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Transmission SystemLoadability Improvement using FACTs

Mariya Mohammed[1],Mohammed Ali Abdallah[2]

Abstract: *-Due to the increasing demand for electricity and transactions in power markets, existing power grids need to be enhanced in order to increase their loadability.Flexible AC Transmission Systems (FACTS) technology is very beneficial in enhancing power flow along transmission lines and making the power grid more efficient and controllable. In this paper two types of FACTS devices, STATCOM and TCSC, placed on buses and transmission lines. Many cases studywere taken to test how the system acts in the presence and absence STATCOM or/and TCSC under increase load and outage line conditions. Both STATCOM and TCSC in same zone work to reduce the over load line, improve the bus voltage, and return the system to its working limits after contingency conditions. STATCOM or/and TCSC steady-state model was adopted on the IEEE-30 bus test system and tested using the MATLAB programming language. Newton-Raphson numerical analysis approach was used to solveSTATCOM or/and TCSC load flow.*

1. Introduction

The power flow in transmission lines is important with growth of modern power grid. The key requirements for transmission services are adequate enhancement of the transmission capability. Flexible ac transmission devices (FACTS) help to reduce power flow on overloaded lines, which increase improvement of the voltage profile, loadability, and reduce transmission loss. New emerging technology will be FACTs and its function is to enhance controllability and power transfer capability in AC systems. FACTS controller is capable of controlling interrelated line parameters and other operating variables governing transmission system operation which includes line impedance Z, current, voltage, phase angle δ, and oscillation damping .FACTs controller allow transmission line to transport power close to its thermal ratings.[1]

Flexible AC transmission system should offer benefits in increasing system transmission capacity and power flow control flexibility[2].Under stressed conditions, providing reactive power support with a shunt FACTS controller at exact locations is required to save the system from voltagecollapse. By positioning FACTS devices, the system's voltage profile and voltage stability margin can be maintained [3]. high voltage lines have high reactance and shunt capacitance in the series. Controlling the voltage, Stability by traditional means, so discovering solutions to these problems and restricting technological advancement within FACTS devices are desirable.

FACTS devices increase the reliability of the network system by re-dispatching the line flow in a manner that does not surpass the thermal willfully violating. The function of FACTS devices carried out by supplying or absorbing reactive power demand in order to increase or decrease voltage and control series impedance Transmission lines, or angles of phase is presented in[2][4]. In [5],sensitivity based approach was used to locate STATCOM for improving the power system loadability. Authors in[6] TCSC used to improve system performance by regulating power flows in the network and to reduce / eliminate overloads on transmission lines under network contingencies. The Newton-Raphson Power Flow Approach was used to perform the above-mentioned studies. The performance of the proposed algorithm was tested for the IEEE-14 bus network. Programming of the Power Flow Test MATLAB. In[7],FACTS power grid. Different indicators were chosen for the correct TCSC position. The quest was checked on the IEEE-30 Bus network, and the findings revealed a decrease in line loading as the incident triggered accumulation of fonts near to operational limits.

MSc. Student [1], Asst. Prof. Dr[2]
Electrical Engineering Department College of Engineering University of Mosul

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devices such as TCSC, STATCOM, static var compensators (SVC), and unified power flow controllers (UPFC) control the power outputs in the network, thereby reducing the burden of flow through heavily loaded lines by increasing loadability, reducing system losses, improving system stability and reducing production costs. In[8] is modifyTCSC the reactance of the transmission line to regulate its efficiency and to reduce the risk impact on the

In this paper, two different controllers are chosen. The first is the Static Synchronous Compensator (STATCOM), which is used to produce or absorb reactive power at the bus, supplying the mounted bus with voltage support. The second is Thyristor Controlled Series Compensator (TCSC), which is used in a transmission network to control the active power flow as desired. Numerical analysis is performed on standard IEEE-30 bus system to demonstrate the TCSC and STATCOM performance.

2. FACTS Modelling:

FACTS devices have to be mathematically modelled for the steady state analysis. In this approach (TCSC) and (STATCOM) are used as FACTS devices within the transmission network.

2.1Thyristor Controlled Series Compensator (TCSC):

By modifying the line reactance TCSC functions as either an inductive or a capacitive compensator. The maximum capacitance value is set at (-0.7XLine)and the maximum inductance value is(0.3XLine) where XLine is the line reactance. [10][11]

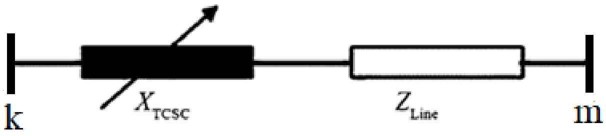

Fig (1): TCSC with transmission line

TCSC allows for quicker transmission line impedance changes. Fig (1) shows the mathematical model of transmission line connected with TCSC,whereXLineis the reactance ofthe transmission line; andr_{TCSC} is the coefficient which represents the compensationdegree of TCSC

$$Z_{Line} = R + X_{Line} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$X_{km} = X_{Line} - X_{TCSC} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$X_{TCSC} = r_{TCSC} \times X_{Line} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The TCSC power flow model proposed in this study is based on the simple concept of a variable series reactance, whose value is automatically adjusted to constrain the power flow across the branch to a specified value. The total amount of reactance is easily measured using Newton 's method. The changing XTCSC reactance shown in Fig (1) which is the equivalent reactance of all the TCSC series-connected modules when operating in either the inductive or the capacitive regions.[9]

The variable series compensator transfers admittance matrix shown in Fig (1):

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

For inductive operation:

$$B_{mm} = B_{kk} = -\frac{1}{X_{TCSC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$B_{km} = B_{mk} = \frac{1}{X_{TCSC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

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and the signs are reversedfor capacitive operation.The active and reactive power equations in bus k are as follows

$$P_k = V_k V_m B_{km} \sin(\theta_k - \theta_m) \;\ldots\ldots\ldots..(7)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m) \ldots\ldots\;(8)$$

For power equations in bus m, subscriptions k and m are exchanged in equations (7) and (8). When using TCSC to regulate the flow of power in line k-m, the set of power flow equations is given by

$$\begin{bmatrix} \Delta P_K \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{X_{TCSC}} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial P_m}{\partial \theta_K} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial P_{km}^{X_{TCSC}}}{\partial \theta_k} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial \theta_m} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_k} V_k & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_m} V_m & \frac{\partial P_{km}^{X_{TCSC}}}{\partial X_{TCSC}} X_{TCSC} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta \theta_m \\ \frac{\Delta V_K}{V_K} \\ \frac{\Delta V_m}{V_m} \\ \frac{\Delta X_{TCSC}}{X_{TCSC}} \end{bmatrix} \ldots\ldots(9)$$

$$\Delta P_{km}^{X_{TCSC}} = P_{km}^{reg} - P_{km}^{X_{TCSC},cal} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\;(10)$$

$$\Delta X_{TCSC} = X_{TCSC}{}^{(i)} - X_{TCSC}{}^{(i-1)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\;(11)$$

At the end of each iteration stage the series controller 's state variable XTCSC is changed according to: [10][11]

$$X_{TCSC}{}^{(i)} = X_{TCSC}{}^{(i-1)} + \left(\frac{\Delta X_{TCSC}}{X_{TCSC}}\right)^{(i)} X_{TCSC}{}^{(i-1)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(12)$$

2.2.Static Synchronous Compensator (STATCOM):

STATCOM is able to share only reactive power with the power systems. It can regulate the magnitude of the bus voltage by injecting or absorbing reactive power from or to the bus on which it is connected. The bus that connected to the STATCOM is represented as a PV bus, which may change to a PQ bus in the event that limits are violated. In such a case, the reactive power generated or absorbed would correspond to the infringed limit. Unlike the SVC, the STATCOM is a voltage source for the full range of operations, which allows a more robust voltage support mechanism.[12]

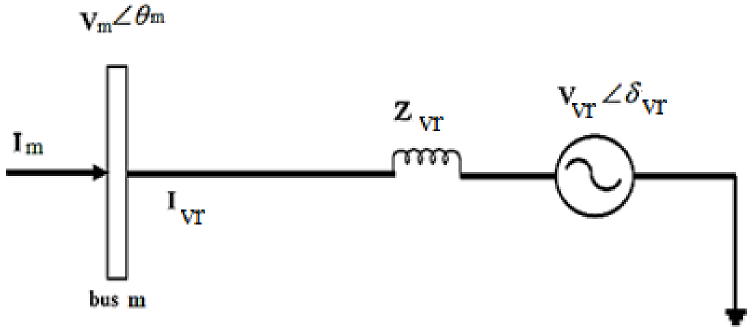

Fig (2):STATCOM Connected with Bus

The STATCOM equivalent circuit shown in Fig (2) is used to extract the controller's mathematical model power-flow algorithms.

The STATCOM power flow equations are derived from fig (2) below, and assume the following representation of the source of voltage:

$$E_{vr} = V_{vr}(\cos\delta_{vr} + j\sin\delta_{vr}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\;(13\,)$$

$$S_{vr} = V_{vr} I_{vr}^{*} = V_{vr} Y_{vr} (V_{vr}^{*} - V_m) \;\; \ldots\ldots\ldots\ldots\ldots\ldots(14\,)$$

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For the converter and bus m, the following active and reactive power equations are obtained after conducting certain complex operations, respectively:

$$P_{vr} = V_{vr}^2 G_{vr} + V_{vr} V_m [G_{vr} \cos(\delta_{vr} - \theta_m) + B_{vr} \sin(\delta_{vr} - \theta_m)] \quad \ldots\ldots\ldots (15)$$

$$Q_{vr} = -V_{vr}^2 G_{vr} + V_{vr} V_m [G_{vr} \sin(\delta_{vr} - \theta_m) - B_{vr} \cos(\delta_{vr} - \theta_m)] \quad \ldots\ldots (16)$$

$$P_m = V_m^2 G_{vr} + V_{vr} V_m [G_{vr} \cos(\theta_m - \delta_{vr}) + B_{vr} \sin(\theta_m - \delta_{vr})] \quad \ldots\ldots (17)$$

$$Q_m = -V_m^2 G_{vr} + V_{vr} V_m [G_{vr} \sin(\theta_m - \delta_{vr}) - B_{vr} \cos(\theta_m - \delta_{vr})] \quad \ldots\ldots (18)$$

The linearized STATCOM model is shown below using these power equations, where the voltage magnitude V_{vr} a nd phase angleδ_{vr} are taken as the state variables:[14][13][11]

$$\begin{bmatrix} \Delta P_m \\ \Delta Q_m \\ \Delta P_{vr} \\ \Delta Q_{vr} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \delta_{vr}} & \frac{\partial P_m}{\partial V_{vr}} V_{vr} \\ \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \delta_{vr}} & \frac{\partial Q_m}{\partial V_{vr}} V_{vr} \\ \frac{\partial P_{vr}}{\partial \theta_m} & \frac{\partial P_{vr}}{\partial V_K} V_m & \frac{\partial P_{vr}}{\partial \delta_{vr}} & \frac{\partial P_{vr}}{\partial V_{vr}} V_{vr} \\ \frac{\partial Q_{vr}}{\partial \theta_m} & \frac{\partial Q_{vr}}{\partial V_m} V_m & \frac{\partial Q_{vr}}{\partial \delta_{vr}} & \frac{\partial Q_{vr}}{\partial V_{vr}} V_{vr} \end{bmatrix} \begin{bmatrix} \Delta \theta_m \\ \frac{\Delta V_m}{V_m} \\ \Delta \delta_{vr} \\ \frac{\Delta V_{vr}}{V_{vr}} \end{bmatrix} \quad \ldots\ldots\ldots (19)$$

3. Case Study and Results:

In this section, the proposed methodology is tested on the IEEE-30 bus system The system consists of 30 buses 6 generator bus,21 load bus and 41 lines [15][16].The configurationof IEEE 30 busshown in Fig (3).

Load flow analysis is performed with and without FACTS devicesunder single line contingency (outage line 2-4), increased load 7 with line contingency(outage line 5-7) and increase loaded (26,29,30).

FACTS devices proposed are STATCOM and TCSC simulated as described in section 2 and incorporated with a tolerance level of 1e-12 into the Newton Raphson load flow algorithm. STATCOM and TCSC are installed and their performance is analyzed in the test systems.

In all study cases presented were calculated ,voltage magnitude for buses, power flow in the transmission lines at with and without STATCOM and\or TCSC and find out how the addition of STATCOM and\or TCSC can maximize from the loadability and reduce from overload line.

The suitable size, location and the number of STATCOM and\or TCSC device choose based on the maintenance of limited bus voltage, reducing the power flow in overloaded lines.

In normal case (Base case), the voltage magnitudes of all busses and lines power flow are within the optimal limits as shown in fig (3) and fig (4).

In first study case, single line contingency (line 2-4is outage line). Fig (5) shows that the voltage magnitudes of several busses are not within the optimal limits. Fig (6) shows that line overloaded(2-6) and (6-8)carriers which indicate overloading. By adding two STATCOMs, one at bus 30to regulate busvoltage to 1.0 p.u and STATCOM at bus 8 to improves the reactive power flow in the nearby transmission lines,thenadding TCSC. TCSC are placed in line (1-3) the power flow line (1-3) is raised up to the its maximum flow limit of 128.7MVAthen line 2-6 carries power below the flow limit, continuity in power flow under the flow limit is achieved.and adding STATCOM and TCSC together regulate buses voltage and reduce power flow in overloaded lines as shown in table.1and table 2.

In second study case,increasedloads (26,29,30) by 100%. fig (8) shows that the voltage magnitudes of several busses are not within the optimal limits. fig (9) shows that lines overloaded (2-6) and (6-8) carriers which indicate overloading. when STATCOM is placed in bus 30 to regulate the voltage to 1.00 p.u. from 0.9260p.u, also improve the voltage of the nearby buses and improves the reactive power flow in the nearby transmission lines, then adding

TCSC at line (4-6) and line (6-8),to reducepower flow in overloaded lines, adding STATCOM and TCSC together in the system toregulate buses voltage, reduce power flow in overloaded lines as shown in table.1 and table 3.

In third study case, single line contingency (line 5-7 is outage line) and load 7 increase by 100%. Fig (6) shows that the voltage magnitudes of several busses are not within the optimal limits. Fig (10) shows that lines overloaded (1-2) and (6-8) carriers which indicate overloading. By adding one STATCOM at bus 7 regulate bus voltage to 1. pu from 97. 51p.u,the reactive power injected by the STATCOM the reactive power flow in the nearby transmission lines improves, so it reduces power flow in line (6-8) from 35.057 MVA to 30.15 MVA,which is an acceptable value under thermal limit.

The power flows in remaining lines are also in desirable limitsalso enhance the loadability of the neighborhoodline, then adding TCSC at line (1-3) to reduce power flow in overloaded lines, and adding one STATCOM at bus 7 to regulate buses and one TCSC at line (1-3) the power flow line is raised up to 104.388 MVA,reduce power flow in overloaded lines and enhance the loadability of the system as shown in table.1 and table.4.

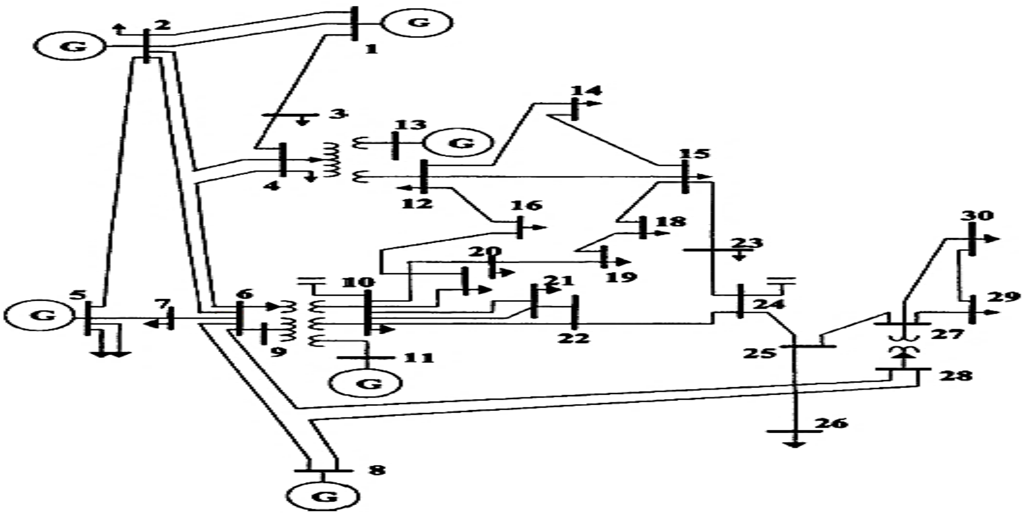

Fig (3):IEEE-30 bus system

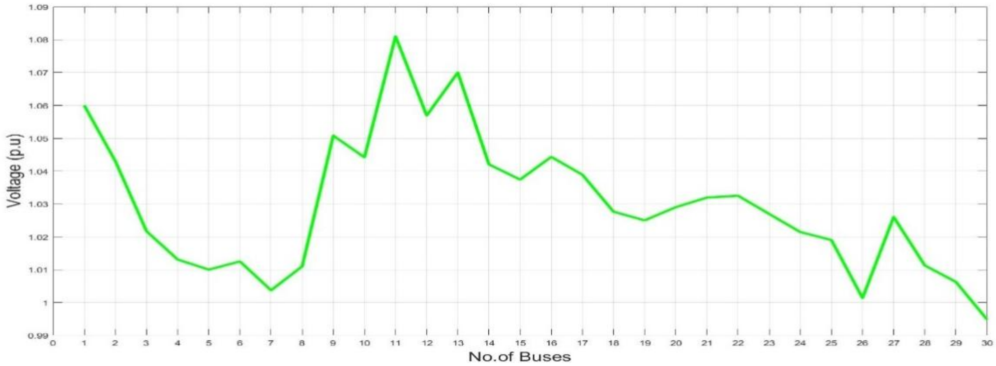

Fig (4): Voltages Magnitudes at the buses for IEEE-30 bus system base case

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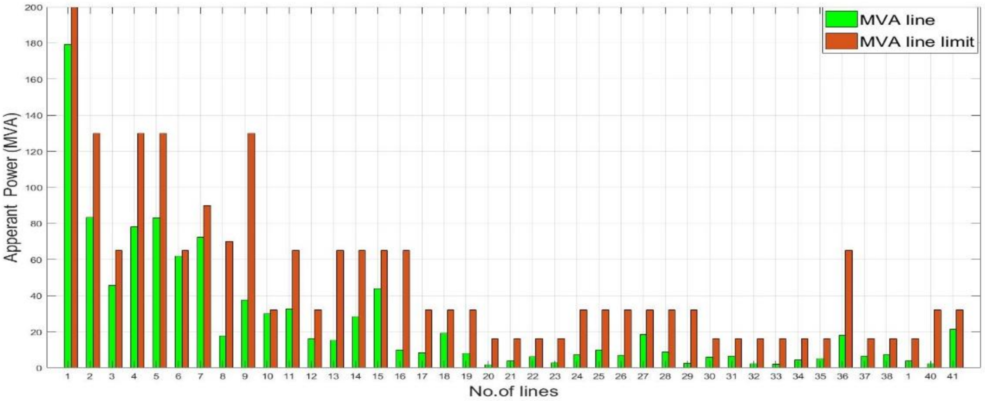

Fig (5): MVA base case and MVA line limit for IEEE-30 bus system base case

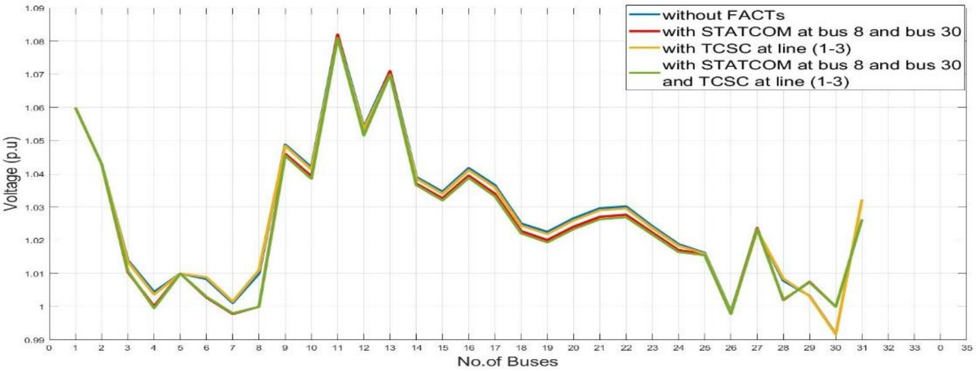

Fig (6): Voltages Magnitudes at the buses for IEEE-30 bus system line (2-4) outage

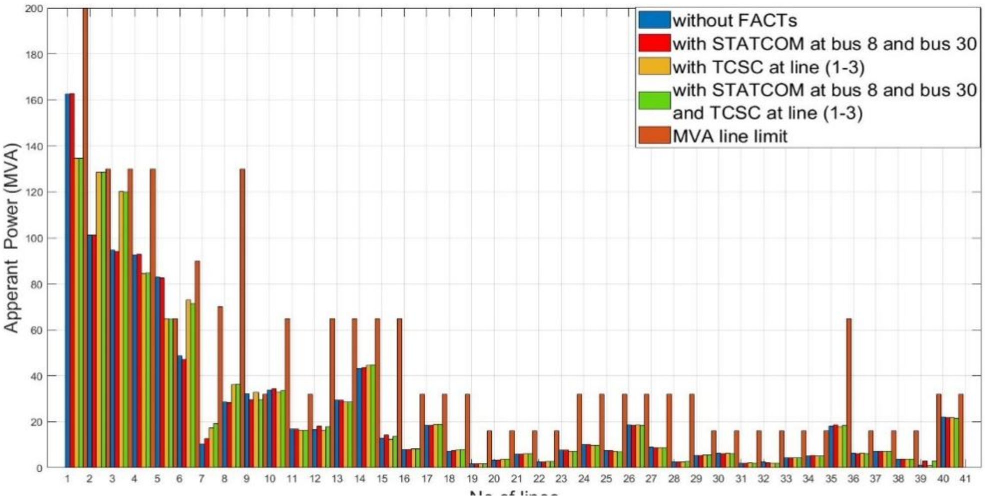

Fig (7): MVA at all lines in IEEE-30 bus system line(2-4) outage

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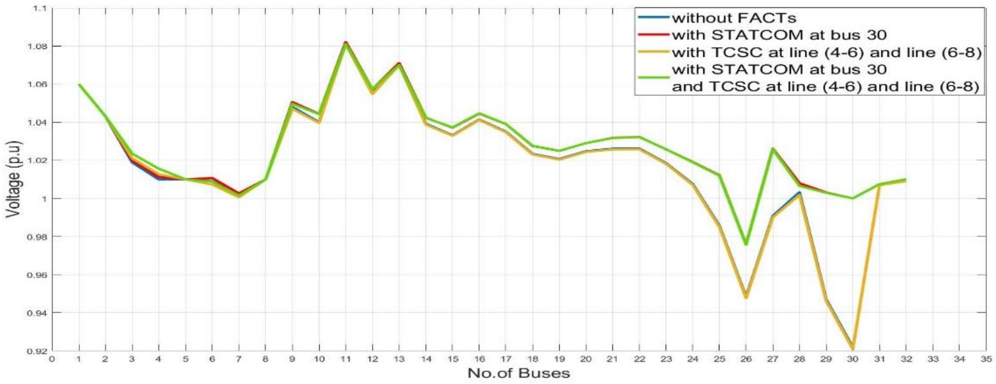

Fig (8): Voltages Magnitudes at the buses for IEEE-30 bus system

increased loads (26,29,30) by 100%

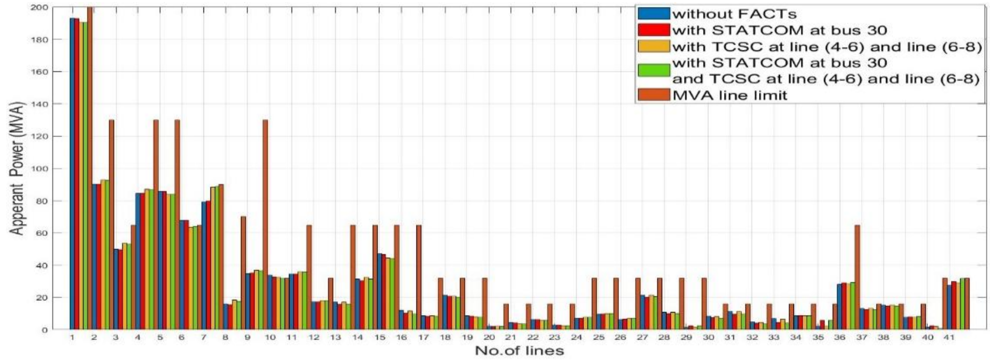

Fig (9) :MVAat all lines for IEEE-30 bus system increased loads(26,29,30) by 100%

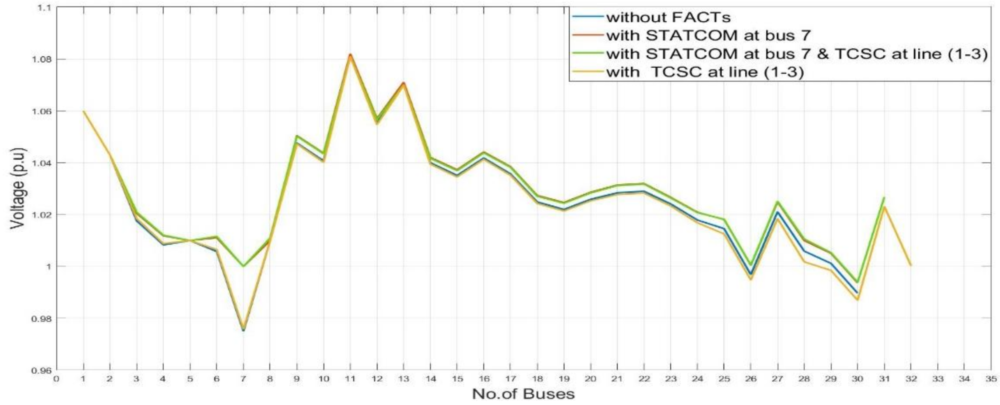

Fig (10): Voltages Magnitudes at the buses for IEEE-30 bus system
with line (5-7) outage and increasedload 7 by 100%

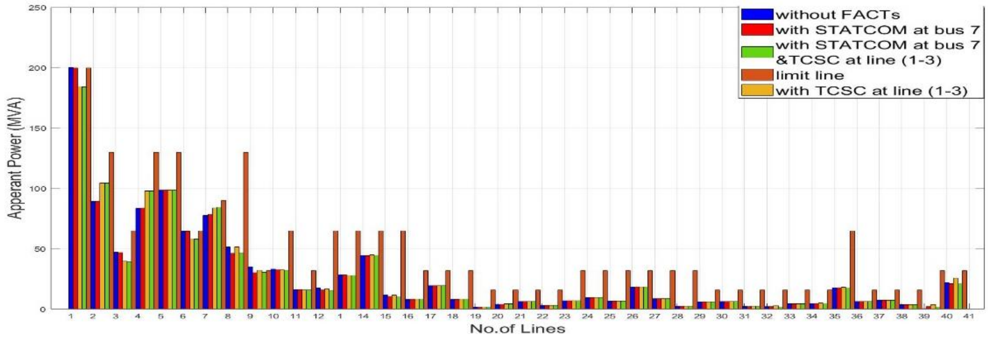

Fig (11):MVA at all linesfor IEEE-30 bus system
with line (5-7) outageand increasedload 7 by 100%

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Table 1:Matlab result with FACTs device

Case Study		**FACT Location**	**FACT Size**	**Overloaded Line**
Outage Line (2-4)	without FACTs			(2-6),(6-8)
	with SATCOM	Bus 8 Bus 30	Vvr_1= 1.0Tvr_1=-13.642 $PQSSC_1$ (p.u)0.0+ 0.0i Vvr_2= 1.0209 Tvr_2=-19.918 $PQSSC_2$ (p.u)0.0 - 0.0214i	(2-6),(6-8)
	with TCSC	Line 2 (1-3)	X_{TCSC} (p.u.)-0.1009 P_{TCSC} (p.u.)1.22, -1.22 Q_{TCSC} (p.u.) -0.264, 0.117	(6-8)
	with SATCOM & TCSC	Buses8,30 & line 2 (1-3)	Vvr_1= 1.0 Tvr_1 =-10.872 $PQSSC_1$ (p.u) 0.0 + 0.0i Vvr_2= 1.0217 Tvr_2 =-17.097 $PQSSC_2$ (p.u) 0.00 - 0.022i X_{TCSC} (p.u.) -0.1011 P_{TCSC} (p.u.) 1.27, -1.27 Q_{TCSC} (p.u.) -0.2313, 0.0833	None
Increased loads 26,29,30 by 100%	without FACTs			(2-6),(6-8)
	with SATCOM	Bus 30	Vvr= 1.10Tvr =-25.0 PQSSC (p.u) 0.00 - 0.1100i	(2-6),(6-8)
	with TCSC	Line 7 (4-6) & Line10 (6-8)	XTCSC1 (p.u.) -0.0232 PTCSC1 (p.u.) 0.85, -0.85 QTCSC1 (p.u.) -0.256, 0.2381 X TCSC2 (p.u.) 0.0156 PTCSC2 (p.u.) 0.305, -0.305 QTCSC2 (p.u.)0.112,-0.1135	None
	with SATCOM & TCSC	Bus 30 & Line 7 (4-6) Line 10 (6-8)	Vvr= 1.10 Tvr =-24.728 PQSSC (p.u) 0.00 - 0.0110i XTCSC1 (p.u.)-0.0218 PTCSC1 (p.u.) 0.85, -0.85 QTCSC1 (p.u.) -0.264, 0.247 X TCSC2 (p.u.) 0.0156 PTCSC2 (p.u.) 0. 306, -0. 306 QTCSC2 (p.u.) 0.0785, -0.08	None
Outage Line (5-7) & Increased Load bus (7) 100%	without FACTs			(1-2),(6-8)
	with SATCOM	Bus 7	Vvr= 1.0232Tvr =-14.445 PQSSC (p.u) 0.0 - 0.237i	(1-2)
	with TCSC	Line 2 (1-3)	XTCSC1 (p.u.) -0.0579 PTCSC1 (p.u.) 1.0, -1.0 QTCSC1 (p.u.) -0.11, 0.055	None
	with SATCOM & TCSC	Bus 7 & Line 2 (1-3)	Vvr= 1.0232Tvr =-11.43 PQSSC (p.u) 0.0 - 0.2392i XTCSC (p.u.) -0.0580 PTCSC (p.u.) 1.0, -1.0 QTCSC (p.u.) -0.1305, 0.754	None

Table 2: Improvement Loadablity in Case 2-4 Outage Line

Over load Line		without FACTs	line limit MVA	STATCOM		TCSC		STATCOM &TCSC	
From	To			Power flow (MVA)	improvement %	Power flow (MVA)	improvement %	Power flow (MVA)	improvement %
2	6	82.7	65	82.7	0.01	64.86	21.6	61.68	21.84
6	8	32.22	32	29.668	7.9	32.6	-	29.58	8.18

Table 3: Improvement Loadablity in Caseincreased loads (26,29,30) by 100%

Overload Line		without FACTs	line limit MVA	STATCOM		TCSC		STATCOM &TCSC	
From	To			Power flow (MVA)	improvement %	Power flow (MVA)	improvement %	Power flow (MVA)	improvement %
6	2	67.74	65	67.73	0.2	63.51	6.25	63.74	6

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6	8	33.76	32	32.79	2.9	32.55	3.6	31.6	6.3

Table 4: Improvement Loadablity in Case 5-7 Outage Line
and increase 100% load bus 7

Over load Line		without FACTs	line limit MVA	STATCOM		TCSC		STATCOM &TCSC	
From	To			Power flow (MVA)	improvement %	Power flow (MVA)	improvement %	Power flow (MVA)	improvement %
1	2	200.13	200	199.79	0.17	184.43	7.85	184.17	8
6	8	35.057	32	30.15	14.00	34.87	0.52	30.40	13.28

4. Conclusions: -

In this paper, the problem of loadability improvement is solved in the presence of STATCOM and TCSC while satisfying limitations on bus voltage, MVA limit of the transmission lines and device limits. The results obtained show that the series device (TCSC) enhances line active power flow by line's reactance thereby enhancing power flow and reducing congestion. The shunt device (STATCOM) enhances bus voltage thereby enhances reactive power flow of line, from the case studies shown FACTS devices (TCSC, STACOM) that improve bus voltages, line flows thereby enhancing line loadability and reduce congestion due to simultaneous control of active and reactive power. But, the results obtained in the found of both STATCOM and TCSC are compared with the results obtained in the found of individual device.

From third study case, obtained the best result when placed both STATCOM and TCSC in same zone work to reduce the over load line, and return the system to its working limits after it has been reached due to increase load bus 7 and line outage (5-7).

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