Enhanced Genetic Algorithm for Optimal Electric Power Flow using TCSC and TCPS

K. Kalaiselvi, V. Suresh Kumar, and K. Chandrasekar

Abstract—**An enhanced genetic algorithm (EGA) for the solution of the optimal power flow (OPF) with use of controllable FACTS devices is studied. Two types of FACTS devices, thyristor-controlled series compensator (TCSC) and thyristor-controlled phase shifter (TCPS) are considered in this method. The specified power flow control constraints due to the use of FACTS devices are included in the OPF problem in addition to normal conventional constraints. The sensitivity analysis is carried out for the location of FACTS. This method can provide an enhanced economic solution with the use of controllable FACTS devices. Advanced and problem-specific operators are introduced in order to enhance the algorithm's efficiency and accuracy. IEEE standard 30-bus system is taken and results are presented to show the feasibility and potential of this approach.**

Index Terms— **Computational intelligence, FACTs, Genetic Algorithm, Power flow.**

I. Introduction

Deregulation of the electricity supply system becomes an important issue in many countries. Flexible AC Transmission System (FACTS) devices become more commonly used as the power market becomes more competitive. They may be used to improve the transient responses of power system and can also control the power flow (both active and reactive power). The main advantages of FACTS are the ability in enhancing system flexibility and increasing the loadability [1].

One of the current researches on FACTS devices is on the power flow control and economic operation such as optimal power flow (OPF). OPF is part of the standard tools of the supervisory, control and data acquisition (SCADA) and energy management system (EMS). It schedules power system controls to optimize an objective function while satisfying non-linear equality and linear equality constraints. In steady state operation of power system, unwanted loop flow and parallel power flow between utilities are problems in heavily loaded interconnected power systems. These two power flow problems are sometimes beyond the control of generators or it may cost too much with generator regulations. However, with the FACTS controllers, the unwanted power flow can be easily regulated [2].

In OPF, the main objective is to minimize the costs of meeting the load demand for the power system while satisfying all the security constraints. Since OPF is a non-linear problem, decouple of the control parameter of the FACTS device is a highly nonlinear problem so that GA is used as a methodology to solve. In this context, more control facilities may complicate the system operation. As control facilities influence each other, a good coordination is required in order to bring all devices to work together, without interfering with each other. Therefore, it becomes necessary to extend available system analysis tools, such as optimal power flow to represent FACTS controls. It has also been noted that the OPF problem with series compensation may be a non-convex and non-linear problem, which will lead the conventional optimization method stuck into local minimum. The GA-OPF approaches overcome the limitations of the conventional approaches in the modeling of non-convex cost functions, discrete control variables, and prohibited unit-operating zones. However, they do not scale easily to larger problems, since the solution deteriorates with the increase of the chromosome length.

In this work, the conventional OPF problem is solved with simple GA (SGA) and enhanced GA (EGA) approaches along with two powers flow constraints [3][4]. The probabilities of crossover and mutation are varied by adaptive genetic algorithm [5][6]. In addition to the basic genetic operators of the SGA used in [7] and the advanced ones used in [8] problem-specific operators, inspired by the nature of the OPF problem, have been incorporated in the proposed EGA. With the incorporation of the problem-specific operators, the EGA can solve larger OPF problems.

The approach minimize total cost as well as iteratively evaluates the control settings of TCSC and TCPS that are needed to maintain specified line flows. The sensitivity analysis is carried to position the TCSC and TCPS in test system [9][10]. The results obtained shows that EGA is superior in convergence compared to SGA. Here EGA is used to obtain economic dispatch of generators such that these generations give minimum cost as well as does not result in line flow violation.

II. Problem Formulation

In this study, the optimal power flow problem has the objective of minimizing the total cost of operating the spatially separated generating units subject to the set of equations that characterize the flow of power through the

Manuscript received October 21, 2008.
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system and all operational and security constraints [3]. The TCSC reactance and TCPS phase shift parameters constraints are included in the OPF problem. The optimal power flow problem in flexible AC transmission systems is therefore expressed as follows.

$$\text{Objective function} = \min \sum_{i \in NG} (a_i P_{gi}^{\ 2} + b_i P_{gi} + c_i)$$

$$s.t. P_{gi} + P_{is}(\phi) - P_{di} - \sum_{i \in NG} V_i V_j Y_{ij}(x_c)\cos(\theta_{ij} + \delta_j - \delta_i) = 0 \forall i = N$$

$$s.t. Q_{gi} + Q_{is}(\phi) - Q_{di} - \sum_{i \in NG} V_i V_j Y_{ij}(x_c)\sin(\theta_{ij} + \delta_j - \delta_i) = 0 \forall i = N$$

$$P_{gi}^{\ \min} \le P_{gi} \le P_{gi}^{\ \max} \qquad \forall \text{ i} \in \text{NG}$$

$$Q_{gi}^{\ \min} \le Q_{gi} \le Q_{gi}^{\ \max} \qquad \forall \text{ i} \in \text{NG}$$

$$T_{gi}^{\ \min} \le T_{gi} \le T_{gi}^{\ \max} \qquad \forall \text{ i} \in \text{NT}$$

$$F_{ij}^{\ \min} \le F_{ij} \le F_{ij}^{\ \max} \qquad \forall \text{ i} \in \text{NB}$$

$$X_{ci}^{\ \min} \le X_i \le X_{ci}^{\ \max} \qquad \forall \text{ i} \in \text{NP}$$

$$\theta_i^{\min} \le \theta_i \le \theta_i^{\max} \qquad \forall \text{ i} \in \text{NS}$$

A. Enhanced Genetic Algorithm

In the EGA, shown in Fig. 1, after the application of the basic genetic operators (parent selection, crossover, and mutation) the advanced and problem-specific operators are applied to produce the new generation. All chromosomes in the initial population are created at random (every bit in the chromosome has equal probability of being switched ON or OFF).

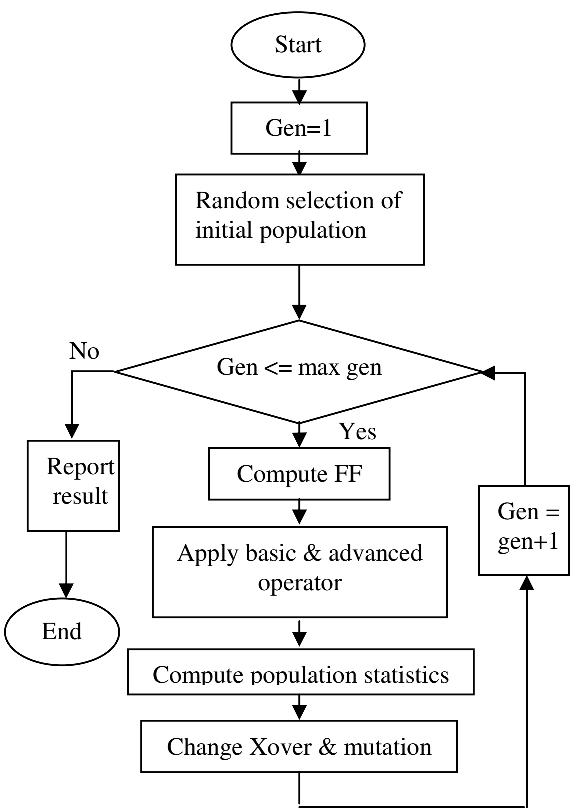

Fig. 1 Enhanced genetic algorithm

Due to the decoding process selection, the corresponding control variables of the initial population satisfy their upper–lower bound or discrete value constraints. Population statistics are then used to adaptively change the crossover and mutation probabilities [6]. If premature convergence is detected the mutation probability is increased and the crossover probability is decreased. The contrary happens in the case of high population diversity.

B. Advanced and Problem-Specific Genetic Operators

One of the most important issues in the genetic evolution is the effective rearrangement of the genotype information. In the SGA, crossover is the main genetic operator responsible or the exploitation of information while mutation brings new nonexistent bit structures. It is widely recognized that the SGA scheme is capable of locating the neighborhood of the optimal or near-optimal solutions, but in general, requires a large number of generations to converge. This problem becomes more intense for large-scale optimization problems with difficult search spaces and lengthy chromosomes, where the possibility for the SGA to get trapped in local optimal increases and the convergence speed of the SGA decreases.

At this point, a suitable combination of the basic, advanced, and problem-specific genetic operators must be introduced in order to enhance the performance of the GA. Advanced and problem-specific genetic operators usually combine local search techniques and expertise derived from the nature of the problem. A set of advanced and problem-specific genetic operators has been added to the SGA in order to increase its convergence speed and improve the quality of solutions. Here the interest is focused on constructing simple yet powerful enhanced genetic operators that effectively explore the problem search space.

Hill Climbing*:* In order to increase the GA search speed at smooth areas of the search space a hill-climbing operator is introduced, which perturbs a randomly selected control variable. The modified chromosome is accepted if there is an increase in FF value; otherwise, the old chromosome remains unchanged. This operator is applied only to the best chromosome (elite) of every generation [5].

Gene Swap Operator (GSO): T*his operator randomly selects two genes in a chromosome and swaps their values as shown in Fig. 2. This operator swaps the active power output of two units, the voltage magnitude of two-generation buses, etc. Swapping among different types of control variables is not allowed.

Gene Cross-Swap Operator (GCSO): The GCSO is a variant of the GSO. It randomly selects two different chromosomes from the population and two genes, one from every selected chromosome, and swaps their values as shown in Fig. 3. While crossover exchanges information between high-fit chromosomes, the GCSO searches for alternative alleles, exploiting information stored even in low-fit strings.

Gene Copy Operator (GCO): This operator randomly selects one gene in a chromosome and with equal probability copies its value to the predecessor or the successor gene of the same control type as shown in Fig. 4. This operator has been introduced in order to force consecutive controls (e.g., identical units on the same bus) to operate at the same output level.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

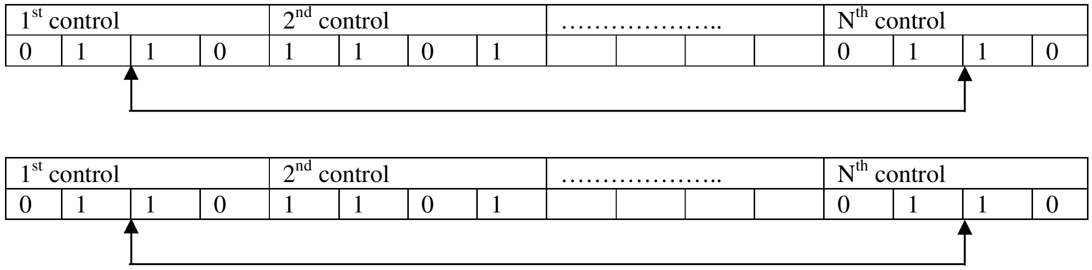

Fig. 2 Gene swap operator

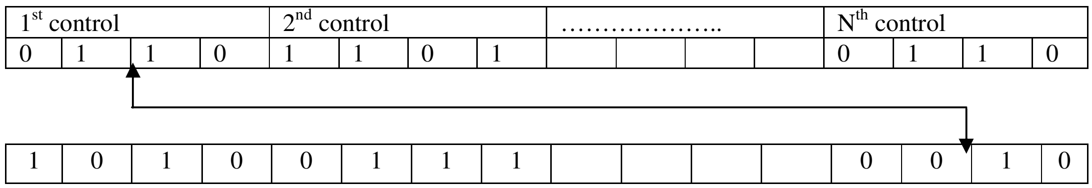

Fig. 3 Gene cross swap operator

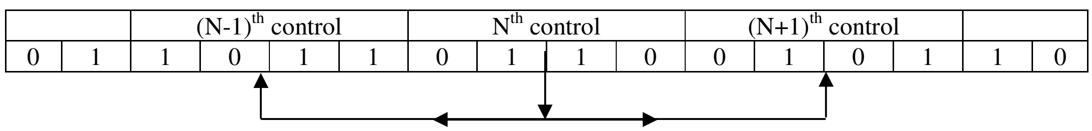

Fig. 4 Gene copy operator

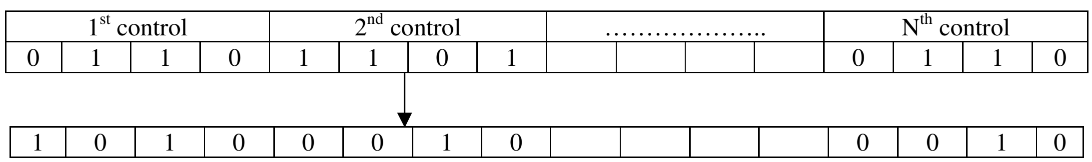

Fig. 5 Gene inverse operator

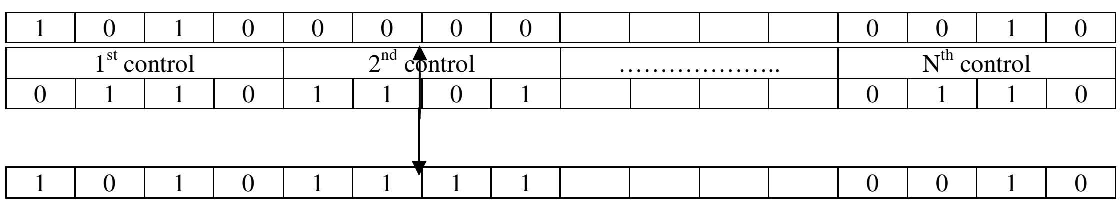

Fig. 6 Gene max-min operator

Gene Inverse Operator (GIO): This operator acts like a sophisticated mutation operator. It randomly selects one gene in a chromosome and inverses its bit-values from one to zero and vice versa as shown in Fig. 5. The GIO searches for bit-structures of improved performance, exploits new areas of the search space far away from the current solution, and retains the diversity of the population.

Gene Max-Min Operator (GMMO): The GMMO tries to identify binding control variable upper/lower limit constraints. It selects a random gene in a chromosome and, with the same probability (0.5), fills its area with 1s or 0s as shown in Fig. 6.

III. Case Studies

In this work, the standard IEEE 30-bus test system has been used to test the effectiveness of the proposed method. It has a total of 8 control variables as follows: six unit active power outputs, TCSC constraints and TCPS constraints. The gene length for unit power output is 12 bits and for other parameter is 6 bits. They are both treated as continuous controls.

The reactance of the TCSC is between 0 and 0.20 (p.u), while the voltage shift angle limit of TCPS are between 0 and 0.07 (radian). The GA population size is taken equal to 20; the maximum number of generations is 75. In this problem the probabilities of crossover and mutation are varied depending on the fitness values of the solutions in the evolution process to prevent premature convergence and refine the convergence performance of genetic algorithm.

Three cases have been studied; Case 1 is the conventional OPF without FACTS devices and (N-I) security constraints using SGA. Case 2 is the conventional OPF with FACTS devices using SGA. Case 3 is the conventional OPF with FACTS devices using EGA. The main optimization results are listed in Table I.

Without FACTS devices the cost of OPF is 805.0132 and cost of OPF with FACTS using SGA and EGA is 807.4227 and 805.3789 respectively. The results show that the generation cost increase with FACTS device since the

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

parameter constraint of TCSC and TCPS are included. However, FACTS can change the power distribution effectively and reduce the system losses.

TABLE I
IEEE 30-BUS SYSTEM CASE STUDY RESULTS

P_{Gi} (MW)	Case 1	Case 2	Case 3
P_{G1} (MW)	183.1800	192.5400	189.8200
P_{G2} (MW)	43.9700	48.6200	47.4100
P_{G5} (MW)	18.4400	19.5200	20.6200
P_{G8} (MW)	25.6200	11.7500	12.5500
P_{G11} (MW)	10.4300	10.2000	11.7400
P_{G13} (MW)	12.0000	12.1100	12.2100
$\sum P_{Gi}$(MW)	293.6400	294.7400	294.3500
$\sum$cost($/hr)	805.0132	807.4227	805.3789

Two set of test runs are performed, the first (SGA) one is with only the basic GA operators and the second (EGA) one is with all operators, including advanced and problem-specific operators. The FF evolution of the best of these runs is shown in Fig. 7. The operating costs of the SGA and EGA solutions are 807.4227 $/h and 805.3789 $/h, respectively. The operating cost of all EGA-OPF solutions is slightly less than the SGA. Fig. 7 demonstrates the improvement achieved with the inclusion of the advanced and problem-specific operators. It is found that the real power flows in lines are within the rating limit.

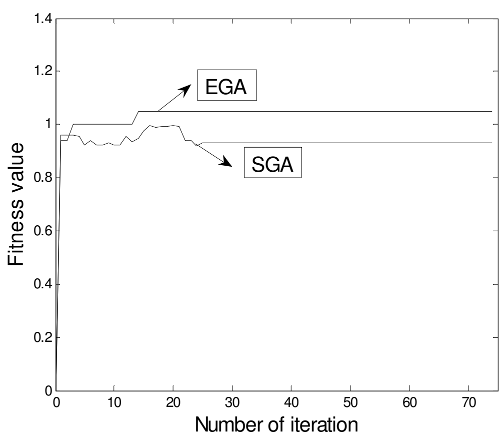

Fig. 7 FF comparison for IEEE 30-bus system

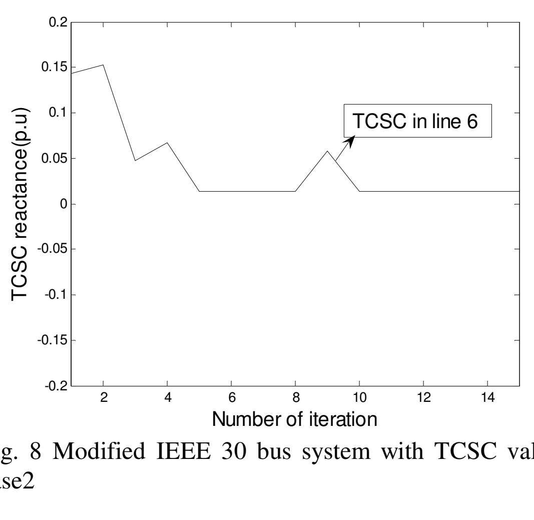

Fig. 8 Modified IEEE 30 bus system with TCSC value in case2

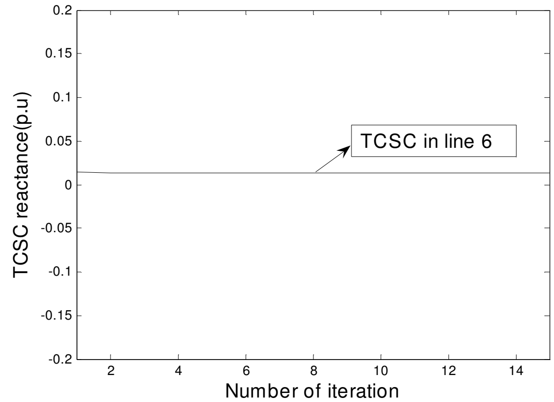

Fig. 9 Modified IEEE 30 bus system with TCSC value in case3

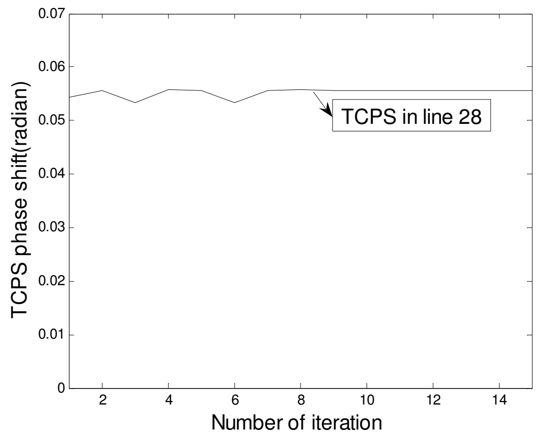

Fig. 10 Modified IEEE 30 bus system with TCPS value in case 2

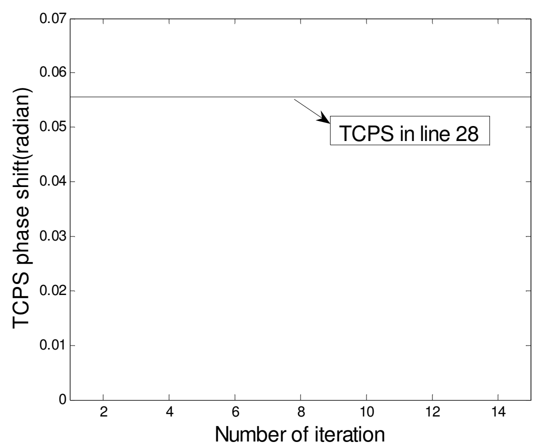

Fig. 11 Modified IEEE 30 bus system with TCPS value in case 3

Along with the conventional OPF, the power through line numbers 6 and 28 has been taken as additional constraints. The specified values of power are to be achieved by placing TCSC in line 6 and TCPS in line 28. Now the next step is to find the value of TCSC reactance and TCPS phase shift that are needed to maintain the specified power flow. These values

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

are found by SGA and EGA method, with their convergence is shown in Fig. 8 through Fig. 11. The corresponding power flows found iteratively for SGA and EGA have been shown on Fig. 12 and Fig. 13 respectively.

With the SGA being optimization method used, the power flow through line 6 converge to the required value of 0.33 p.u approximately after 11 iterations, where as the power flow through line 28 converge to the required value of 0.18 p.u approximately after 8 iterations. With the EGA being optimization method used, the power in the line 6 and 28 are converged very fast than SGA and the results show that the proposed approach is effective. This improvement is achieved with the inclusion of the advanced and problem specific operators.

If the power flow control constraints are not some specified values but some ranges, it is possible to use appropriate convergent threshold to achieve this. For example, suppose the power flow control value of one branch is between 0.5 and 0.6 p.u, it can be set the specified branch flow at 0.55 and set the convergent threshold at 0.05 p.u. Thus, when the problem converges, this branch power flow is between 0.5 and 0.6 p.u using this method, and fulfills different power flow control needs.

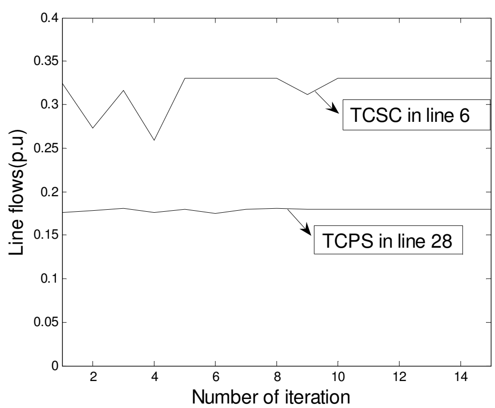

Fig. 12 Modified IEEE 30 bus system with specified line flows in case 2

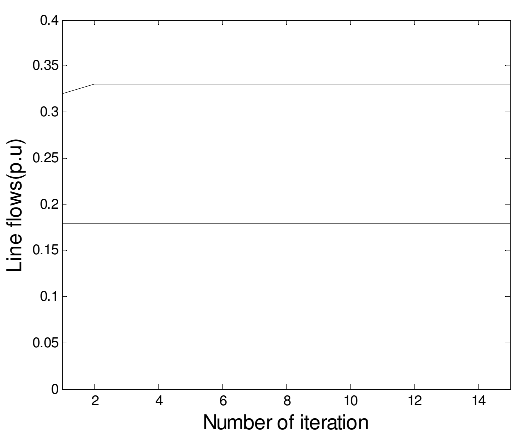

Fig. 13 Modified IEEE 30 bus system with specified line flows in case 3

IV. Conclusions

An enhanced genetic algorithm method was presented to solve the optimal power flow problem of power system with FACTS devices. The proposed method introduces the injected power model of FACTS devices into a conventional AC optimal power flow problem to exploit the new characteristic of FACTS devices. Case studies on modified IEEE test system show the potential for application of EGA to determine the control parameter of the power flow controls with FACTS. It can be shown that the FACTS device cannot reduce the generation cost (i.e. it is not a cost saving device) compared with normal system OPF. However, it can increase the controllability and feasibility of the system and provide wider operating margin and higher voltage stability with higher reserve capacity. In this method, EGA effectively finds the optimal setting of the control parameters using the conventional OPF method. It also shows that the EGA was suitable to deal with non-smooth, non-continuous, non-differentiable and non-convex problem, such as the optimal power flow problem with FACTS devices.

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