Congestion Management in Deregulated Power System by Fuzzy Based Optimal Location and Sizing of UPFC

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Abstract: - This paper presents a congestion management methodology in deregulated power systems by optimal location and sizing of Unified Power Flow Controller (UPFC) in a transmission network. A multi-objective optimization problem has been developed by considering total congestion cost, power loss and system severity. A Fuzzy based approach has been proposed to identify the optimal location and sizing of UPFC for relieving congestion in a deregulated power system. The reliability of the proposed work has been analyzed under severe contingencies and line overloading. Simulation results obtained from the Fuzzy method are compared with the solutions obtained by the conventional Sequential Quadratic Programming (SQP) approach. This comparison confirms the effectiveness of the proposed fuzzy method for relieving congestion. The validation of the proposed work is analyzed using IEEE 30-bus system.

Key-Words: - FACTS, UPFC, Congestion Management, LMP, Fuzzy Logic Technique, RPPI.

1 Introduction

In the deregulated environment, congestion is said to occur when the transmitted power exceeds the capacity or transfer limit of the transmission line. Congestion is undesirable and it distorts the electricity market. Hence Congestion management remains the central issue in transmission management in deregulated power systems [1]. The congestion relieve can be achieved by fast power flow control in a transmission system over a long distance without affecting the stability and security of the power systems. The fast power flow control over the transmission line can be achieved by installing new devices such as Flexible AC Transmission Systems (FACTS). FACTS devices by controlling the power flows in the network without generation rescheduling or topological changes can improve the performance considerably [2-4]. The family of FACTS controllers based on Voltage Source Converters (VSC) are the Static Synchronous Compensator (STATCOM), Static Synchronous Series compensator (SSSC) and Unified Power Flow Controller (UPFC).

Different approaches have been presented for optimal placement of FACTS devices including sensitivity analysis [5-8], congestion management by interline power flow controller and unified power flow controller (UPFC) [9-11]. [12] Reviews a fuzzy interactive multi-objective approach considering minimisation of total fuel cost, minimisation of active power losses, and maximisation of system loadability and minimisation of investment cost of UPFC as the proposed multi-objective functions for the optimal location of UPFC to enhance power system operation. A PSO-based algorithm is used in [13] to find the optimal location and the parameters setting of UPFC to increase loadability.

In this paper a fuzzy based technique has been proposed for managing congestion. The main intent of this paper is to propose an algorithm that deals with the optimal location and sizing of UPFC for managing congestion in competitive power markets. A Fuzzy based approach has been proposed to relieve congestion by optimally locating an UPFC in a transmission line. The approach is to relieve congestion based on the total losses, total congestion cost, and real power performance index. The performance of the proposed algorithm is tested with IEEE 30-bus system under severe line outages and line overloads. The fuzzy based results are compared with the conventional Sequential Quadratic Programming method and the results are tabulated. This comparison confirms the efficiency of the proposed method by suitably placing a FACTS device to relieve congestion.

2 Mathematical Model of UPFC

Integration of FACTS devices in load flow analysis and issues related to optimal power flow (OPF) has been reported in [9-16]. Among the various FACTS devices, in this paper UPFC is used to relieve congestion in a transmission network because of its flexibility and abilities in regulating the bus voltage and simultaneously controlling the active and reactive power flow. The power injection model of UPFC is described in this chapter.

Newton–Raphson power flow formulation is used and UPFC is represented using the power injection model [9-16]. This will allow easy integration of UPFC into the existing power system software tools and retains the symmetrical structure of the admittance matrix. UPFC consists of two back-to-back voltage-source converters connected to power system through series and parallel power transformers.

Impacts of UPFC on the network is reflected by a series connected voltage source $V_T \leq \varphi_T$ and shunt current sources I_T and I_q, connected to the network through series and shunt transformers as shown in Fig. 1. Therefore UPFC includes three adjustable parameters: voltage magnitude and phase angle of the series transformer ($V_T \; and \; \varphi_T$) and reactive current (I_q) of the shunt transformer.

Fig 1. Model of Transmission Line with an UPFC

a) Structure

b) Power injection model

According to Fig. 1, UPFC can be modelled based on the following equations

$$I_i = I_T + I_q + I_i^{'} \qquad (1)$$

$$I_T = \frac{Re[V_T \times I^{'*}]}{V_i} \qquad (2)$$

$$V_i^{'} = V_T + V_i \qquad (3)$$

The real and reactive power injections at buses i and j with a UPFC unit connected in line ij can be expressed as [9-16].

$$S_{ij} = P_{ij} + jQ_{ij} = V_i \times I_{ij}^{*}$$

$$= V_i \times (I_i + jV_i B/2)^{*} \qquad (4)$$

$$S_{ji} = P_{ji} + jQ_{ji} = V_j \times I_{ji}^{*}$$

$$= V_j \times \left(jV_j B/2 - I_i^{'}\right)^{*} \qquad (5)$$

$$P_{is} = -g_{ij}V_T^2 - 2V_iV_Tg_{ij}cos\left(\varphi_T - \delta_i\right) + V_jV_T\left[g_{ij}cos(\varphi_T - \delta_i) + b_{ij}sin(\varphi_T - \delta_i)\right]\Big) \qquad (6)$$

$$P_{js} = V_jV_T\left[g_{ij}cos(\varphi_T - \delta_i) - b_{ij}sin(\varphi_T - \delta_i)\right] \qquad (7)$$

$$Q_{is} = V_iI_q + V_iV_T\left[g_{ij}sin(\varphi_T - \delta_i) + b_{ij}cos(\varphi_T - \delta_i)\right] \qquad (8)$$

$$Q_{js} = -V_jV_T\left[g_{ij}sin(\varphi_T - \delta_i) + b_{ij}cos(\varphi_T - \delta_i)\right] \qquad (9)$$

Where, B - line charging admittance

g_{ij} - conductance of line ij

b_{ij} - susceptance of line ij

P_{is}, Q_{is}, P_{js} and Q_{js} are active and reactive power injections at buses i and j, respectively. Equations (6) - (9) are added to the Jacobin matrix in load flow formulations.

3 Problem Formulation

3.1 Objective Function

The general problem formulation for solving the multi-objective function by satisfying the equality and inequality constraints for the optimal location of UPFC can be formulated as follows:

Minimize, $F(x) = [f_1(x), \cdot, f_i(x), \cdot, f_N(x)]$ (10)

subject to: $g_j(x) \leq 0$, j = 1, 2, ...,M.

$h_k(x) = 0$, k = 1, 2, ...,K.

Where, x is a decision vector that represents the solution and f_i is the i^{th} objective function. N, M and K denote the number of objective functions, inequality constraints and equality constraints respectively. The components of the objective function are:

3.1.1 Total Congestion Cost (TCC)

$$TCC=\sum_{i,j=1}^{Nb} |LMP_i\text{-}LMP_j|*P_{ij} \qquad (11)$$

Where,

LMP_k is the Locational marginal pricing at the k^{th} bus.

P_{ij} is the real power flow from i^{th} to j^{th} bus.

LMP at bus i can be calculated using the following equation,

$$LMP_i = LMP_{ref} – (L_i* LMP_{ref}) - (\sum_{j=1}^{Nc} (\mu_j \times SF_{ji}) \quad (12)$$

Where LMP_i - Nodal price at bus i.
LMP_{ref} - Nodal price at the reference bus.
L_i - Marginal loss factor at bus i.
L_i - $(\partial P_{loss}/\partial P_i)$.
P_i - Power injection at bus i and P_{loss} is the system losses.
μ_j - Shadow price of constraint j.
SF_{ji} - Shift factor for real load at Bus i

Nc - Number of constraints.

3.1.2 Real Power Performance Index (RPPI)

Real Power Performance Index is an index for quantifying the severity of the system loading under normal and contingency cases.

$$RPPI=\sum_{i=1}^{Nl} \beta_l(P_l/P_{lmax})^{2n} \qquad (13)$$

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.
β_l - Weighting factor, which may be used to reflect the importance of some lines.

We consider that n=1 and β_l =1. P_l and P_{lmax} are the real power flow and maximum real power flow permitted. 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 [17].

3.1.3 Power Loss (P_{loss})

Transmission power loss in the network causes a major revenue loss for the utility. The transfer capability can be enhanced by minimizing the transmission losses. Hence, in this paper the power loss has been used as a parameter for the optimal location of FACTS device to relieve congestion.

A multi- objective function is reformulated as indices with respect to base case values and incorporated in the minimization function. Base case values refer to the operation of the network without FACTS devices. Equation (14) is multi-objective formulation with weights and not a pure multi-objective formulation.

Thus the multi–objective optimization problem for each iteration i, is defined with respect to the above indices and is expressed as,

Minimize

$$F=\sum_{i=1}^{Ns} (TCC_i/TCC_{base})+(RPPI_i/RPPI_{base})+(Ploss_i/Ploss_{base}) \qquad (14)$$

3.2 Operating Constraints

The minimization function is subjected to the following constraints.

3.2.1 Power Injection

The net injections of real and reactive power at each bus are set to zero.

3.2.2 Generation Limits

The limits on the maximum and minimum active (P_G) and reactive (Q_G) power generation of the generators are included as

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}$$
$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}$$
$$i = 1,2, . . .N_G$$

3.2.3 Voltage Limits

Voltage limit at each bus is expressed as

$$V_{imin} \leq V_i \leq V_{imax}$$

3.2.4 Compensation Limits

The minimum and maximum limits of UPFC parameters are given as

$$V_T^{min} \leq V_T \leq V_T^{max}$$

$$\varphi_T^{min} \leq \varphi_T \leq \varphi_T^{max}$$

$$I_q^{min} \leq I_q \leq I_q^{max}$$

The Fuzzy based technique is used for solving the above multi-objective optimization problem given in equation (14). The application of fuzzy technique to solve the objective function in order to optimally locate the UPFC in the transmission network is described in next session.

4 Proposed Methodology

The optimal location of UPFC is identified using Fuzzy technique considering various system indices and the effect of power flow in overloaded lines. The fuzzy logic represents the expert systems. TCC, RPPI and Power loss are given as input to the fuzzy technique. For all the possible combinations for location of one UPFC unit, the three input variables are evaluated .The objective function F is considered as the output variable. The fuzzy logic system is trained with various input and output relationships and thus for any loading condition and during uncertain situation the best location can be identified. The least value of F among all possible locations will be obtained through the output of the Fuzzy Logic and the optimal location is found. As the power systems are nonlinear and large-scale systems, the system constantly undergoes disturbances from minor fluctuations in load, generation and experiences more severe disturbances from line faults or other equipment outages. Thus for various loading condition and contingencies, fuzzy logic can be used to cope with all the uncertainties and provides better solution for locating the FACTS device. Hence great emphasis has been put into applying expert system like fuzzy to power transmission system congestion management.

The performance of the Fuzzy technique for optimal location of UPFC is described in the following steps:

Step -1: Conduct power flow analysis for an IEEE 30-bus system before incorporating UPFC in the system. The total power loss, congestion cost and real power performance index are calculated under the congested condition. These values are considered as the base values in this paper.

Step -2: Then various cases are considered to understand the impact of UPFC on various system indices and the effect of power flow in overloaded lines. A Fuzzy based approach is proposed for obtaining the optimal location of UPFC in the transmission network.

Step -3: Various process involved in application of Fuzzy method to determine the optimal location of UPFC are discussed as follows.

1. **Fuzzification**

   Fuzzification is a process whereby the input variables are mapped into fuzzy variables. The fuzzy input variables considered in this paper are TCC, RPPI and P_{loss}. The membership functions of the input variables are shown in Figures 2, 3 and 4. The solution of objective function (F from eqn(14)) is considered as the output variable. The membership function of the output variable is shown in Figure 5.

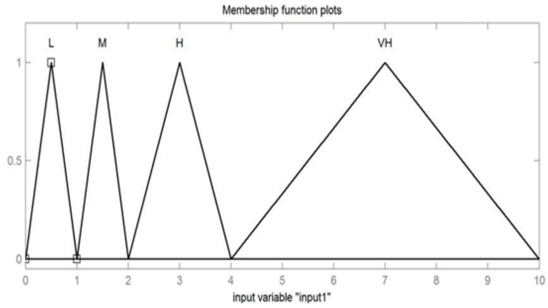

Fig 2. Membership Function of Input Variable- TCC

Fig 3. Membership Function of Input Variable- RPPI

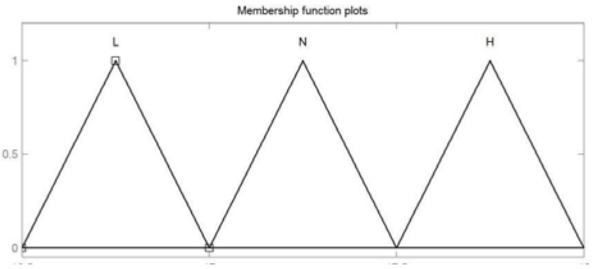

Fig 4. Membership Function of Input Variable- P_{loss}

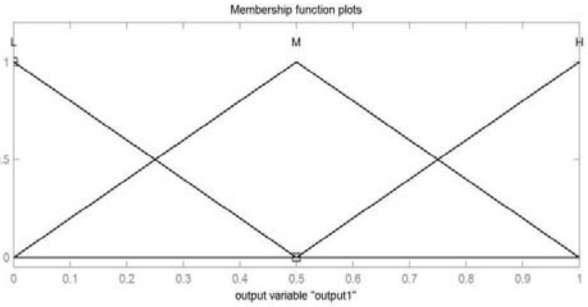

Fig 5. Membership Function of Output Variable- F

2. **Fuzzy control rules**

After fuzzification, the fuzzy input variables enter to inference mechanism level and with considering membership function and rules; outputs are sent to defuzzification to calculate the final output. Each rule of fuzzy control follows the basic if-then rule. In this paper, for the input variable 1 (ie., TCC) four fuzzy subsets are used and for rest of the input variables and output variable three fuzzy subsets are used. They are L(low), M(medium), H(high) and VH(very high). The triangular membership functions are used for the above subsets.

3. **Range selection for fuzzy subsets**

The various ranges of input and output variables selected for fuzzy subsets are mentioned in the table I.

Fuzzy Subsets	Input Variables			Output Variable
	TCC ($)	RPPI	P_{loss} (MW)	F
Low	<402	<6	<16	<0.5
Medium	402-405	6-11	16-17.5	0-1.5
High	405-6000	>12	>18	>1.5
Very High	>6000	-	-	-

Table1. Ranges of the Fuzzy Input and Output variable for IEEE 30-bus system

4. **Fuzzy Inference System**

By feeding the three inputs to the fuzzy box, the input control variables are fuzzified through control rules. Then this signal is defuzzified with Centre of Gravity (COG) method to get the output signal. The basic control parameters for the fuzzy algorithm is given as follows:

Type	'Mamdani'
Number of Inputs	3
Number of Outputs	1
Number of Rules	36
And Method	'min'
Or Method	'max'
Implication Method	'min'
Aggregation Method	'max'
Defuzzification	'centroid'

5. **Defuzzification**

After evaluating inputs and applying them to the rule base, the fuzzy logic controller will generate a control signal. The output variables of the inference system are linguistic variables. This will be evaluated for the derivation of the output control signal. The Centre of Gravity (COG) method is used for defuzzification.

After defuzzification, the optimal location and sizing of UPFC is identified by adjusting the device rating of UPFC and the congestion is relieved. Simulation results obtained by fuzzy is compared with SQP method and the results are tabulated in the next chapter.

5 Results and Discussion

This section deals with the results and analysis of the proposed work for the optimal location and sizing of UPFC unit with transmission line flow constraints. The proposed methodology has been analyzed using the Fuzzy Logic Technique for optimal location and sizing of UPFC and is implemented using IEEE 30-bus system. This test system contains 6 generation units and 41 transmission lines and includes 24 load points. In order to demonstrate the ability of the Fuzzy technique in relieving congestion four case studies are considered in this paper. The proposed techniques can alleviate all line overload conditions and contingencies occurring in practical systems. The results, however, suggest an investigation of the possibility of managing congestion using UPFC. First of all, base values of TCC, P_{loss} and RPPI are calculated for the IEEE 30 bus system without UPFC. Then various cases are considered to understand the impact of UPFC on various system indices and the effect of power flow in overloaded lines. In order to validate the performance of the proposed method, simulation results generated by the fuzzy method are compared with those calculated using conventional Sequential Quadratic Programming method.

Cases	Operating Conditions
A	With UPFC and a Line Outage (line 1 connecting bus 1 and 2)
B	120% loading with line flow constraints with UPFC
C	200% loading with line flow constraints with UPFC
D	With UPFC 120% loading and a Line Outage (line 1 connecting bus 1 and 2)

LMP is calculated by considering variable pricing offered by all GENCOs. LMP is generally composed of three components, a marginal energy component, a marginal loss component and a congestion component. From the LMP values, TCC is calculated considering the change in power flow across the transmission lines. The difference in re-dispatch costs for the case with and without FACTS gives a measure of the benefit of using FACTS. The benefits of using FACTS can also be viewed as the reduction in congestion costs when FACTS are used.

The difference in LMP between two buses gives direct hint regarding the level of congestion in that line [18]. Though LMP difference is highest for the overloaded lines, the overloaded lines are not always the best locations for the placement of FACTS devices [19]. Hence along with congestion cost other indices like losses and real power performance index are also included for the determination of optimal location of UPFC to relieve congestion. The optimal location of UPFC is shown in table VI.

Table II describes the device ratings of UPFC under different cases. Table III reviews the congested lines of IEEE 30-bus system under various case studies before incorporating UPFC as a result of power flow analysis. Table IV and V clearly shows that the congestion is relieved after incorporating UPFC in the transmission network using Fuzzy and SQP. On comparing table IV and V, it is clear that the proposed Fuzzy method produce better results than SQP. Comparison of values of the optimization indices are shown in table VII. A congestion cost comparison for each case study has been represented in Figure 6. Figure 7 and 8 represent the comparison plots of RPPI and losses on each case for the best locations identified through fuzzy and SQP. This comparison also confirms the effectiveness of the proposed algorithm for relieving congestion and the optimal location and sizing of UPFC.

It can be seen that at low load levels, congestion cost will not have much impact. In contrast, raising load levels will increase the congestion cost considerably. As the line flow constraints are enforced, it introduces congestion in the transmission lines. Line flow constraints cause a significant increase in total generation capacity and total transmission capacity. Therefore line flow constraints are the main cause of high TCC. Independent system operator (ISO) cannot achieve minimum total system cost by merely rescheduling generators. Instead of rescheduling, FACTS devices can be used for compensation by achieving minimum cost. UPFC can be used to compensate the congested lines and transfer cheaper power from generators to consumers. Moreover, the losses are also minimized after implementing UPFC in the transmission network. The optimal location and size of UPFC is determined by minimizing total congestion cost, losses and decreasing real power performance index taking into account the system constraints.

Parameter	Case A	Case B	Case C	Case D
r(%)	0.5	0.51	0.498	0.445
μ(rad)	0.32	0.314	0.321	0.254
B_{se}(p.u)	1.76	1.762	1.763	1.762
Rating (MVAr)	17.48	26.24	54.25	48.21

Table 2. Device Settings for Different Cases

Line Flows in Congested Lines (MW)							
Case-A		Case-B		Case-C		Case-D	
Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)
1-3	147.19	1-2	106.90	1-2	172.38	1-3	171.78
3-4	136.06	-	-	2-5	115.88	3-4	157.47
-	-	-	-	-	-	4-6	93.89

Table 3. Congested Lines under Various Case Studies- Before UPFC

Line Flows in Congested Lines (MW)							
Case-A		Case-B		Case-C		Case-D	
Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)
1-3	84.45	1-2	98.99	1-2	99.76	1-3	71.99
3-4	79.17	-	-	2-5	97.08	3-4	67.50
-	-	-	-	-	-	4-6	29.17

Table 4. Line Flows Through Congested Lines - After UPFC using Fuzzy

Line Flows in Congested Lines (MW)							
Case-A		Case-B		Case-C		Case-D	
Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)	Line i-j	Line Flow (MW)
1-3	86.91	1-2	98.49	1-2	99.85	1-3	72.68
3-4	81.46	-	-	2-5	97.29	3-4	68.15
-	-	-	-	-	-	4-6	29.68

Table 5. Line Flows Through Congested Lines - After UPFC using SQP

Cases	Optimal Location of UPFC					
	Fuzzy			SQP		
	Initial bus	Final bus	Line number	Initial bus	Final bus	Line number
A	12	14	17	12	14	17
B	21	22	29	21	22	29
C	3	4	4	3	4	4
D	1	3	2	1	3	2

Table 6. Optimal Location of UPFC comparison using Fuzzy and SQP

Cases	Congestion cost($)		Total Loss (MW)		RPPI	
	Fuzzy	SQP	Fuzzy	SQP	Fuzzy	SQP
A	10115.45	10375.56	10.23	10.48	19.21	19.76
B	8675.87	8985.43	7.21	8.85	20.14	20.62
C	12287.10	12356.67	17.20	17.43	21.17	21.24
D	11289.78	11368.88	16.50	16.72	18.30	18.68

Table 7. Comparison of Values of the Optimization Indices using Fuzzy and SQP

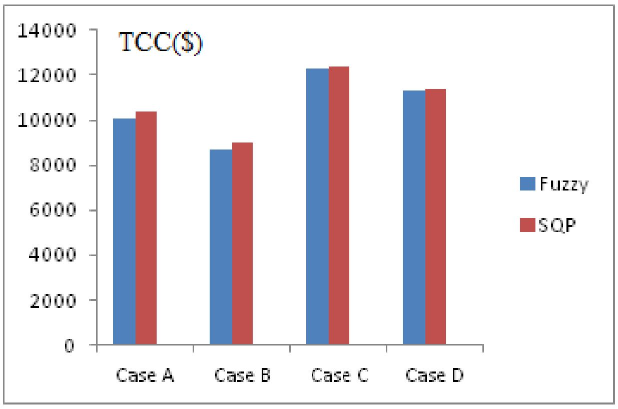

Fig 6. Comparison of Congestion Cost for Various Cases

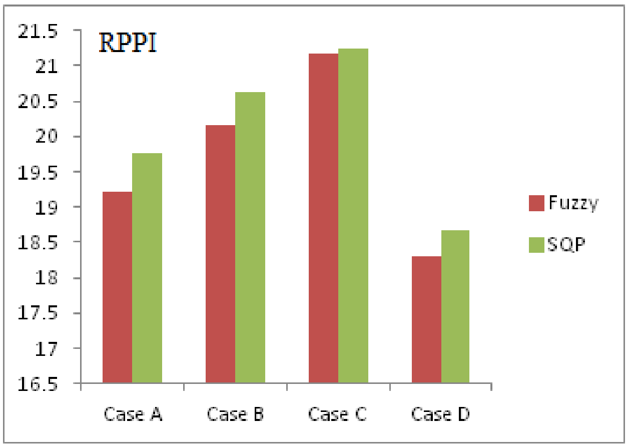

Fig 7.Comparison of RPPI for various cases

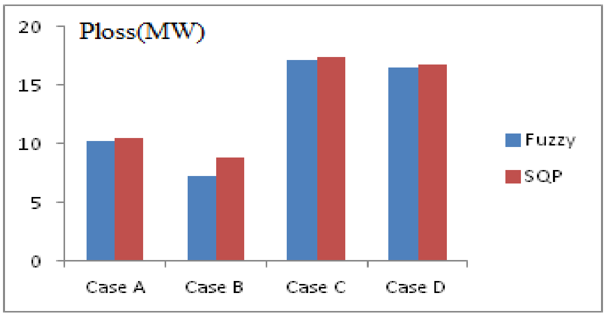

Fig 8. Comparison of Total losses for various cases

6 Conclusion

In this paper, fuzzy based approach is proposed for optimal location and sizing of UPFC for congestion management in deregulated power systems. The performance of the proposed algorithm is tested with IEEE 30-bus system under severe line outages and overloads. Optimal location of UPFC to relieve line congestion is treated as a multi-objective optimization problem considering minimization of congestion cost, total losses and severity index as objectives. It is observed that the location which is presented as optimal solution with respect to the objectives relieve congestion in a better way by adjusting the device rating of UPFC. It can also be extended to other critical lines as UPFC can provide compensation to multiple transmission lines concurrently.

The fuzzy based results are compared to the solution given by the conventional Sequential Quadratic Programming method. This comparison confirms the efficiency of the proposed method, and the results could be effectively used for determining the optimal location of UPFC 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. Compared with other optimisation techniques such as SQP, the proposed fuzzy method achieves better solutions.

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