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Active Line Flow Control of Power System Network with FACTS Devices of choice using Soft Computing Technique

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ABSTRACT

FACTS technology opens up new opportunity for operation and control of power system. Out of the various FACTS devices (viz-TCSC, TCPST, UPFC etc.), the right choices for the maximization of power flow in power system network demands attention which helps to achieve the active power flow up to their line limits without any constraint violation and with optimal investment on FACTS devices. In this paper, an algorithm has been developed for right choices of various combination of FACTS in the power network to enhance the power transfer capability of existing lines under normal condition very close to their line limits and has been applied for modified IEEE 14- bus system. This helps the optimal investment in FACTS devices and easy control. The proposed method is based on load flow and line flow equation In this paper Newton Raphson and modified simulated annealing technique are proposed

General Terms

Newton Raphson, IEEE 14- bus system, FACTS devices

Keywords

FACTS, TCSC, TCPST.

1. INTRODUCTION

Deregulation of the electricity supply system becomes an important issue in many countries. The global deregulation trends in Electric Supply Industry (ESI) throughout the world act as a vital force in favor of new technologies to best suit the existing power system resources without compromising the system security and social maximization [1,2]. It demands the efficient control of power system network. Under these circumstances, flexible A.C. transmission system (FACTS) appears to be the most appropriate solution for controlling power flow in a power system network because of its excellent flexibility and versatility [3,4,5]. The FACTS technology helps to extend the capacity of existing power system networks up to its thermal limits without the necessity of adding new transmission lines. This capability is helping the ESI to overcome the difficulties to add new transmission lines due to environmental and right- of- way restrictions. FACTS is an outcome of the development of solid state power electronics converters which are being used for power flow control at transmission level of the power system network [6]. In many situations it becomes necessary to increase the power transfer capability of some lines with the installation of facts devices. The main advantages of FACTS are the ability in enhancing system flexibility and increasing the laudability.[7]

In steady state operation of power system, unwanted loop flow and parallel power flow between utilities are problems in heavily loaded interconnected power systems. However ,with the FACTS Controllers, the unwanted power flow can be easily regulated[8,9,10].In this paper, TCSC, TCPST FACTS devices is used for the maximization of power flow in power system network which helps to achieve the active power flow up to their line limits without any constraint violation and with optimal investment on FACTS devices. This paper focuses on the use of multiple FACTS devices to increase the active power flow for selected lines up to its thermal limits. This paper analyses the right choices of various combination of FACTS devices to eliminate the shortcomings of individual ones. Authors have developed an algorithm for proper choice of multiple FACTS devices in the power network to enhance the power transfer capability of existing lines under normal condition very close to their line limits .This algorithm has been applied for modified IEEE 14- bus system[11,13] .

2. MODELING OF FACTS DEVICES

Facts technology opens up new opportunities for controlling line power flows, minimizing losses and maintaining bus voltages at desired level in a power system network. These are done by controlling one or more of the interrelated system parameters including series impedance, shunt impedance, current, voltage, phase angle etc. with the insertion of facts controllers in a power system network. Facts controllers may be categorized into four types:

- Series Controllers
- Shunt Controllers
- Combined Series-Series Controllers
- Combined Series-Shunt Controllers

Only one FACTS device of a given type per branch may be allowed.

2.1 Thyristor-Controlled Series Compensator (TCSC)

It is basically a variable impedance, such as capacitor, reactor etc. Series Controllers inject voltage in series with the line. As long as the voltage is in phase quadrature with the line current, the Series Controller only supplies or consume variable reactive power. Any other phase relationship, it will involve handling of real power. The value of TCSC (X_{TCSC}) is function of the reactance of the line X_L where the device is located. The maximum value of capacitive type TCSC is fixed at $-0.8X_L$. For inductive type, the maximum value is $0.2X_L$ [11].This type device can be cost-effective means of controlling the power flow when the angle between two bus voltages is small.

The equivalent circuit of TCSC is shown in Figure.1

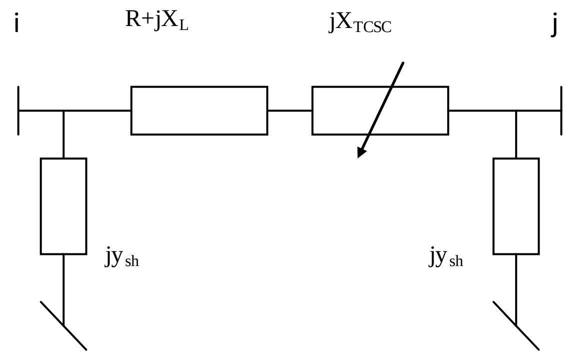

Figure.1. **Equivalent Circuit of TCSC**

The real and reactive power flow from bus i to bus j can be expressed as

$$P_{ij} = V^2{}_i G_{ij} - V_i V_j G_{ij} \cos(\delta_i - \delta_j) - V_i V_j B_{ij} \sin(\delta_i - \delta_j)$$

$$Q_{ij} = V^2{}_i (B_{ij} + B_{sh}) - V_i V_j G_{ij} \sin(\delta_i - \delta_j) + V_i V_j B_{ij} \cos(\delta_i - \delta_j)$$

Similarly, the real and reactive power flow from bus j to bus i can be expressed as

$$P_{ji} = V^2{}_j G_{ij} - V_i V_j G_{ij} \cos(\delta_i - \delta_j) + V_i V_j B_{ij} \sin(\delta_i - \delta_j)$$

$$Q_{ji} = -V^2{}_j (B_{ij} + B_{sh}) + V_i V_j G_{ij} \sin(\delta_i - \delta_j) + V_i V_j B_{ij} \cos(\delta_i - \delta_j)$$

The active and reactive power loss on each line k can be formulated as

$$P_{LK} = P_{ij} + P_{ji} = V_j^2 G_{ij} + V_i^2 G_{ij} - 2V_i V_j B_{ij} \cos(\delta_i - \delta_j)$$

$$Q_{LK} = Q_{ij} + Q_{ji} = -V_i^2 (B_{ij} + B_{sh}) - V_j^2 (B_{ij} + B_{sh}) + 2V_i V_j \cos(\delta_i - \delta_j)$$

2.2 Thyristor-Controlled Phase Shifting Transformer (TCPST)

This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner. In principle, combined series and shunt Controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. The model of the transmission line with TCPST [12] is shown in Figur

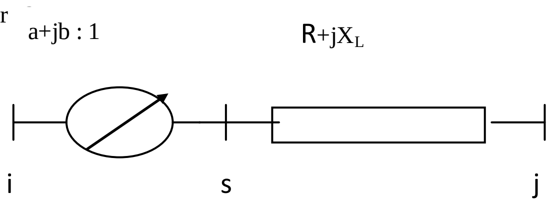

Figure 2. **Equivalent Circuit of TCPST.**

This device can control the voltage phase shift angle. By varying the voltage phase shift angle, active power flow is controlled. The active power flow of a overloaded line can be decreased with negative phase shift and that of a under-loaded line can be increased up to almost the rated capacity.

The real and reactive power flows from bus i to bus j can be derived as,

$$P_{ij} = \frac{V_i^2 G_k}{t_s^2} - \frac{V_i}{t_s} V_j G_k \cos(\delta_i - \delta_j - \varphi) - \frac{V_i}{t_s} V_j V_i B_k \sin(\delta_i - \delta_j - \varphi)$$

$$Q_{ij} = \frac{V_i G_k}{t_s^2} - \frac{V_i}{t_s} V_j G_k \sin(\delta_i - \delta_j - \varphi) - \frac{Vi}{t_s} V_j B_k \cos(\delta_i - \delta_j - \varphi)$$

$$P_{ji} = V_i^2 G_k - \frac{V_i}{t_s} V_j G_k \cos(\delta_i - \delta_j - \varphi) - \frac{V_i}{t_s} V_j B_k \sin(\delta_i - \delta_j - \varphi)$$

The real and reactive power loss (P_{LK}, Q_{LK}) in the line having the TCPR can be expressed as,

$$P_{LK} = -\frac{V_i}{t_s^2}^2 G_K + V_i G_K - \frac{2}{t_s} V_i V_j G_K \cos(\delta_i - \delta_j - \varphi)$$

The range of the phase shift angle is

$$-15 \deg. \le \delta_{TCPST} \le 15 \deg.$$

2.3 Static Var Compensator (SVC)

The SVC is a Shunt type Controller and may be variable impedance, variable sources or a combination of these. In principle, it injects current into the system at the point of connection. As long as the injected current is in phase quadrature with the line voltage, it only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. This device is used to maintain bus voltages at desired level. The compensator is inductive if reactive power has to be absorbed and capacitive if reactive power has to be supplied to maintain the voltage level within specified limit.

3. MATHEMATICAL FORMULAE

Let a line has series impedance $z = R + j X_L$. When a variable series reactance X_{TCSC} is inserted in the line then series admittance of the line will be modified as

$$y = 1/\left[R + j\left(X_L - X_{TCSC}\right)\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

and the bus admittance matrix can be written as

$$[Y_{BUS}] = [Y] + [Y_{sh}] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where $[Y]$ is a square matrix of net series admittance and

$[Y_{sh}]$ is a diagonal matrix of half line charging susceptance.

Insertion of TCPST having a complex tapping ratio $a + jb : 1$ will modify $[Y]$ as

$$[Y_{\mathrm{mod}\,i}] = \begin{bmatrix} Y_{ii}/T_s^2 & -Y_{ij}/T_s^* \\ -Y_{ji}/T_S & Y_{jj} \end{bmatrix}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, $T_s = a + jb$

$$= t_s \angle \phi$$

Now, if a SVC is also connected to a bus then modified bus admittance matrix can be written as

$$[Y_{BUS}]\mathrm{mod}\,i = [Y_{\mathrm{mod}\,i}] + [Y_{sh}] + [B_{SVC}] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where $[B_{SVC}]$ is a diagonal matrix of variable shunt susceptance (b_{SVC})

3.1 Loss sensitivity indices

The proposed method utilizes the sensitivity of total transmission loss (P_L) with respect to the control parameters of FACTS devices for their optimal placement. The control parameters for the three FACTS devices include line net series reactance (X_K placed in line k) for TCSC, phase angle shift (φ_k placed in line k) for TCPST and reactive power injection (Q_i placed at bus i) for SVC. Thus, the loss sensitivity factors with respect to the parameters of these devices can be defined as,

$a_k = \dfrac{\partial P_L}{\partial X_k}$ = Loss sensitivity with respect to TCSC placed in line k (k=1,…..N_l)

$b_k = \dfrac{\partial P_L}{\partial \varphi_k}$ = Loss sensitivity with respect to TCPAR placed in line k (k=1,…..N_l)

$c_i = \dfrac{\partial P_L}{\partial Q_i}$ = Loss sensitivity with respect to SVC placed at bus I (i=1,…..N_l)

These factors can be computed at a base load flow solution as given below.

Consider a line k connected between bus i and bus j and having series impedance R_k+jX_k. X_k is the net reactance considering the reactance of the series compensator, if present in the line. Let the complex voltages at the buses i and j be V $\angle\delta_i$ and $V\angle\delta_j$, respectively. $\varphi_k = \delta_i - \delta_j$ is the net phase shift in the line k including the effect of the phase shifter. The loss sensitivity with respect to the TCSC parameter will be,

$$\frac{\partial P_L}{\partial X_k} = \left[\frac{V_i}{t_s^2} + V_j - 2\frac{V_i}{t_s}V_j\cos(\delta_i - \delta_j)\right] \left[2\frac{R_k X_k}{(R_k^2 + X_k^2)^2}\right]$$

, $k=1\ldots..N_l$

and the loss sensitivity index of phase shift (φ_k) to total power loss will be ,

$$\frac{\partial P_L}{\partial \varphi_k} = 2\frac{V_i}{t_s}V_j G_k \sin(\varphi_k),$$

k=1………..Nl

For computing the loss sensitivity index with respect to SVC an exact loss formula has been used , which express PL as,

$$P_L = \sum_{j=1}^{N}\sum_{i=1}^{N}\left[\alpha_{jk}(P_jP_k + Q_jQ_k) + \beta_{jk}(Q_jP_k - P_jQ_k)\right]$$

Where α and β are the loss coefficients defined as,

$$\alpha_{jk} = \frac{r_{jk}}{V_jV_k}\cos(\delta_j - \delta_k)$$

$$\beta_{jk} = \frac{r_{jk}}{V_jV_k}\sin(\delta_j - \delta_k)$$

Pi+jQi is the complex injected power at bus i and rjk is the real part of the jk^{th} element of [Zbus].

At bus i , the sensitivity index with respect to the SVC parameter using the above loss formula can be expressed as,

$$\frac{\partial P_L}{\partial Q_i} = 2\sum_{j=1}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j)\,, \qquad i = 1.........N$$

3.2 Criteria for Optimal Placement

FACTS devices should be placed on the most sensitive bus or line. With the loss sensitivity indices computed for each type of the FACTS devices, the following criteria have been used for their optimal placement.

(1)The TCSC should be placed in a line (m) having most positive loss sensitivity index (am).

(2)The TCPAR should be placed in a line (n) having largest absolute value of the sensitivity factor bn.

(3)The SVC should be placed at a bus i having most negative sensitivity index ci.

The following additional criteria have also been used while deciding on the optimal placement of FACTS. The

devices. The TCSC and TCPAR should not be placed between two generation buses, even though the line sensitivity is highest.

(1)The placement of SVC has been considered at load buses only.

4. EXAMPLE

The proposed method has been tested for special IEEE 14-bus system as shown in Fig.3. Four FACTS devices are inserted in four lines in the given system.

FACTS1, FACTS2, FACTS4 are TCSC devices and FACTS3 is TCPST device. These four devices are connected to increase the active power flows of the selected lines very close to its thermal limits and to find out the minimum values of the devices parameters. The FACTS devices are inserted progressively one at a time. A capacitive type shunt compensator is also connected in bus no. 9. The line parameters and bus parameters are given in tables 1 and 2.

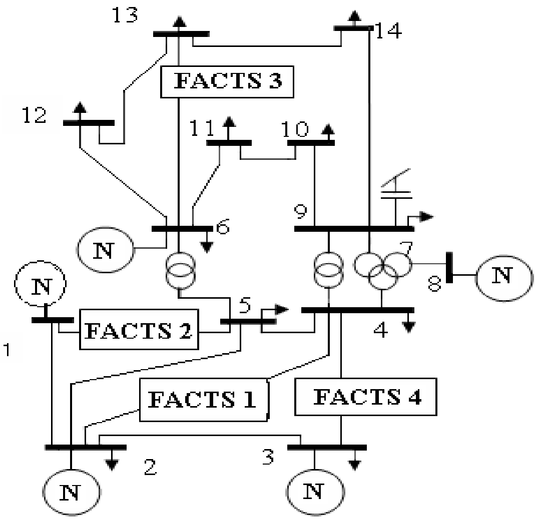

Figure:-3 Modified IEEE14 Bus System with FACTS

Table.1: Line parameters of the modified IEEE-14 bus system

Line Nos	i	j	R	X_L	y_{sh}	t_s
1	1	2	0.01938	0.05917	0.0264	1.00
2	2	3	0.04699	0.19797	0.0219	1.00
3	2	4	0.05811	0.17632	0.0187	1.00
4	1	5	0.05403	0.22304	0.0246	1.00
5	2	5	0.05695	0.17388	0.0170	1.00
6	3	4	0.06701	0.17103	0.0173	1.00
7	4	5	0.01335	0.04211	0.0064	1.000
8	5	6	0.00000	0.25202	0.0000	0.932
9	4	7	0.00000	0.20912	0.0000	0.978
10	7	8	0.0000	0.17615	0.0000	1.000
11	4	9	0.0000	0.55618	0.0000	0.969
12	7	9	.00000	0.11001	0.0000	1.000
13	9	10	0.03181	0.0845	0.0000	1.000
14	6	11	0.09498	0.1989	0.0000	1.000
15	6	12	0.12291	0.25581	0.0000	1.000
16	6	13	0.06615	0.13027	0.0000	1.000
17	9	14	0.12711	0.27038	0.0000	1.000
18	10	11	0.08205	0.19207	0.0000	1.000
19	12	13	0.22092	0.19988	0.0000	1.000
20	13	14	0.17093	0.34802	0.0000	1.000

Table 2: Bus parameters of modified IEEE-14 bus system

Bus Nos	Voltage (V)	Generated Power (P_g)	Real Power Demand (P_d)	Reactive Power Demand (Q_d)	b_{SVC}
1	1.05	0.0	0.000	0.000	0.000

2	1.02	0.4	0.220	0.130	0.000
3	1.01	0.7	0.950	0.200	0.000
4	1.00	0.0	0.450	-0.040	0.000
5	1.00	0.0	0.080	0.020	0.000
6	1.01	0.3	0.120	0.075	0.000
7	1.00	0.0	0.000	0.00	0.000
8	1.03	0.6	0.000	0.00	0.000
9	1.00	0.0	0.300	0.180	0.190
10	1.00	0.0	0.090	0.060	0.000
11	1.00	0.0	0.035	0.018	0.000
12	1.00	0.0	0.060	0.018	0.000
13	1.00	0.0	0.135	0.060	0.000
14	1.00	0.0	0.150	0.050	0.000

5. METHOD OF SOLUTION

A. In this approach nodal admittance matrix is modified considering the presence of series compensators, phase shifter, static Var compensator and tap setting transformer in the power system network. A Newton Raphson load flow programme has been developed on MATLAB platform. Conventionally, installation of one FACTS device increases the dimension of Jacobean matrix by one. In the proposed techniques dimension of Jacobean matrix is kept unaltered. The line flow equations are solved and checked for convergence after ensuring the convergence of load flow solution for small increment of the values of FACTS devices. Thus the number of equations to be solved in each iteration reduces and consequently takes less time.

B.Modified Simulated Annealing: Simulated annealing is a method based on local search in which each movement is accepted if improves the system energy. Other possible solutions are also accepted according to a probabilistic criterion. Such probabilities are based on the annealing process and they are obtained as a function of the system temperature. The SA strategy starts with a high temperature giving a high probability to accept non-improving movements. The temperature and probability levels diminish as long as the algorithm advances to the optimal solution. In this way, a diversification procedure in the search algorithm is performed with care in the system energy. Therefore, SA has the ability to escape from local minima by accepting non-improving energy solutions during the first and medium stages of the algorithm. SA gives acceptable solutions when the initial temperature is high associated with a slow cooling procedure.

The three most important parameters of the SA technique required to solve any optimization problem are as follows:

1) The annealing temperature (T): This parameter permits the SA technique not to be entrapped in local minima through the use of the Boltzmann's function.
2) The number of iterations at constant temperature (Mo): A low number of Mo will result in being trapped in local minimum.
3) Cooling strategy (ρ_0): If the annealing temperature is decreased too fast the algorithm will be trapped in local minimum regardless of the proper T and Mo tuning.

Besides these three parameters, selection of initial solution plays an important role in the convergence process. In general, SA technique is based on initial solution taken from the randomly chosen variables. In this modified SA approach, the novelty is to take initial solution through N-R method which helps to achieve fast convergence and satisfactory results.

6. RESULTS AND ANALYSIS

Active line flows are studied with the given example in four stages. The results are tabulated in table nos. 3 to 6.

Stage-I: Line loss sensi6tivity is calculated for line no.3 to 20 and result is shown in fig.4.

Stage-II :Active line flows and angle between the bus voltages are calculated and results are tabulated in table no.3.

Stage-III: This stage includes four cases-

Case1-A capacitive type TCSC is connected in line no.3 to increase its active power flow up to 0.25 p.u. (25MW). The optimal value of reactance of series capacitor is -0.0647 p.u.

.Case2- A capacitive type TCSC is connected in line no.4 to increase its active power flow up to 0.30 p.u. (30MW). The optimal value of reactance of series capacitor is - 0.0888 p.u.

Case3- A capacitive type TCSC is connected in line no.6 to increase its active power flow up to 0.085 p.u. (8.5MW). It is found that active line flows fail to increase up to the required value even with maximum value of TCSC (0.8XL). This is due to the fact that the angle (δ_{ij}) between the two bus voltages (ref. Table-1) is not large enough to increase the active power flow of the line up to its line limits. Also Line No.6 is less sensitive than line nos. 2 and 3. Hence use of TCPST is a must in line no.6.

Case4- Similarly, a capacitive type TCSC is connected in line no.16 to increase its active power flow up to 0.35 p.u. (35MW). The active line flows fails to increase up to the required value due to the same reason as discussed in case3. And so use of TCPST is also a must in line no.16.

Stage-IV: Three TCSCs are inserted in line nos.3,4&6 and one TCPST is connected in line no.16.

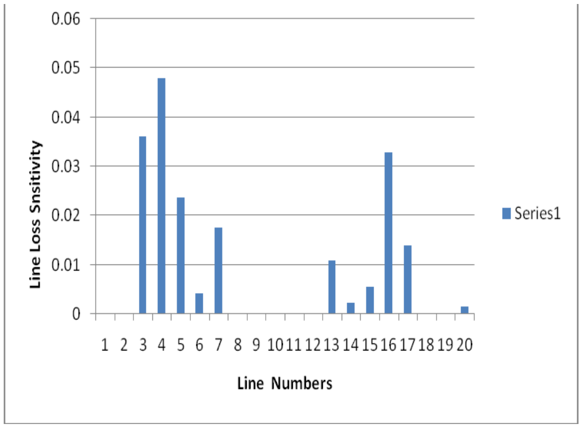

Figure 4 Line loss sensitivity Vs Line Numbers

Table-3: The line flows of modified IEEE-14 bus system at stage-I

Line Nos	i	j	δ_{ij} in degrees	Active line flows in p.u
1	1	2	0.8206	0.3921
2	2	3	2.3725	0.2165
3	2	4	1.8387	0.1966
4	1	5	2.1650	0.2192
5	2	5	1.3444	0.1535
6	3	4	-0.5339	-0.0356
7	4	5	-0.4943	-0.1857
8	5	6	1.3452	0.1013
9	4	7	-1.6471	-0.1436
10	7	8	-5.7860	-0.6000
11	4	9	1.1501	0.0378
12	7	9	2.7972	0.4564
13	9	10	0.2659	0.0801
14	6	11	0.4340	0.0455
15	6	12	0.8943	0.0730
16	6	13	0.9739	0.1628
17	9	14	1.4104	0.1141
18	10	11	-0.1310	-0.0102
19	12	13	0.0797	0.0123
20	13	14	0.7356	0.0381

Table-4: The controlled line flows of modified IEEE-14 bus system at stage-II

			Actve line flows in p.u.			
Line Nos	i	j	Case-1	Case-2	Case-3	Case-4
1	1	2	0.4076	0.3125	0.3928	-0.3871
2	2	3	0.2014	0.2026	0.2204	-0.2182
3	2	4	**0.2500**	0.1689	0.1949	-0.1927
4	1	5	0.2042	**0.2999**	0.2192	-0.2156
5	2	5	0.1305	0.1160	0.1519	-0.1506
6	3	4	0.0505	0.0493	**-0.0318**	0.0329
7	4	5	0.1507	0.2252	-0.1849	0.1855
8	5	6	0.0991	0.1025	0.1007	-0.1007
9	4	7	0.1422	0.1445	-0.1434	0.1434
10	7	8	0.6000	0.6000	-0.6000	0.6000
11	4	9	0.0386	0.0374	0.0381	-0.0381
12	7	9	0.4578	0.4555	0.4566	-0.4566
13	9	10	0.0814	0.0793	0.0803	-0.0800
14	6	11	0.0441	0.0463	0.0452	-0.0450
15	6	12	0.0729	0.0731	0.0729	-0.0722
16	6	13	0.1621	0.1632	0.1626	**-0.1606**
17	9	14	0.1149	0.1137	0.1144	-0.1125
18	10	11	0.0089	0.0111	-0.0100	0.0100
19	12	13	0.0122	0.0124	0.0122	-0.0122
20	13	14	0.0373	0.0385	0.0378	-0.0375

Table-5: The controlled line flows of modified IEEE-14 bus system at stage-III by NR Method

Line Nos	i	j	δ_{ij} in degrees	Active line flows in p.u.
1	1	2	0.5884	0.3256
2	2	3	1.8047	0.1673
3	2	4	1.0483	**0.2500**
4	1	5	1.2665	**0.3000**
5	2	5	0.6780	0.0833
6	3	4	-0.7563	**-0.0840**
7	4	5	-0.3703	-0.1466
8	5	6	1.9683	0.1489
9	4	7	-1.9032	-0.1667
10	7	8	-5.7805	-0.6000
11	4	9	0.7498	0.0247
12	7	9	2.6530	0.4333
13	9	10	0.4643	0.1159
14	6	11	-0.0515	0.0098
15	6	12	-1.1882	-0.0308
16	6	13	-3.3411	**0.3500**
17	9	14	0.0465	0.0421
18	10	11	0.3324	0.0254
19	12	13	-2.1528	-0.0923
20	13	14	2.5394	0.1112

Table-6: The controlled line flows of modified IEEE-14 bus system at stage-III By MSA

Line Nos	i	j	δ_{ij} in degrees	Active line flows in p.u.
1	1	2	0.8531	0.3913
2	2	3	1.8323	0.1697
3	2	4	0.9499	**0.2498**
4	1	5	1.5533	**0.2998**
5	2	5	0.7001	0.0902
6	3	4	-0.8825	**0.0849**
7	4	5	-0.2498	0.0969
8	5	6	1.6773	0.1265
9	4	7	-1.8002	0.1573
10	7	8	-5.7854	0.6004
11	4	9	0.9099	0.03000
12	7	9	2.7101	0.4428
13	9	10	0.4083	0.1065
14	6	11	0.879	0.0189
15	6	12	-0.4669	0.0033
16	6	13	-1.8429	**0.3500**
17	9	14	0.5481	0.0687
18	10	11	0.1973	0.0150
19	12	13	-1.3761	0.0565
20	13	14	1.8734	0.0845

7. CONCLUSION

In this study the major breakthrough is that instead of using 2 TCSC and 2 TCPST, the system network achieved its active power flow to its line limits by using three TCSC and one TCPST. This demands a cost effective solution and ease of control in power system network. It is also observed that this algorithm helped to arrive at the optimal ratings of the FACTS devices parameters for steady operation of a power network. The proposed algorithm works satisfactorily for larger systems as well.

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