Journal of Electrical and Electronics Engineering Research Vol. 4(1), pp. 12-20, August 2012
Available online at http://www.academicjournals.org/JEEER
DOI: 10.5897/JEEER11.143
ISSN – 2141 – 2367 ©2012 Academic Journals

Full Length Research Paper

Congestion management in deregulated power sector using fuzzy based optimal location technique for series flexible alternative current transmission system (FACTS) device

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Accepted 6 June, 2012

The deregulated power sectors suffer from congestion management problems. The congestion occurs when the generation and consumption of electric power causes the transmission system to operate beyond transfer limits. Flexible alternative current transmission system (FACTS) devices can be used to reduce the flows in heavily loaded lines, resulting in low power loss and improved stability of the system. In this paper, a fuzzy technique is proposed in determining the optimal location of thyristor controlled series capacitor (TCSC) to control active power flows and reduction of congestion in a transmission line. A line utilization factor (LUF) and real power performance index (RPPI) factor is used to determine the level of congestion in a transmission line. Sensitivity parameters for the total system losses are derived as a function of the real power at the individual load points in the presence of TCSC. These sensitivity parameters are used to compare the alternative locations available for allocating generation and percentage of congestion. The effectiveness of the proposed algorithm has been simulated on IEEE 14-bus system. The fuzzy based results have been compared with the solution given by sensitivity method. The simulation results proved the efficiency of the proposed approach by optimal placement of the FACTS device to minimize congestion in a power system network.

Key words*:* Flexible alternative current transmission system (FACTS), thyristor controlled series capacitor (TCSC), congestion management, line utilization factor (LUF), real power performance index (RPPI), fuzzy logic controller.

INTRODUCTION

Electrical power generation in a country has a bigger challenge to meet the growing demands for more power. The demand is increasing due to rapid industrialization, urbanization and increase in population of the developing countries. As a measure to meet the increasing demand ensuring adequate availability and reliability, private participation is being encouraged. Because of this, the power trading, grid maintenance. etc., become complex issues. Among them, congestion management is a prime issue. When the generation and consumption of electric power causes the transmission system to operate beyond transfer limits, the system is said to be under congestion. Congestion is the most fundamental transmission management problem. Congestion management is the process to avoid or relieve the congestion. In a broader sense, congestion management is considered as a systematic approach for scheduling and matching generation and loads in order to reduce congestion. Installation of flexible alternative current transmission

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system (FACTS) devices can handle issues related to congestion management.

In general, two paradigm methods were employed to relieve congestion in transmission lines. One is cost free method and the other is non-cost free method where the former include actions like outage of congested lines or operation of transformer taps or phase shifters or FACTS devices. These means are termed as, ‘cost free’ because the marginal costs (and not the capital costs) involved in their usage, are nominal. Non-cost free methods include re-dispatch of generation and curtailment of pool loads and/or by curtailment of bilateral networks. The former method relieves congestion technically, while the latter being related more with economics (Nabivi et al., 2011; Vijaya et al., 2011).

Among the mentioned two main techniques, cost free means do have advantages such as not involving economical matters; so generation companies and distribution companies will not be involved. Hence, optimal operation of FACTS devices as one such technology can reduce the transmission congestion and leads to better usage of the existing grid infrastructure, along with many other benefits (Acharya and Nadarajah, 2007). Besides, using FACTS devices gives more opportunity to independent system operators (ISO). Various issues associated with the usage of FACTS devices are, their optimal location, appropriate size, setting, cost and modeling. This paper deals with the optimal location of thyristor controlled series capacitor (TCSC) for congestion management in competitive power markets. Up to now, the sensitivity factor method is being used to find the best location to enhance the static performance of the system (Nabivi et al., 2010; Singh and David, 2001). However, there are some disadvantages for this method such that it may not capture the non-linearity associated with the power system (Nabivi et al., 2011). The performance index and var index methods along with contingency analysis are used to relieve congestion (Rajalakshmi et al., 2011). A fuzzy logic method for location and control of series facts devices to maximize load expansion by means of single contingency analysis had analyzed (EL Kady, 2003). Genetic algorithm in conjunction with fuzzy systems has also been used for location and for reduction of power oscillation damping (Nayeripour et al., 2009). However, the relieving of congestion in the lines using fuzzy systems has not been indicated so far.

The objective of this paper is to develop an algorithm to relieve congestion by optimally locating a TCSC in a transmission line. A line utilization factor (LUF) is used to determine the level of congestion in the transmission line. Sensitivity parameters for the total system losses are derived as a function of the real power at the individual load points in the presence of TCSC. These sensitivity parameters are used in comparing the alternative locations available for generation capacity and percentage of congestion. A fuzzy logic controller is proposed to control active power flow for congestion management. The proposed algorithm is tested successfully on the IEEE 14-bus system. The fuzzy based results are compared with the solution given by sensitivity method. This comparison confirms the efficiency of the proposed method, which makes it promising to solve congestion problem in a power system network by suitably placing a FACTS device.

METHODOLOGY

Sensitivity methods for congestion management

These approaches are based upon two new factors. With the help of these factors, the level of congestion in transmission line can be determined.

Line utilization factor (LUF)

It is the measure of utilization of a particular line or overall system. It gives an idea about how much percentage of the line is used for the power flow. If the value of utilization is less, it means that less power has been transferred and the system will be less congested and vice-versa.

$$LUF_{ij} = MVA_{ij} / MVA_{ij}^{MAX} \quad (1)$$

Where,

LUF_{ij} is the line utilization factor (LUF) of the line connected to bus - i and bus- j.

MVA_{ij}^{MAX} is the mega volt ampere (MVA) rating of the line between bus- i and bus-j.

MVA_{ij} is the actual MVA rating of the line between bus-i and bus- j.

Real power performance index (RPPI)

An index for quantifying the extent of line overloads defined in terms of real power performance index.

$$RPPI = \sum_{l=1}^{NL} \varepsilon_l \left[\frac{P_l}{P_l^{Lim}} \right]^{2n} \quad (2)$$

Where,

P_l = Mega Watt flow of line l.

P_l^{Lim} = Mega Watt capacity of the line.

NL = Number of lines in the system.

n = Specified exponent.

ε_l = Weighting factor, which may be used to reflect the importance of some lines.

In this paper, we consider that n=1 and ε_l =1. RPPI will be small when all the lines are within their limits and reach a high value where there are overloads. Thus, it provides a good measure of severity of line overloads for a given state of the power system (EL Kady, 2003).

TCSC modeling

For static application like congestion management, FACTS devices

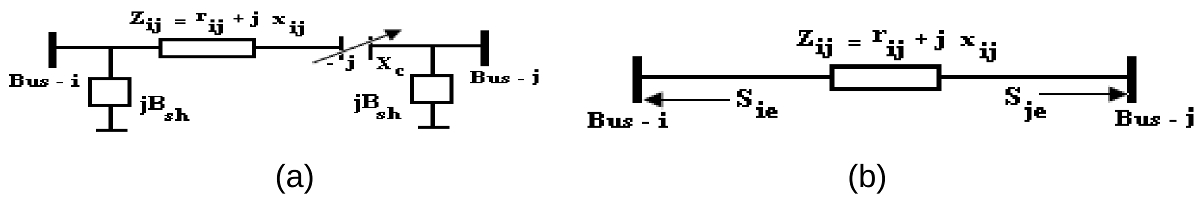

Figure 1. (a), TCSC model; (b), Injection model of TCSC.

can be modeled as power injection model. The injection model describes the FACTS devices as a device that injects a certain amount of active and reactive power to a node, so that the FACTS devices are represented as PQ elements. The advantage of power injection model is that it does not destroy the symmetrical characteristic of the admittance matrix and allows efficient and convenient integration of FACTS devices into existing power system analytical tools (Naresh and Mithulananthan, 2007).

During steady state operation, TCSC can be considered as an additional reactance $-jx_c$. The value of x_c is adjusted according to control scheme specified. Figure 1a shows a model of transmission line with one TCSC which is connected between bus-i and bus-j. The line flow change is due to series capacitance which is represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Figure 1b.

The real power injections at bus-i(P_{ic}) and bus-j(p_{jc}) are given by (Rajalakshmi et al., 2011):

$$P_{ic}=V^2_i \Delta G_{ij} - V_i V j[\Delta G_{ij} \cos\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}] \quad (3)$$

$$P_{jc}=V^2_j \Delta G_{ij} - V_i V j[\Delta G_{ij} \cos\delta_{ij} - \Delta B_{ij} \sin\delta_{ij}] \quad (4)$$

Similarly, the reactive power injections at bus-i (Q_{ic}) and bus- j (Q_{jc}) can be expressed as:

$$Q_{ic}= - V^2_i \Delta B_{ij} - V_i V j[\Delta G_{ij} \sin\delta_{ij} - \Delta B_{ij} \cos\delta_{ij}] \quad (5)$$

$$Q_{jc}= -V^2_j \Delta B_{ij} + V_i V j[\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \cos\delta_{ij}] \quad (6)$$

Where:

$$\Delta G_{ij} = \frac{x_c\, r_{ij}\,(x_c - 2x_{ij})}{\left(r_{ij}^2 + x_{ij}^2\right)\left(r_{ij}^2 + \left(x_{ij} - x_c\right)^2\right)}$$

$$\Delta B_{ij} = \frac{-x_c\left(r_{ij}^2 - x_{ij}^2 + x_c x_{ij}\right)}{\left(r_{ij}^2 + x_{ij}^2\right)\left(r_{ij}^2 + \left(x_{ij} - x_c\right)^2\right)}$$

Where ΔG_{ij} and ΔB_{ij} are the change in conductance and change in susceptance of the line i-j.

This model of TCSC is used to properly modify the parameters of transmission lines with TCSC for optimal location (Nabivi et al., 2010).

Proposed approach

Step by step algorithm to relieve congestion for an IEEE 14-bus system

Step 1: Run power flow for a standard IEEE 14-bus system. The UF and RPPI for the test system are calculated.

Table 1 shows the LUF and RPPI of each line in a 14-bus system. If the utilization and performance index reaches a high value, it indicates that the system is more congested. Highlighted values are the congested lines.

Step 2: Conduct power flow analysis for the congested lines before and after series compensation. In this paper, 50% of the line compensation is used.

The maximum utilized and congested lines 1 to 2, 3 to 4, and one of the minimum utilized line 9 to 10 are considered. The TCSC is placed on these lines individually and analyzed. The changes in line flow in the considered lines are shown in Table 2. In the same manner, line losses for the above lines are also considered.

From Table 2, it is observed that line flows are reduced in the maximum congested lines. However, no significant effect is observed in the minimum congested line. The above method if applied for all the lines, involves a lot of computation. Hence, fuzzy method is applied for simplifying the procedure.

Step 3: Applying fuzzy method for locating TCSC to relieve congestion.

a) Fuzzification: Fuzzification is a process whereby the input variables are mapped into fuzzy variables. The fuzzy input variables considered in this paper are line flow before compensation (P_{line}) and change in line flow after series compensation (ΔP_{line}). The membership functions of input variables are shown in Figures 2 and 3.

To relieve congestion, the location for placement of TCSC is considered as a major issue. Hence, TCSC can be placed where the low power loss occurs in the line. Therefore, the change in power loss (ΔP_{loss}) is taken as an output variable. The membership function of output variable is shown in Figure 4 and also the fuzzy variables for the test case are shown in Table 3.

b) Range selection for fuzzy subsets: The ranges of input and output variables selected for fuzzy subsets are shown in Table 4.

c) Fuzzy control rules: To begin with P_{line} and ΔP_{line}, values will be converted into fuzzy variables. After the fuzzification, fuzzy inputs enter to inference mechanism level and with considering membership function and rules; outputs are sent to defuzzification to calculate the final outputs. Each rule of fuzzy control follows the basic if –then rule.

In this work, for both the inputs P_{line} and ΔP_{line} and the output ΔP_{loss}, five fuzzy subsets are used. They are S (small), SM (Small medium), M (Medium), MH (Medium high) and H (High). The triangular membership functions are used for the above sub-sets. Twenty-five control rules yield by these fuzzy sub-sets, are shown in Table 5.

d) Defuzzification: After evaluating inputs and applying them to the rule base, the fuzzy-logic controller will generate a control signal.

Table 1. Power flow, LUF and RPPI for IEEE 14-bus test system.

Bus No.	Line i-j	Line flow (MW)	Line capacity (MW)	% Line utilization factor (LUF)	Real power performance index (RPPI)
1	**1-2**	**157.556**	**184.155**	**85.56**	**0.732**
2	1-5	74.441	128.816	57.79	0.334
3	**2-3**	**75.052**	**129.989**	**57.74**	**0.3334**
4	**2-4**	**57.188**	**98.35**	**58.15**	**0.3381**
5	**2-5**	**39.912**	**60**	**66.52**	**0.4425**
6	**3-4**	**-27.553**	**-24.765**	**87.03**	**1.2378**
7	**4-5**	**-60.014**	**97.847**	**61.33**	**0.3762**
8	4-7	28.596	59.011	48.46	0.2348
9	**4-9**	**16.935**	**25.093**	**67.49**	**0.4555**
10	**5-6**	**42.72**	**59.753**	**71.49**	**0.5111**
11	6-11	6.543	14.059	46.54	0.2166
12	6-12	7.721	15.24	50.66	0.2567
13	**6-13**	**17.339**	**29.544**	**58.69**	**0.3444**
14	7-8	0.006	0.01809	33.17	0.11
15	7-9	28.592	53.602	53.34	0.2845
16	9-10	6.095	13.189	46.21	0.2136
17	**9-14**	**9.932**	**15.058**	**65.96**	**0.435**
18	10-11	-2.968	-14.012	21.18	0.0449
19	12-13	1.498	6.9959	21.41	0.0458
20	13-14	5.09	15.129	33.64	0.1132

Values in bold are the congested lines.

Table 2. Line flow before and after compensation in IEEE 14-bus system.

Bus No.	Line i-j	Line flow (MW)			
		Before TCSC	After TCSC		
			Line 1-2	Line 3-4	Line 9-10
1	**1-2**	**157.556**	**147.522**	**158.217**	**157.581**
2	1-5	74.441	84.54	73.761	74.46
3	2-3	75.052	73.439	77.949	75.013
4	2-4	57.188	53.835	55.835	57.157
5	2-5	39.912	35.293	38.898	39.925
6	**3-4**	**-27.553**	**-23.056**	**-18.814**	**-21.547**
7	4-5	-60.014	-64.514	-58.515	-59.845
8	4-7	28.596	28.417	28.644	28.471
9	4-9	16.935	16.829	16.959	16.857
10	5-6	42.72	42.994	42.647	42.974
11	6-11	6.543	6.714	6.493	6.851
12	6-12	7.721	7.742	7.716	7.622
13	6-13	17.339	17.426	17.317	17.2
14	7-8	0.006	0.011	0.008	0.001
15	7-9	28.592	28.417	28.633	28.438
16	**9-10**	**6.095**	**5.926**	**6.143**	**5.692**
17	9-14	9.932	9.83	9.964	10.143
18	10-11	-2.968	-3.131	-2.922	-3.294
19	12-13	1.498	1.517	1.493	1.49
20	13-14	5.09	5.199	5.067	5.006

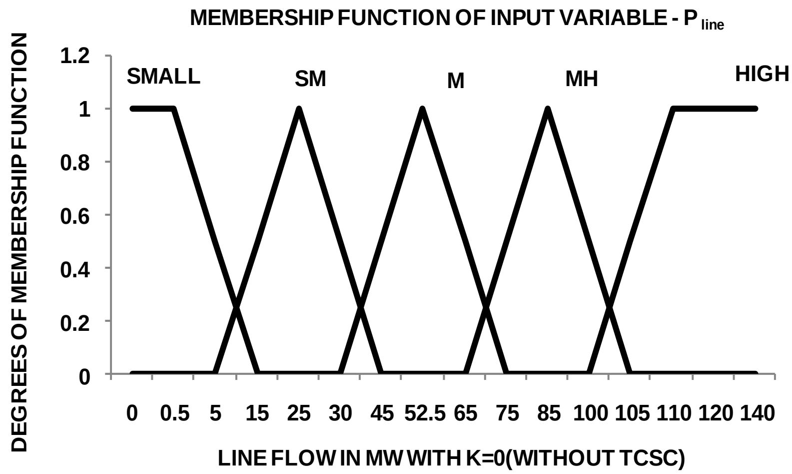

Figure 2. Membership function of input variable-P_{line}.

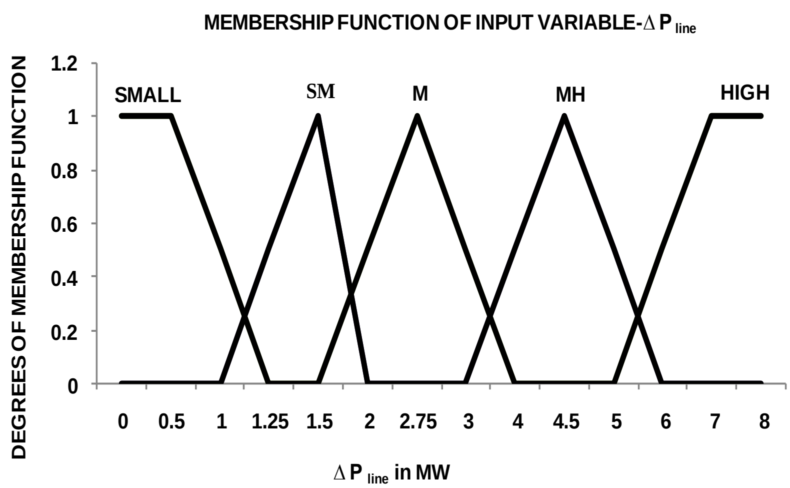

Figure 3. Membership function of input variable-ΔP_{line}.

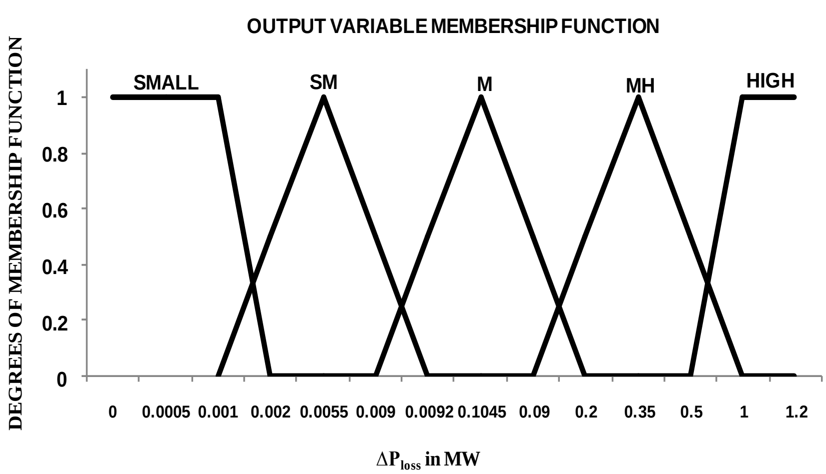

Figure 4. Membership function of output variable-ΔP_{loss}.

Table 3. The fuzzy input and output variable for IEEE 14-bus system.

Line	Input variable		Output variable
	Line flow (MW)	ΔP_{Line} (MW)	ΔP_{Loss} (MW)
1-2	157.55	10.034	0.983
1-5	74.44	-10.099	-0.79
2-3	75.052	1.613	0.099
2-4	57.188	3.353	0.179
2-5	39.912	4.619	0.17
3-4	-21.553	1.503	-0.061
4-5	-60.014	4.5	-0.078
4-7	28.596	0.179	0
4-9	16.935	0.106	0
5-6	42.72	-0.274	0
6-11	6.543	-0.171	-0.001
6-12	7.721	-0.021	0
6-13	17.339	-0.087	-0.002
7-8	0.006	0.005	0
7-9	28.592	0.173	0
9-10	6.095	0.169	0.001
9-14	9.932	0.102	0.002
10-11	-2.968	0.163	-0.001
12-13	1.498	-0.019	0
13-14	5.09	-0.109	-0.001

Table 4. Ranges of the fuzzy input and output variable for IEEE 14-bus system.

Fuzzy subsets	Input variable		Output variable
	Line flow (MW)	Change in line flow (ΔP_{Line}) (MW)	Change in power loss (ΔP_{Loss}) (MW)
Small	<15	<1.25	<0.002
Small medium	5-45	1-2	0.001-0.01
Medium	35-75	1.5-4	0.009-0.2
Medium high	65-105	3-6	0.09-1
High	>100	>5	>0.5

The output variables of the inference system are linguistic variables. This will be evaluated for the derivation of the output control signal. This process is the defuzzification. The defuzzification has been achieved using the centre of gravity (COG) method and the output of the fuzzy coordinated controller is COG (set of real numbers).

$$\text{COG}\ (A) = \frac{\sum_{X_{min}}^{X_{max}} x.A(x)}{\sum_{X_{min}}^{X_{max}} A(x)} \tag{7}$$

Where; X_{min} =1; X_{max} =25; A(x) = $P_{loss,}$

Corresponds to the value of controlled output for which the membership values in the output sets are equal to unity.
X = Membership function.

In this method 'AND' relationship between mappings of two variables are considered. The membership function of the defuzzification, are shown in Figure 5. After applying COG, the priorities for the location of TCSC were considered for the method shown in Table 6.

Step 4 (Analysis of the fuzzy method): The output result of the proposed fuzzy method is analyzed. The defuzzyfied results are compared with the change in power loss of each line and optimized for the location to place the TCSC to relieve congestion.

SIMULATION RESULTS AND DISCUSSION

To minimize the congestion, the fuzzy based analysis is carried out on standard IEEE 14-bus system. The optimized location of TCSC after fuzzy technique

Table 5. Fuzzy control rules.

P_l \ ΔP_l	**S**	**SM**	**M**	**MH**	**H**
S	S	S	S	S	S
SM	S	SM	SM	SM	SM
M	S	SM	M	MH	M
MH	S	SM	M	MH	MH
H	S	SM	M	MH	H

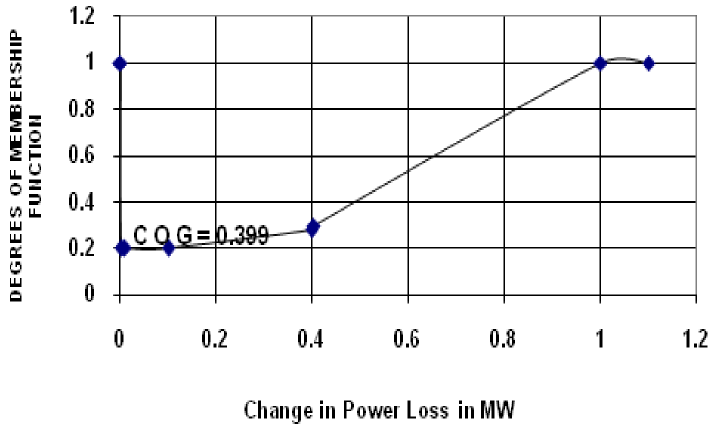

Figure 5. Defuzzification by COG.

Table 6. Fuzzy based priority table for location of TCSC for IEEE 14 Bus systems.

SL No.	TCSC location in line	% LUF	Priority for placing TCSC using fuzzy
1	3-4	87.03	10
2	**1-2**	**85.56**	**1**
3	5-6	71.49	9
4	**2-4**	**58.15**	**2**
5	2-3	57.74	4
6	**2-5**	**66.52**	**3**
7	4-9	67.49	8
8	9-14	65.96	5
9	4-5	61.33	7
10	6-13	58.69	6

implementation is shown in Figure 6. The other congested lines are also highlighted. A MATLAB simulation package version 7.6.0.324 is used for simulations.

The defuzzyfied results obtained on IEEE14-bus system were compared with the output variable (change in power loss) of each line and it is found that the line **1 to 2** matched well compared to other lines. Hence, line 1 to 2 is considered as the optimal location for placement of TCSC to relieve congestion and shown in Figure 6. By locating TCSC in the line 1 to 2, the percentage of LUF has reduced from 85.6 to 76.45%.

Priority list would capture the congested lines as well as the neighborhood lines that are linked to the congested lines through which the power can be diverted after placement of FACTS devices. The number of lines

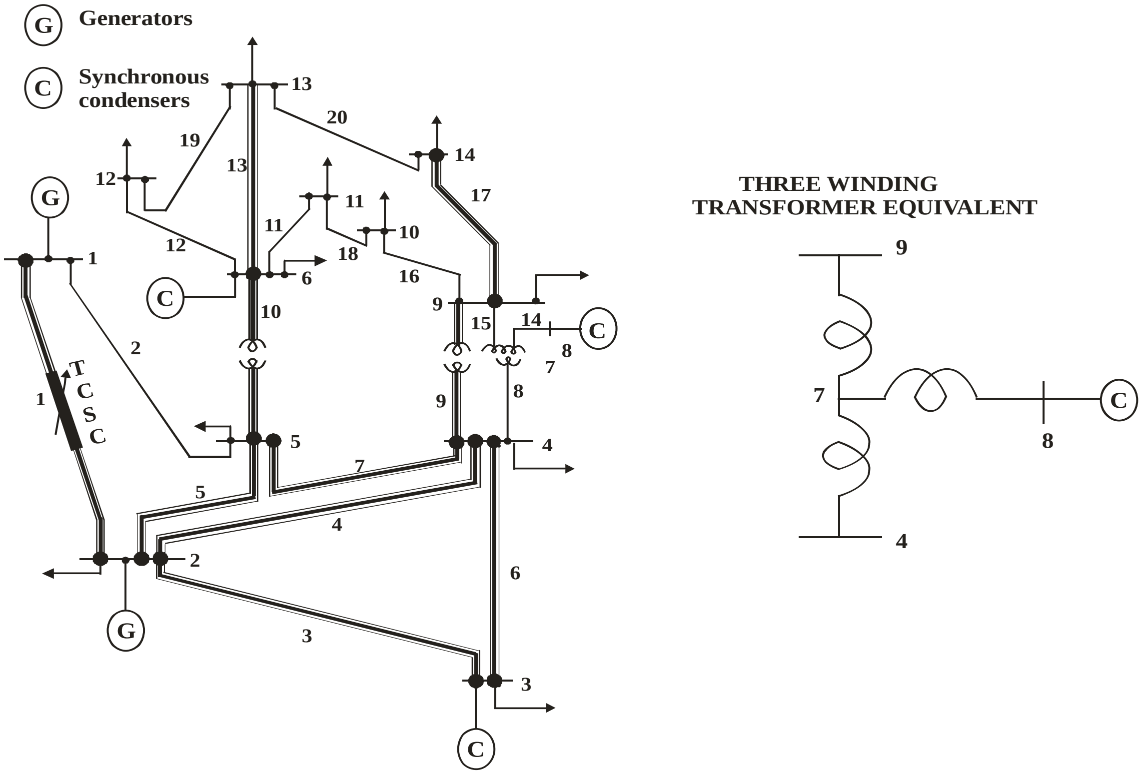

Figure 6. IEEE 14-bus system.

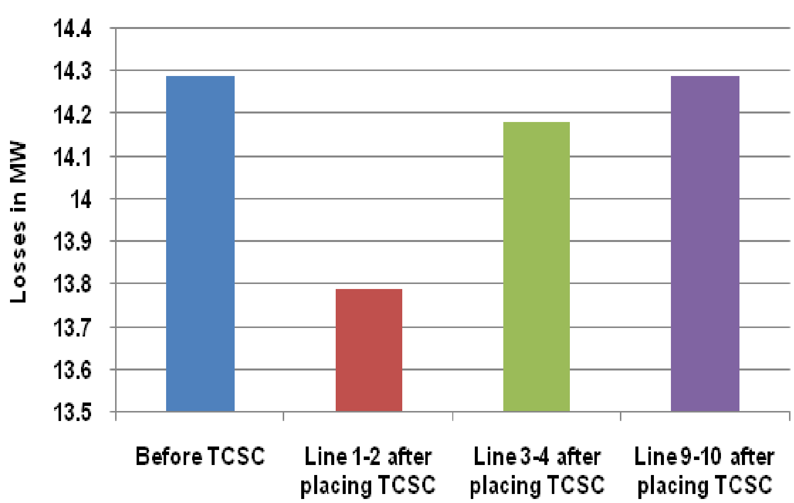

Figure 7. Power loss in the system before and after placement of TCSC.

to be considered for priority list depends upon the size of the system, and has no hard and fast rule. However, it should at least be greater than the number of congested lines in the system.

Fuzzy rules have been applied to the overloaded lines and results tabulated in priority Table 6. The parameters of ΔP_{loss} and ΔP_{line}, are being considered for the optimum location of TCSC to relieve congestion. By placing TCSC in the line 1 to 2, the congestion has reduced from 85.6 to 76.45% and the line losses reduced from 5.017 to 4.034 MW. A chart of power loss in the transmission lines before and after placement of TCSC is shown in Figure 7. Results obtained from fuzzy method and conventional method confirmed that, the optimum location of FACTS device is between the lines 1 to 2, to relieve congestion for the considered power system. It is observed from priority table that the placement of TCSC in the line 1 to 2 is suitable for relieving congestion in the transmission line. If the first optimal location is not suited, then 2 or 3 optimal locations can be considered based on priority Table 6.

The advantage of the proposed method helped to form the priority list, for series FACTS device location to relieve congestion directly from fuzzy results and avoid excessive computation. Only few line in the priority list need to be examined in detail to assess the best location to relieve congestion.

Conclusion

Congestion management is an important issue in deregulated power systems. In this paper, fuzzy method is proposed for optimal placement of TCSC to control the active power flows for congestion management. The sensitivity parameters are used in comparing the alternative locations available for generation capacity and percentage of congestion. The simulations are carried out successfully on the IEEE 14-bus system. The fuzzy technique results are compared to the solution given by the conventional sensitivity method. The comparison confirmed the efficiency of the proposed method, and the results could be effectively used for determining the optimal location of TCSC to solve congestion problem in a power system network. Hence, fuzzy method is an alternative means of dealing with congestion and can be applied easily to any number of buses to relieve congestion in a power system.

ACKNOWLEDGEMENT

The authors express their sincere thanks to Dr. A. D. Kulkarni, Professor, Department of E&EE, NIE Mysore, India for the useful guidance in this work.

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