

An IPM-EPSO Based Hybrid Method for Security Enhancement Using SSSC

Ch. Padmanabha Raju¹, K.Vaisakh², and S. Sivanaga Raju³

¹ PVP Siddhartha Institute of Technology, EEE Department, Vijayawada, AP, India

Email: pnraju78@yahoo.com

² Andhra University College of Engineering, EE Department, Visakhapatnam, AP, India

³ JNT University Kakinada, EEE Department, Kakinada, AP, India

Email: vaisakh_k@yahoo.co.in, sirigiri70@yahoo.co.in

Abstract—This paper presents an Interior Point Method (IPM) and Evolutionary Particle Swarm Optimization (EPSO) based hybrid method to solve optimal power flow in power system incorporating Flexible AC Transmission Systems (FACTS) such as Static Synchronous Series Compensator (SSSC) for security enhancement in the power systems. A fuzzy logic composite criteria based severity index is also used as an objective to be minimized to improve the security of the power system. The proposed optimization process with IPM-EPSO is presented with case study example using IEEE 30-bus test system to demonstrate its applicability. The results are presented to show the feasibility and potential of this new approach.

Index Terms—Optimal power flow, evolutionary particle swarm optimization, flexible AC transmission, SSSC

I. INTRODUCTION

The problem of power system security has obtained much attention in the present day modern power industry. To meet the load demand in a power system and satisfy the stability and reliability criteria, either the existing transmission lines must be utilized more efficiently, or new line(s) should be added to the system. The latter is often impractical. The reason is that building a new power line is in many countries, a very time consuming process and sometimes an impossible task, due to environmental problems. Therefore, the first alternative provides an economically and technically attractive solution to power system security problem by use of some efficient controls, such as controllable series capacitors, phase shifters, and load shedding, etc., [1]–[5]. Several techniques have been proposed in the past for the adjustment of phase shifter or the adjustment of controllable series capacitor to alleviate line overloads [4], [5].

The main method uses the model of series capacitor or phase shifter in power flow program without generation rescheduling. It is possible to alleviate power flow violation and enhance power system security in an electrical power system by use of phase shifter without optimal generation rescheduling. However, it is well known that the phase shifter adjustment under given contingencies may fail to yield convergence. Thus, optimal power flow (OPF) with phase shifter is a good choice.

The goal of optimal power flow is to determine optimal control variables and quantities for efficient

power system planning and operation. Several optimization techniques have been proposed to handle the OPF problem [6]–[8]. Recently, the research in OPF such as interior point (IP) using new optimization techniques, has been gaining wider attention in power system operation [9], [10]. The interior point method is faster and more reliable for achieving feasibility and convergence. Due to the limitation of IP, the model of discrete variable such as phase shifter has not been investigated in the common OPF.

Heuristic algorithms, such as genetic algorithms (GA) [11] and evolutionary programming [12], have been recently proposed for solving the OPF problem. The results reported were promising and encouraging for further research in this direction. Unfortunately, recent research has identified some deficiencies in GA performance [13]. This degradation in efficiency is apparent in applications with highly epistatic objective functions, i.e. where the parameters being optimized are highly correlated. In addition, the premature convergence of GA degrades its performance and reduces its search capability.

Recently, a new evolutionary computation technique, called particle swarm optimization (PSO), has been proposed and introduced [14–17]. This technique combines social psychology principles in socio-cognition human agents and evolutionary computations. PSO has been motivated by the behavior of organisms such as fish schooling and bird flocking. Generally, PSO is characterized as simple in concept, easy to implement, and computationally efficient. Unlike the other heuristic techniques, PSO has a flexible and well-balanced mechanism to enhance and adapt to the global and local exploration abilities.

This paper presents an IPM-EPSO (Evolutionary Particle Swarm Optimization) integrated hybrid approach to study the OPF with SSSC for removing line overloads. The objective functions of OPF include fuzzy logic composite criteria, and combined fuzzy severity index and real power loss. The proposed approach is examined with the IEEE 30-bus test system with 1 SSSC at a time.

II. FACTS DEVICES

FACTS technology is proven to be a promising solution for various power system problems. FACTS devices (especially series FACTS devices such as TCSC,

SSSC) are considered one such technology that reduces the transmission congestion and allows better utilization of the existing grid infrastructure, along with many other benefits [18]. Various issues associated with the use of FACTS devices are proper location, appropriate size and setting, cost, modeling and controller interactions. This paper deals with the optimal setting aspect of the series FACTS device such as SSSC, especially to manage congestion in the deregulated electricity markets.

The location of FACTS devices can be based on static or dynamic performances of the system. The sensitivity factor methods are generally used to find the best location to enhance the static performance of the system. In [19], an overload sensitivity factor (power flow index) is used for optimal location of series FACTS devices (i.e. TCSC and TCPAR) for static congestion management. A loss sensitivity factor method is used in [20] to determine the suitable location for FACTS devices. For large systems, the enumerative approach is not practical given the large number of combinations that have to be examined. In [21] the Tabu search method and in [22] the Genetic algorithm is used to solve the combinatorial (i.e. to determine number and location) problem of FACTS device allocation. However, these methods are computationally demanding and less reliable.

1) Equivalent circuit of SSSC

The equivalent circuit of SSSC is as shown in the fig.1. A SSSC usually consists of a coupling transformer, an inverter and a capacitor. SSSC will be connected in series with a transmission line through a coupling transformer. In steady-state operation, the SSSC performs a similar function to the static phase shifter; it injects voltage in quadrature with one of the line end voltages in order to regulate active power flow. However, the SSSC is a far more versatile controller than the phase shifter because it does not draw reactive power from the AC system; it has its own reactive power provisions in the form of a DC capacitor. This characteristic makes the SSSC capable of regulating not only active but also reactive power flow or nodal voltage magnitude. A schematic representation of the SSSC and its equivalent circuit are shown in Figures 1(a) and (b), respectively.

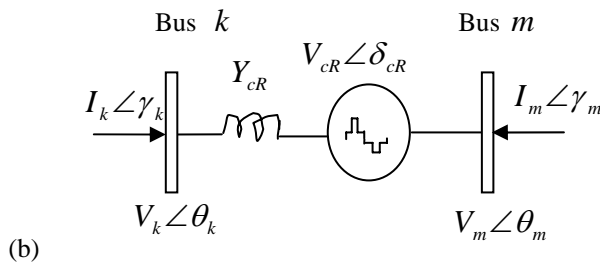
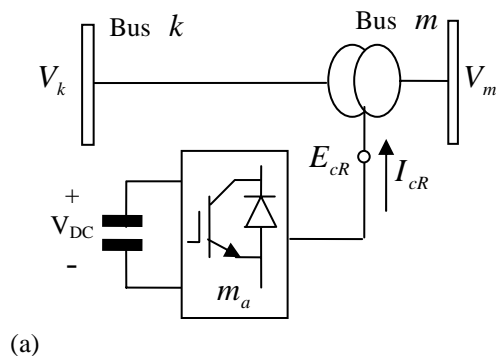


Figure 1. Solid state compensator (SSSC) system: (a) voltage source converter (VSC) connected to the AC network using a series transformer and (b) series solid state voltage source

The series voltage source of the SSSC may be represented by

$$E_{cr} = V_{cr} (\cos \delta_{cr} + j \sin \delta_{cr}) \tag{1}$$

The magnitude and phase angle of the SSSC model are adjusted by using any suitable iterative algorithm to satisfy a specified active and reactive power flow across the SSSC. The maximum and minimum limits will exist for the voltage magnitude V_{cr} , which are a function of the SSSC capacitor rating; the voltage phase angle δ_{cr} can take any value between 0 and 2π radians.

The active power flow constraint is as in eqn. (2)

$$P_{ji} - P_{ji}^{specified} = 0 \tag{2}$$

where $P_{ji}^{specified}$ is specified active power flow.

The reactive power flow constraint is as in eqn. (3)

$$Q_{ji} - Q_{ji}^{specified} = 0 \tag{3}$$

where $Q_{ji}^{specified}$ is specified reactive power flow.

The equivalent voltage injection $V_{cr} \angle \theta_{cr}$ bound constraints are given in eqns. (4-5)

$$V_{cr}^{min} \leq V_{cr} \leq V_{cr}^{max} \tag{4}$$

$$\delta_{cr}^{min} \leq \delta_{cr} \leq \delta_{cr}^{max} \tag{5}$$

This paper presents a new methodology for network overload alleviation using fuzzy logic composite criteria and optimal setting of series FACTS device such as SSSC under network contingency conditions. The proposed methods are applicable to any type of series FACTS devices; however, in the paper they are used to optimal setting of SSSC.

The rest of the paper is organized as follows: Section 3 describes the fuzzy logic composite criteria for the determination of overall system severity index. Section 4 presents the formulation of OPF incorporating SSSC and the solution approach used to solve OPF. The proposed placement methodologies for series FACTS devices in the modern power system described in Section 5. Numerical results along with some observations and discussions are presented in Section 6. Finally, the major contributions and conclusions of the paper are summarized in Section 7.

III. FUZZY LOGIC COMPOSITE CRITERIA

The pre/post-contingent quantities are first expressed in fuzzy set notation before they can be processed by the fuzzy reasoning rules [23].

1) *Line Loadings*

Each pre/post-contingent percentage line loading is divided into four categories using fuzzy set notations: Lightly Loaded (LL), 0-50%, Normally Loaded (NL), 50-85%, Fully loaded (FL), 85-100%, Over Loaded (OL), above 100%.

The output membership functions to evaluate the severity of a pre/post -contingent quantity are also divided into four categories using fuzzy set notations: Less Severe (LS), Below Severe (BS), Above Severe (AS) and More Severe (MS).

After obtaining the severity indices of all the lines the Overall Severity Index (OSI_{LL}) of the line loading for a particular line outage is obtained using the wing expression.

$$OSI_{LL} = \sum w_{LL} SI_{LL}$$

where w_{LL} = Weighting coefficient for a severity index,

SI_{LL} = Severity Index of a pre/post -contingent quantity

The weighting coefficients used for the severity indices are

$w = 0.25$ for LS, 0.50 for BS, 0.75 for AS and 1.00 for MS

The effect of these weighting coefficients is that the overall severity index is first dominated by fourth category of severity index (MS) next by third, second and first category of severity index respectively. Thus the overall severity index reflects the actual severity of the system for a pre/post contingency condition.

2) *Bus Voltage Profiles*

In this case each pre/post-contingent bus voltage profile is divided into three categories using fuzzy set notations: Low Voltage (LV), below 0.9pu, Normal Voltage (NV), 0.9-1.02pu and Over Voltage (OV), above 1.02pu.

The output membership functions used to evaluate the severity of a post -contingent quantity are also divided into three categories using fuzzy set notations: Below Severe (BS), Above Severe (AS) and MS (More Severe). After obtaining the severity indices of all the voltage profiles the Overall Severity Index (OSI_{VP}) of the bus voltage profiles for a particular line outage is obtained using the expression

$$OSI_{VP} = \sum w_{VP} SI_{VP}$$

The weighting coefficients used for the severity indices are

$w_{VP} = 0.30$ for BS, 0.60 for AS and 1.00 for MS.

3) *Voltage Stability Indices*

Each pre/post-contingent voltage stability index is divided into five categories using fuzzy set notations: Very Low Index (VLI), 0-0.2, Low Index (LI), 0.2-0.4, Medium Index (MI), 0.4-0.6, High Index (HI), 0.6-0.8 and Very High Index (VHI), 0.8 above.

The output membership functions to evaluate the severity of a pre /post -contingent quantity are also divided into five categories using fuzzy set notations: Very Less Severe (VLS), Less Severe (LS), Below Severe (BS), Above Severe (AS) and More Severe (MS).

After obtaining the severity indices of all the voltage stability indices the Overall Severity Index (OSI_{VSI}) of the bus voltage stability index for a particular line outage is obtained using the expression

$$OSI_{VSI} = \sum w_{VSI} SI_{VSI}$$

The weighting coefficients used for the severity indices are

$w_{VSI} = 0.20$ for VLS, 0.40 for LS, 0.60 for BS, 0.80 for AS and 1.00 for MS

TABLE I
FUZZY RULE BASE FOR DETERMINATION OF SEVERITY INDEX

<i>Line Loadings</i>					
<i>Input</i>	LL	NL	FL	OL	
<i>Output</i>	LS	BS	AS	MS	
<i>Voltage Profiles</i>					
<i>Input</i>	LV	NV	OV		
<i>Output</i>	MS	BS	MS		
<i>Voltage stability Indices</i>					
<i>Input</i>	VLI	LI	MI	HI	VHI
<i>Output</i>	VLS	LS	BS	AS	MS

4) *Fuzzy Severity Index*

The overall severity index is obtained using the parallel operated fuzzy inference systems, as shown in Fig.2, for the pre/post contingency operating conditions. The overall severity index for line loading, voltage profiles, and voltage stability indices are added and the sum is used as the Fuzzy Logic Composite Criteria (FLCC). Table I gives the fuzzy rules used for evaluating the severity index.

IV. OPTIMAL POWER FLOW PROBLEM FORMULATION

The optimal power flow problem is a nonlinear optimization problem with nonlinear objective function and nonlinear constraints. The solution methods to optimal power flow using conventional methods are the widely used Newton method, gradient methods and interior point methods. Handling of a large number of different types of constraints is a limitation with these methods. Successful applications of evolutionary programming methods like genetic algorithms, evolutionary computation, PSO, etc. has reduced the limitations of the conventional methods to a great extent.

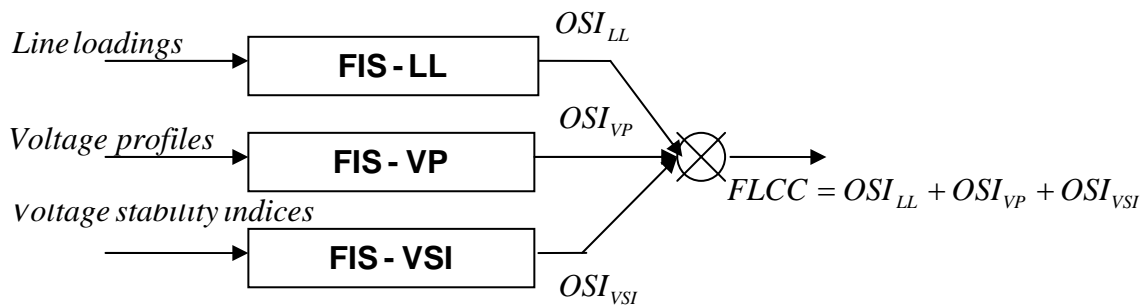


Figure 2 Parallel operated fuzzy inference systems

Problem variables

The OPF problem requires the solution of nonlinear equations, describing optimal and/or secure operation of a power system. The general OPF problem can be expressed as:

Minimize $F(x, u)$, (6)

Subject to $g(x, u) = 0$, (7)

$h(x, u) \leq 0$, (8)

where

$x^T = [\delta \ V_L^T]$, (9)

$u^T = [P_G^T \ V_G^T \ t^T]$, (10)

$F(x, u)$ the objective function,

$g(x, u)$ a set of nonlinear equality constraints (power flow equations), and

$h(x, u)$, a set of nonlinear inequality constraints of a vector argument x and u .

1) *Objective Functions*

The following are the objective functions considered for minimization.

Objective Function 1:

$$\text{Min(Ploss)} = \min \left(\sum_{i=1}^{NL} G_{ij} (V_i^2 + V_j^2 - 2V_i V_j \cos \theta_{ij}) \right)$$
 (11)

Objective Function 2:

$$\text{Min J2} = \min (W1 * \text{FLCC} + W2 * \text{Ploss})$$
 (12)

where $W1$ & $W2$ weights.

V. IPM-EPSO BASED HYBRID METHOD

1) *Hybrid Method Combining IPM with EPSO*

Basically, the hybrid method involves two steps. The first step employs IPM to solve OPF approximated as a continuous problem and introduced into the initial populations of EPSO [24]. The second part uses EPSO to obtain the final optimal solution. In initial population, all individuals (obtained from IPM) are produced randomly. The main reason for using the IPM is that it is often closer to optimal solutions than other random individuals.

In the hybridization of IPM and PSO, the IPM

generates best initial solutions from random initial solutions and EPSO evaluate them by solving the OPF, which yields to the global optimal solutions for control variables.

VI. RESULTS OF IEEE-30 BUS SYSTEM

The proposed approach has been tested on the standard IEEE 30-bus test system shown in Fig. 3. The system line and bus data are given in [25]. The system has six generators at buses 1, 2, 5, 8, 11, and 13 and four transformers with off-nominal tap ratio in lines 6-9, 6-10, 4-12, and 28-27. The minimum and maximum limits on control variables along with the initial operating point are given in [25].

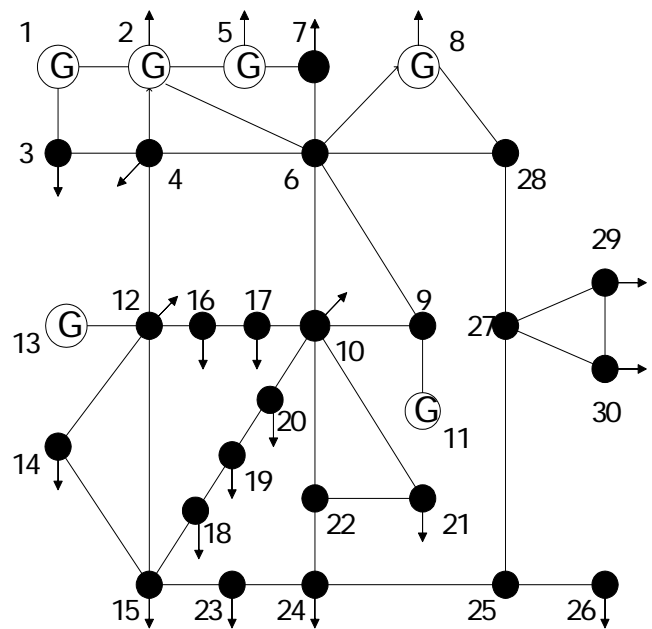


Figure 3. Single-line diagram of IEEE 30-bus system

Table II gives the classification of buses into different severity categories under the selected two most severe network contingencies. From the Table II it can be observed that the proposed IPM-EPSO method is effectively able to improve the security with both the fuzzy logic composite criteria based objectives and

SSSC.

TABLE II. BUSES UNDER DIFFERENT SEVERITY CATEGORIES

Contingency	Objective Function	SSSC Location	Line Loadings				Voltage Profiles			Bus Voltage Stability Indices				
			LS	BS	AS	MS	BS	AS	MS	VLS	LS	BS	AS	MS
2-5	Objective Function 1	Without FACTS	31	9	0	0	0	6	18	24	0	0	0	0
		With SSSC	31	9	0	0	0	9	15	24	0	0	0	0
	Objective Function 2	Without FACTS	34	6	0	0	0	24	0	24	0	0	0	0
		With SSSC	35	5	0	0	0	24	0	24	0	0	0	0
8-11	Objective Function 1	Without FACTS	35	4	1	0	0	13	11	24	0	0	0	0
		With SSSC	34	6	0	0	0	8	16	24	0	0	0	0
	Objective Function 2	Without FACTS	37	3	0	0	0	23	1	24	0	0	0	0
		With SSSC	37	3	0	0	0	23	1	24	0	0	0	0

VII. CONCLUSION

In this paper, a new IPM-EPSo hybrid method has been presented to solve the optimal power flow problem with a FACTS device. The proposed method introduces the voltage source model of FACTS devices into a conventional AC optimal power flow problem to exploit the new characteristic of FACTS devices. Case studies on IEEE-30 bus test system show the potential for application of IPM-EPSo to alleviate the network overloads with FACTS. It has been shown that the FACTS device can effectively improve the security of the system under the selected network contingency conditions.

REFERENCES

[1] N. Srinivasan, K. S. Prakaesa, and S. S. Venkata, "On-line computation of phase shifter distribution factors and line load alleviation," *IEEE Trans. on Power Systems*, vol. PAS-104, no. 7, pp. 1656–1662, 1985.

[2] B. Stott and E. Hobson, "Power system security control calculations using linear programming—Part I," *IEEE Trans. on Power Systems*, vol. PAS-97, pp. 1713–1719, 1978.

[3] R. Baldick and E. Kahn, "Contract paths, phase shifters, and efficient electricity trade," *IEEE Trans. on Power Systems*, vol. 12, no. 2, pp.749–755, 1997.

[4] M. R. Irvani and D. Maratukulam, "Review of semiconductor-controlled (static) phase shifters for power system applications," *IEEE Trans. on Power Systems*, vol. 9, no. 4, pp. 1833–1839, 1994.

[5] T. K. P. Medicherla, R. Billinton, and M. S. Sachdev, "Generation rescheduling and load shedding to alleviate line overloads—Analysis," *IEEE Trans. on Power Systems*, vol. PAS-98, pp. 1876–1884, 1979.

[6] A. D. Papalexopoulos, C. F. Imparato, and F. F. Wu, "Large scale optimal power flow: Effects of initialization decoupling and discretization," *IEEE Trans. on Power Systems*, vol. 4, pp. 748–759, 1989.

[7] O. Alsac and B. Stott, "Optimal power flow with steady-state security," *IEEE Trans. on Power System*, vol. 93, pp. 745–751, 1974.

[8] J. Z. Zhu and G. Y. Xu, "A new real power economic dispatch method with security," *Electric Power Systems Research*, vol. 25, no. 1, pp. 9–15, 1992.

[9] S. Granville, J. C. O. Mello, and A. C. G. Melo, "Application of interior point methods to power flow unsolvability," *IEEE Trans. on Power System*, vol. 11, pp. 1096–1103, 1996.

[10] J. A. Momoh, L. G. Dias, S. X. Guo, and R. A. Adapa, "Economic operation and planning of multi-area interconnected power system," *IEEE Trans. on Power System*, vol. 10, pp. 1044–1051, 1995.

[11] Lai LL, Ma JT. Improved genetic algorithms for optimal power flow solutions under both normal and contingent operation states. *Int J Elec Pwr Syst* 1997;19(5):287-92.

[12] Yuryevich J, Wong KP. Evolutionary programming based optimal power flow algorithm. *IEEE Trans Pwr Syst* 1999;14(4):1245-50.

[13] Fogel DB. Evolutionary computation toward a new philosophy of machine intelligence. New York: IEEE Press, 1995.

[14] Kennedy J. The particle swarm: social adaptation of knowledge. *Proc 1997 IEEE Int Conf Evol Comput ICEC*, 97, Indianapolis, IN, USA 1997:303-8.

[15] Angeline P. Evolutionary optimization versus particle swarm optimization: philosophy and performance differences. *Proc 7th Annu Conf Evol Prog* 1998:601-10.

[16] Shi Y, Eberhart R. Parameter selection in particle swarm optimization. *Proc 7th Annu Conf Evol Prog* 1998:591-600.

[17] Ozean E, Mohan C. Analysis of a simple particle swarm optimization system. *Intel Engng Syst Artif Neural Networks* 1998;8:253-8.

[18] N. Acharya, A. Sody-Yome, N. Mithulananthan, Facts about flexible ac Transmission systems (FACTS) controllers: Practical installations and benefits, in: Australasian Universities Power Engineering Conference (AUPEC), Australia, September 25-28, 2005, pp.533-538

[19] S.N. Singh, A.K. David, Optimal location of FACTS devices for congestion management, *Electr. Power Syst. Res.* 58(2001), pp.71-79.

[20] P. Preedavichit, S.C. Srivastava, Optimal reactive power dispatch considering FACTS devices, *Electr. Power Syst. Res.* 46(1998) pp.251-257.

[21] H. Mori, Y. Goto, A parallel Tabu Search based method for determining optimal allocation of FACTS in power systems, in: International Conference on Power System Technology Proceedings, vol.2., 2000, pp.1077-1082.

[22] S. Gerbex, R. Cherkaoui, J. Germond, Optimal location of multi-type FACTS devices in a power system by means of genetic algorithms, *IEEE Trans. Power Syst.* 16(3)(2001) pp.537-544.

[23] Thukaram, D and Jenkins, L and Khincha, HP and Visakha, K and Ravikumar, B (2007) *Fuzzy logic application for network contingency ranking using composite criteria*. In: *Engineering Intelligent Systems*, 15 (4), pp. 205-212.

[24] Vladimiro Miranda and Nuno Fonseca, "EPSo - Evolutionary Particle Swarm Optimization, a New Algorithm with Applications in Power Systems" <http://www.engenheiros.pt/~nunomikel/papers/artigo152.pdf>

[25] K Y Lee, Y M Park and J L Ortiz. 'A United Approach to Optimal Real and Reactive Power Dispatch'. *IEEE Transactions on Power Apparatus and System*, vol 104, 1985, pp1147-1153.