Optimal Allocation of FACTS Devices to Enhance Total Transfer Capability Using Evolutionary Programming

Weerakorn Ongsakul and Peerapol Jirapong
School of Environment, Resources, and Development
Asian Institute of Technology, Pathumthani, Thailand
ongsakul@ait.ac.th and st029131@ait.ac.th

Abstract—**In this paper, an evolutionary programming (EP) is proposed to determine the optimal allocation of FACTS devices for maximizing the total transfer capability (TTC) of power transactions between source and sink areas in deregulated power system. EP simultaneously searches for FACTS locations, FACTS parameters, real power generations except slack bus in source area, real power loads in sink area, and generation bus voltages. Multi-objective optimal power flow (OPF) with FACTS devices including TTC and penalty functions is used to evaluate the feasible TTC value within real and reactive power generation limits, voltage limits, line flow limits, and FACTS devices operation limits. Four types of FACTS devices are included: thyristor-controlled series capacitor (TCSC), thyristor-controlled phase shifter (TCPS), unified power flow controller (UPFC), and static var compensator (SVC). Test results on IEEE 30-bus system indicate that optimally placed OPF with FACTS devices by EP could enhance the TTC value far more than OPF without FACTS devices.**

I. INTRODUCTION

In recent years, with the deregulation of electric power systems, electric utilities are forced by competition to operate their facilities at a higher efficiency. There is an interest in better utilization of the existing power systems to control power flow, improve system dynamics, and increase system reliability by using Flexible AC Transmission Systems (FACTS) [1]. Moreover, FACTS devices can be used to increase power system transfer capability [2], [3].

Total transfer capability (TTC) is a terminology that is used to define the amount of electric power that can be transferred over the interconnected transmission systems in a reliable manner [4]. It is required to be calculated for each control area and posted on a public communication system to enhance the open-access of transmission systems by providing a market signal of the capability of the transmission systems to deliver electric energy [5].

A wide variety of mathematical methods and algorithms have been developed for calculating TTC. These methods can be divided into four types as follows: 1) linear ATC (LATC) method [6], which is based on linear incremental power flow approximation, 2) continuation power flow (CPF) method [7], and 3) repetitive power flow (RPF) method [8], which use common loading factor to determine TTC value, and 4) optimal power flow (OPF) based method, which can be implemented by optimization techniques such as sequential quadratic programming (SQP) [9] and transfer-based security constrained optimal power flow (TSCOPF) method [10]. These methods require convexity of objective function to obtain the optimal solution. However the OPF problem is in general nonconvex and, as a result, many local minima may exist especially in a highly nonlinear system, when FACTS devices are included in the system [11], [12]. Moreover, FACTS parameters are additional control variables that cannot be solved by conventional OPF because these parameters will change the admittance matrix. Therefore, conventional optimization methods might converge to a local optimal point due to its directed search using local information.

Evolutionary programming (EP) is a computational optimization method, which uses the mechanic of evolution to find the global optimal solution of complex optimization problems [13]. It works by evolving a population of candidate toward the global solutions through the use of the mutation operator and selection scheme. This algorithm can move over hills and across valleys to discover a global optimal point. Because of this, EP is more robust than the existing direct search methods. Therefore in this paper, the EP algorithm is proposed to determine the optimal allocation of FACTS devices for maximizing the TTC of power transactions between source and sink areas. EP simultaneously searches for FACTS locations, FACTS parameters, real power generations except slack bus in source area, real power loads in sink area, and generation bus voltages to determine maximum TTC value.

0-7803-8834-8/05/$20.00 ©2005 IEEE.

II. Problem Formulation

The OPF with FACTS devices is used to evaluate the feasible TTC value of power transactions. The objective function is to maximize the power that can be transferred from a specific set of generators in a source area to loads in a sink area, subject to real and reactive power generation limits, voltage limits, line flow limits, and FACTS devices operation limits.

Four types of FACTS devices are included: thyristor-controlled series capacitor (TCSC), thyristor-controlled phase shifter (TCPS), unified power flow controller (UPFC), and static var compensator (SVC). The mathematical models of the FACTS devices are used to perform the steady-state studies. Therefore, the TCSC is modeled to modify the reactance of transmission lines directly. The TCPS, UPFC, and SVC are modeled using the injected power model [14]. The objective function is formulated as (1).

$$\text{Max} \quad F = \sum_{i=1}^{ND\_SNK} P_{Di} \tag{1}$$

Subject to

$$P_{Gi} - P_{Di} + \sum_{k=1}^{m(i)} P_{Pi}(\alpha_{Pk}) + \sum_{k=1}^{n(i)} P_{Ui}(V_{Uk}, \alpha_{Uk}) - \sum_{j=1}^{N} V_i V_j Y_{ij}(X_S) \cos(\theta_{ij}(X_S) - \delta_i + \delta_j) = 0 \tag{2}$$

$$Q_{Gi} - Q_{Di} + \sum_{k=1}^{m(i)} Q_{Pi}(\alpha_{Pk}) + \sum_{k=1}^{n(i)} Q_{Ui}(V_{Uk}, \alpha_{Uk}) + Q_{Vi} + \sum_{j=1}^{N} V_i V_j Y_{ij}(X_S) \sin(\theta_{ij}(X_S) - \delta_i + \delta_j) = 0 \tag{3}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad \forall i \in NG \tag{4}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad \forall i \in NG \tag{5}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad \forall i \in N \tag{6}$$

$$|S_{Li}| \le S_{Li}^{\max} \qquad \forall i \in NL \tag{7}$$

$$0 \le X_{Si} \le X_{Si}^{\max} \tag{8}$$

$$\alpha_{Pi}^{\min} \le \alpha_{Pi} \le \alpha_{Pi}^{\max} \tag{9}$$

$$0 \le V_{Ui} \le V_{Ui}^{\max} \tag{10}$$

$$-\pi \le \alpha_{Ui} \le \pi \tag{11}$$

$$Q_{Vi}^{\min} \le Q_{Vi} \le Q_{Vi}^{\max} \tag{12}$$

Where F is the objective function to be optimized, defined as the total load in sink area. P_{Gi} and Q_{Gi} are the real and reactive power generations at bus i. P_{Di} and Q_{Di} are the real and reactive loads at bus i. $P_{Pi}(\alpha_{Pk})$ and $Q_{Pi}(\alpha_{Pk})$ are the injected real and reactive powers of TCPS at bus i. $P_{Ui}(V_{Uk}, \alpha_{Uk})$ and $Q_{Ui}(V_{Uk}, \alpha_{Uk})$ are the injected real and reactive powers of UPFC at bus i. Q_{Vi} is the fixed injected reactive power of SVC at bus i. V_i and V_j are the voltage magnitudes at bus i and j respectively. $Y_{ij}(X_S)$ and $\theta_{ij}(X_S)$ are the magnitude and angle of the *ij*th element in bus admittance matrix with TCSC included. δ_i and δ_j are the voltage angles of bus i and j. $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the lower and upper limits of real power generation at bus i. $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ are the lower and upper limits of reactive power generation at bus i. $V_i^{\min}$ and $V_i^{\max}$ are the lower and upper limits of voltage magnitude at bus i. $|S_{Li}|$ is the *i*th line or transformer loading and $S_{Li}^{\max}$ is the *i*th line or transformer-loading limit. X_{Si} is the vector of reactance of TCSC. α_{Pi} is the phase shift angle of TCPS at bus i. V_{Ui} is the voltage magnitude of UPFC at bus i. α_{Ui} is the voltage angle of UPFC at bus i. N is the total number of buses. NG is the number of generators. NL is the number of branches, and ND_SNK is the number of load buses in sink area.

During the optimization, equality constraints are satisfied by the convergence of power flow, whereas inequality constraints are enforced by using penalty function as (13).

$$h(x_i) = \begin{cases} (x_i - x_i^{\max})^2 & \text{if } x_i > x_i^{\max} \\ (x_i^{\min} - x_i)^2 & \text{if } x_i < x_i^{\min} \\ 0 & \text{if } x_i^{\min} \le x_i \le x_i^{\max} \end{cases} \tag{13}$$

Where $h(x_i)$ is a penalty function of variable x_i. $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper limits of x_i. Equation (1) is therefore changed to the generalized multi-objective function as (14).

$$\text{Max} \quad F' = \sum_{i=1}^{ND\_SNK} P_{Di} - h(x_i) \tag{14}$$

The sum of real power loads in the sink area at the maximum power transaction is defined as the TTC value.

$$TTC = \sum_{i=1}^{ND\_SNK} P_{Di} \tag{15}$$

III. Evolutionary Programming

The EP algorithm starts with random generation of initial individuals in a population and then the mutation and selection are proceeded until the best individual, which has the highest fitness, is found. The main components of the algorithm are briefly explained as follows.

A. Representation of Solution

Each individual in a population composes of OPF control variables, which are coded by real number. The *k*th individual in a population is represented by a trial solution vector as (16).

$$V_k^T = [P_{Gi}, V_{Gi}, P_{Di}, Loc_i, X_{Si}, \alpha_{Pi}, V_{Ui}, \alpha_{Ui}, Q_{Vi}] \quad (16)$$

Where P_{Gi} is the real power generation at bus i in source area excluding slack bus. V_{Gi} is the voltage magnitude of generator at bus i including the slack bus. P_{Di} is the real power load at bus i in sink area. Loc_i is type and location of FACTS devices. Loc_1, Loc_2 and Loc_3 are line numbers of TCSC, TCPS, and UPFC respectively, and Loc_4 is bus number of SVC. X_{Si}, α_{Pi}, V_{Ui}, α_{Ui}, and Q_{Vi} are the parameters of TCSC, TCPS, UPFC and SVC respectively.

B. Initialization

The initial population is initialized randomly using sets of uniform random number distribution ranging over the feasible limits of each control variable as (17).

$$x_i = x_i^{\min} + u\left(x_i^{\max} - x_i^{\min}\right) \quad (17)$$

Where x_i is the *i*th element of the individual in a population. $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper limits of the *i*th element of the individual. u is a uniform random number in the interval [0,1].

C. Power Flow Solution

During iterations, a power flow is performed for each individual to compute its state variables. A full ac Newton-Raphson (NR) power flow analysis is used.

D. Fitness Function

The fitness of the *k*th individual can be calculated by using (18).

$$f_k = K_f * F' \quad (18)$$

Where f_k is the fitness of the *k*th individual. K_f is an arbitrary constant, and F' is the objective function.

E. Mutation

A new population is generated by using the Gaussian mutation operator. Each element of the *k*th new trial solution vector, V_k', is computed by using (19) and (20).

$$x'_{k,i} = x_{k,i} + N\left(0, \sigma_{k,i}^2\right) \quad (19)$$

$$\sigma_{k,i} = \left(x_i^{\max} - x_i^{\min}\right)\left(\frac{f_{\max} - f_k}{f_{\max}} + a^g\right) \quad (20)$$

Where $x'_{k,i}$ is the value of the *i*th element of the *k*th offspring individual. $x_{k,i}$ is the value of the *i*th element of the *k*th parent individual. $N\left(0, \sigma_{k,i}^2\right)$ is a Gaussian random number with a mean of zero and standard deviation of $\sigma_{k,i}$. $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper limits of the *i*th element of the *k*th parent individual. f_k is the fitness value of the *k*th individual. $f_{\max}$ is the maximum fitness of the parent population. a is a positive number constant slightly less than one and g is the iteration counter.

F. Selection

The selection technique utilized is a tournament scheme, which can be expressed as (21) and (22).

$$w_t = \begin{cases} 1 & if\ f_k > f_r \\ 0 & otherwose \end{cases} \quad (21)$$

$$s_k = \sum_{t=1}^{Nt} w_t \quad (22)$$

Where f_k is the fitness of the *k*th individual in the combined population. f_r is the fitness of the *r*th opponent randomly selected from the combined population based on $r = \lfloor 2 * P * u + 1 \rfloor$. $\lfloor x \rfloor$ is the greatest integer less than or equal to x. u is a uniform random number in the interval [0,1] and P is the population size.

G. Termination Criterion

If the maximum generation number is reached, the iteration process is terminated. Otherwise, the mutation and selection process will be reiterated until the criterion is satisfied.

IV. Case Study And Results

A modified IEEE 30-bus system, shown in Fig. 1, is used as a test system. Bus and line data can be found in [15]. The system has three areas with two generators in each area. Transactions between different control areas are studied. In the simulations, the reactance limit of TCSC in pu. is $0 \le X_{Si} \le 0.02$, phase shifter angle limit of TCPS in radian is $0 \le \alpha_{Pi} \le 0.1$, voltage and angle limit of UPFC are $0 \le V_{Ui} \le 0.1$ in pu. and $-\pi \le \alpha_{Ui} \le \pi$ in radian, and reactive power injection limit of SVC is $0 \le Q_{Vi} \le 11.2$ MVAR. To verify the validity of the results from the proposed algorithm, they are compared with the results from RPF method.

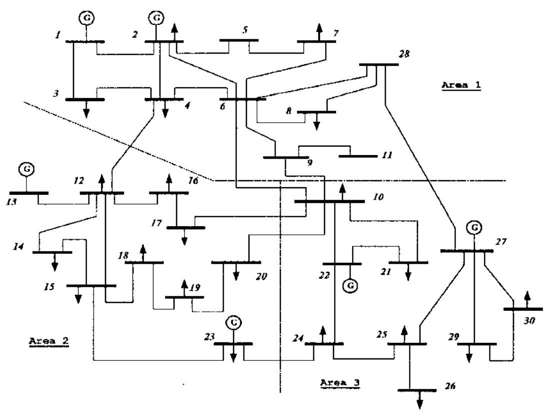

Figure 1. Diagram of the IEEE 30-bus system.

TABLE I. TTC RESULTS FROM THE IEEE 30-BUS SYSTEM

Transfer		Without FACTS				With FACTS	
From Area	***To Area***	**RPF Method**		**EP Method**		**EP Method**	
		TTC (MW)	***Limit Condition***	***TTC (MW)***	***Limit Condition***	***TTC (MW)***	***Limit Condition***
1	2	103.856	P_{G1}	104.219	P_{G1}	115.296	Line 27-25
1	3	53.445	V_{26}	59.306	P_{G1}	67.171	Line 27-25
2	1	122.329	P_{G13}	132.400	P_{G13}	137.885	P_{G13}
2	3	53.605	V_{26}	73.184	Line 27-30	78.468	P_{G13}
3	1	136.269	Line 27-25	143.268	Line 22-21	152.321	Line 27-25
3	2	106.686	V_{19}	134.534	Line 24-23	140.905	Line 12-15

Using the RPF method, the load of area 2 increases from 83.926 MW to 103.856 MW. The real power loads of area 2, given in bus number sequence, are [15.233, 0.00, 9.421, 11.746, 6.282, 12.676, 5.934, 13.257, 4.771, 24.532] MW. TTC value is 103.856 MW and the limiting condition is the expected generation upper limit at bus 1, PG1, if further transfers take place. Using the proposed EP method without FACTS devices, the load of area 2 increases to 104.219 MW. The real power loads of area 2 in bus number sequence are [14.318, 0.0, 10.185, 13.346, 7.250, 12.019, 4.380, 14.375, 3.953, 24.394] MW. The limiting condition is the generation upper limits at bus 1, which is the same as the binding condition of the RPF method. The results show that TTC from RPF is more conservative than that from the proposed method because RPF does not result in the optimal generation, loading, and generator bus voltages.

When multi-type of FACTS devices are incorporated in the system, using the EP method, the TTC value from the transaction from area 1 to area 2 is increased to 115.296 MW. TCSC, TCPS, and UPFC are installed at line number 39, 13, and 11 respectively, and SVC is installed at bus number 7. Parameters of FACTS devices are: X_{Si} = 0.001 pu., α_{Pi} = 0.0032 rad, V_{Ui} = 0.003 pu., α_{Ui} = -2.828 rad, and Q_{Vi} = 0.923 MVAR. Figure 2 shows the rapid convergence characteristic of the fitness of the proposed EP method. For other transfers between different control areas, with and without FACT devices, test results indicate that optimally placed FACTS devices can significantly enhance TTC of the system as shown in Table I.

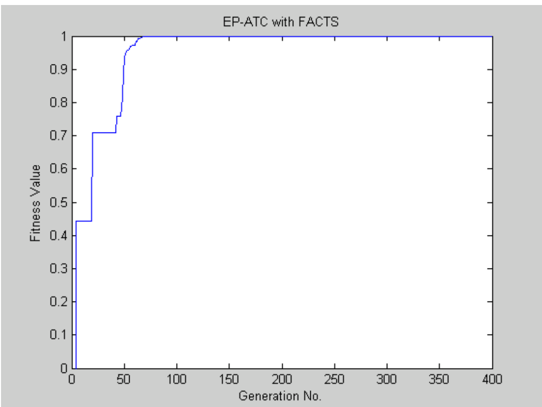

Figure 2. The convergence characteristic of the fitness of the EP method.

V. CONCLUSION

In this paper, the EP approach is effectively and successfully implemented to determine optimal allocation of multi-type of FACTS devices to maximize TTC between different control areas. Test results from the test system indicate that optimally placed OPF with FACTS devices by EP could enhance the TTC value far more than OPF without FACTS devices.

REFERENCES

[1] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, IEEE Press, New York, 1999.

[2] S. Gerbex, R. Cherkaoui, and A. J. Germond, “Optimal location of multi-type FACTS devices in a power system by means of genetic algorithms,” IEEE Transactions on Power Systems, vol. 16, no. 3, August 2001.

[3] Y. Xiao, Y. H. Song, C. C. Liu, and Y. Z. Sun, “Available transfer capability enhancement using FACTS devices,” IEEE Transactions on Power Systems, vol. 18, no. 1, February 2003.

[4] North American Electric Reliability Council, Available Transfer Capability Definitions and Determination, June 1996.

[5] Federal Energy Regulatory Commission, Open Access Same-Time Information System and Standards of Conduct, Order No. 889, Final Rule, April 1996.

[6] G. C. Ejebe, J. G. Waight, S. N. Manuel, and W. F. Tinney, “Fast calculation of linear available transfer capability,” IEEE Transactions on Power Systems, vol. 15, no. 3, August 2000.

[7] G. C. Ejebe, et al., “Available transfer capability calculations,” IEEE Transactions on Power Systems, vol. 13, no. 4, November 1998.

[8] M. H. Gravener and C. Nwankpa, “Available transfer capability and first order sensitivity,” IEEE Transactions on Power Systems, vol. 14, May 1999.

[9] M. Shaaban, Y. Ni, H. Dai, and F. F. Wu, “Calculation of total transfer capability incorporating the effect of reactive power,” Electric Power Systems Research, vol. 64, 2003.

[10] Y. Ou and C. Singh, “Assessment of available transfer capability and margins,” IEEE Transactions on Power Systems, vol. 17, May 2002.

[11] J. Yuryevich and K. P. Wong, “Evolutionary programming based optimal power flow algorithm,” IEEE Transactions on Power Systems, vol. 14, no. 4, Novvember 1999.

[12] A. G. Bakirtzis, P. N. Biskas, C. E. Zoumas, and V. Petridis, “Optimal power flow by enhanced genetic algorithm,” IEEE Transactions on Power Systems, vol. 17, no. 2, May 2002.

[13] L. L. Lai, Intelligent System Applications in Power Engineering: Evolutionary Programming and Neural Networks, John Wiley & Sons, 1998.

[14] P. Bhasaputra and W. Ongsakul, “Optimal power flow with multi-type of FACTS devices by hybrid TS/SA approach,” IEEE ICIT’02, Bangkok, Thailand, pp. 285-290, 2002.

[15] http://www.eng.nsf.gov/iucrc/directory/iucrc_ee.htm