage profile (Vi≈1.05p.u.) along with feasible value state variables of STATCOM |
| 0.7 | 0 | 5 | |
| 0.92 | 0 | 5 | |
| 1.3 | 0 | 5 | |
| 1.5 | 0 | 6 | |
| 1 | -1 | 8 | Too low voltage magnitude below Vi≈1.05p.u. with remarkable rise in state variables of STATCOM which is not feasible to design the STATCOM |
| 1 | 1 | 7 | |
| 1 | 2 | 50 | |
| 1 | -2 | 50 | |
| 1.3 | 1 | 7 | Satisfactory voltage magnitude for flat voltage profile (Vi≈1.05p.u.) along with feasible value state variables of STATCOM |
| 1.5 | -1 | 8 | |

## VI. CONCLUSIONS

This paper presents a systematic modification of the conventional power flow solution technique to include FACTS controller- STATCOM. MATLAB programming based code is found to be effective for analysis of the standard IEEE30 bus test system under different load conditions. This includes load increase pattern which incorporates load change (active, reactive and both active and reactive) at all load buses simultaneously and the line contingencies for steady state power flow calculations of power system with STATCOM. With these arrangements encouraging results are obtained.

The main contribution of this paper can be concluded as –

1. A simple and systematic approach presented to carry load flow analysis with STATCOM, effectively, under novel load increase scenario and line contingencies for the enhancement of voltage stability.
2. It has been shown that proper initialization of STATCOM parameters have significant impact on the power flow analysis.
3. Voltage magnitude on the buses which are far from weak buses gets improved by very little percentage, for installation of single unit of STATCOM at the weak bus. Thus, for such case, multiple STATCOM placements at the concerned buses significantly improve voltage magnitude. For multiple placement of STACOM, weak bus is considered as one bus while the bus, far away from that weak bus have been chosen as other bus. Such STATCOM placement strategy helps to maintain flat voltage profile at all the buses.

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