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Optimal Allocation of FACTS Devices in Power Systems via Evolution Strategies

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Abstract: In this paper, Evolution Strategies (ES) is used to find optimal placement of FACTS devices in power systems. The goal of optimization is to maximize the system loadability. Optimization is based on finding locations and settings of FACTS devices. Simulations are implemented on IEEE 30-bus test system. From different types of FACTS devices, SVC, TCSC and UPFC are used in this research. The results show that using FACTS devices, the loadability of power system increases significantly. It also shows that there exists a maximum number of devices beyond which, the loadability of power system cannot be increased. The implementation results of the method are promising and encouraging, so it is a good method for implementation on the FACTS optimization problem.

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1. Introduction

The continual increase in demand for electricity has caused so problems for utility companies, such as inadequate transmission capacity, stability problems and so on. The Flexible AC Transmission system (FACTS) devices has been created to handle such these problems. However, because of high cost of these devices, the best possible benefits from their use should be extracted, so it is necessary to consider three main issues: the type of FACTS devices, their location and their settings.

The simultaneous solution of the three issues mentioned above represents a very complex and difficult optimization problem. For solving this problem, there are four groups of methods, classical, technical, heuristic and mixed methods. Classical methods such as linear programming (LP), nonlinear programming (NLP) have been used in literature for solving FACTS optimization problem (Lima FG et al, 2003), (Yang et al, 2007). But despite all the advancement in these methods, they do not expose desirable computational behavior, especially because when the size of problem increases, search space in these methods increases exponentially, so, they suffer from convergence problems and have high computational time. Another group of methods used for FACTS optimization problem are those based on pure technical criteria, particularly sensitivity analysis for steady state (Sharma et al, 2003) and modal analysis (Mansour et al, 1994) for transient and dynamic optimization have been used. The main advantages of these methods are their simplicity and their main disadvantage is that they cannot reach a global optimum. Third group of methods are heuristics. Heuristics are techniques such as genetic algorithm, evolutionary programming, differential evolution, evolution strategies, particle swarm optimization which seek optimal or near optimal solutions at a reasonable computational cost, also are usually population-based, stochastic-based and inspired of biological or human intelligence phenomena. Heuristics have been used much to solve FACTS optimization problem in literature, such as in (Baghaee, et al, 2008), (Hao, et al, 2004), (Baghaee, et al, 2008), (Rashed et al, 2007). They have so advantages over other methods, such as

- They are population-based, so are not sensitive to initial condition, and have better convergence behavior.
- They do not require much knowledge about objective function.
- They have not requirements such as continuity and differentiability of objective function, so they are more flexible than other methods.

Forth group of methods that address FACTS optimization problem are those which are a combination of technical methods and technical or heuristic methods (Orfanogianni T, Bacher R, 2003), (Abdullah NRH et al, 2010). In these methods, usually, first, the locations of FACTS devices are found using technical criteria, and next, their settings are determined using classical or heuristic methods. By such strategy, computational burden reduces, but resultant solutions have less quality in comparison to other methods.

In this research, among the mentioned methods, one of heuristics called evolution strategies has been used to solve FACTS optimization problem. From different types of FACTS devices, TCSC, SVC and UPFC have been selected to be optimally located on IEEE 30-bus test system. Simulations are done for different numbers and combinations of these devices in order to maximize the transmitted power in a secure state.

2. FACTS Devices Modeling

A FACTS device is a power electronics based system that controls one or more of the main AC transmission system parameters. These parameters are terminal bus voltage, reactance, phase angle between transmission line ends, real power and reactive power of transmission line (Oudalov, et al, 2001). Via controlling these parameters, FACTS devices enhance the loading capability of lines, enhance system security through raising the transient stability limit, provide greater flexibility in siting new generation, reduce reactive power flows and loop flows, and raise utilization of lowest cost generation (Zhang et al, 1997).

There are many types of FACTS devices, which can be classified by the way which they are connected to transmission lines. Series controllers, shunt controllers and combined series-shunt controllers. Generally series controllers are used for real power control, shunt controllers are used for voltage control, and combined series-shunt controllers are used for both real power and voltage control.

In this research, thyristor Controlled series capacitor (TCSC) as the representative of series FACTS devices, static var Compensator (SVC) as the representative of shunt FACTS devices, and Unified Power flow controller (UPFC) as the representative of combined series-shunt FACTS devices are used.

TCSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to modify the reactance of transmission line and so real power passing through line. It can be capacitive or inductive in order to decrease or increase the reactance of the line, respectively (Hingorani, NG, 2002). (see Fig.1.a)

SVC is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current in order to control specific parameters of the power system, typically bus voltage (Hingorani, NG, 2002). (see Fig.1.b).

UPFC is a combination of static synchronous shunt compensator and static series compensator which are coupled via a common dc link. UPFC can concurrently control active power flow and voltage of transmission line. It is the most versatile member of FACTS family (Hingorani, NG, 2002). (see Fig.1.c).

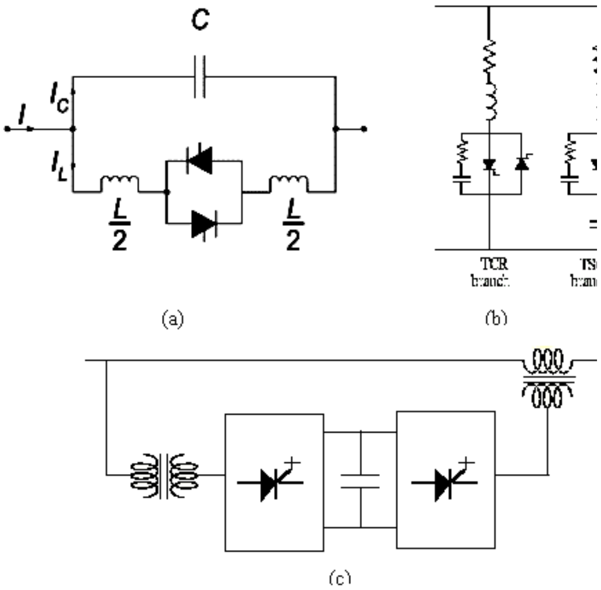

Fig. 1. FACTS devices: (a) TCSC, (b) SVC, and (c) UPFC

3. Evolution Strategies

Evolution strategies (ES) optimization technique was introduced in the early 1960s and developed more in the 1970s by Rechenberg and Schwefel at the University of Berlin, in Germany. It was originally created to solve technical optimization problems, and its first application was in the area of hydrodynamics. Nowadays, ES is recognized as a very strong optimization method capable of solving large scale, multimodal, highly constrained, nonlinear problems (Mendes JC et al, 2002).

The main search procedure in evolution strategies is the mutation operator, that generates random samples around search points (solution candidates) selected from a population of different search points.

The original strategy, denoted (1+1), generates one offspring from a single parent by applying mutation. If the child performs better than its ancestor, it will be as the parent for the next generation (Santiago M, Maldonado R, 2006).

Other variants of ES are population-based strategies. The (μ+1) strategy was the first idea introduced after the simple (1+1) ES. In this one, recombination can be applied to individuals. During the recombination process, two parents are selected randomly and recombined to create an intermediate offspring. The offspring is then mutated and added to the population. From these (μ+1) individuals, the μ best of all are chosen as parents for the next generation. Although, in comparison to the (1+1) strategy, this variant of ES is a better option, but it was never widely used because it did not provide a reasonable way to control the mutation rate (Santiago M, Maldonado R, 2006).

In the developed ES strategies, ((μ+λ) and (μ, λ) strategies), the mutation rate is not directly controlled. It is adapted during the process of evolution. This mechanism to adapt strategy parameters is referred to as self-adaptation, which is one of the most powerful characteristics of ES. μ parents are used to create λ offsprings, where λ > μ (Santiago M, Maldonado R, 2006).

Individuals representing possible solutions to the optimization problem consists of two elements: $\alpha = (x_i, \sigma_i)$(http://www.faqs.org/faqs/aiaq/genetic/part2/section4.html). The first element is the object variable that corresponds to a fixed point in the solution space, and the second variable is the strategy variable representing the probability of mutating the object variable. Such as the (μ+1) strategy, these individuals go through the same operators of recombination, mutation and selection. It is important to mention that the strategy variable undergoes evolution in the same way as the object variable does Santiago M, Maldonado R, 2006).

The recombination operator introduces an exchange of information or knowledge between individuals during evolution process. The most common types of recombination are discrete, intermediate, global discrete and global intermediate. In discrete recombination, an exchange of variables between parents is done; while in intermediate recombination, an arithmetic average is used. In ES, recombination is usually implemented in a different way for each variable. Discrete recombination on object variables and intermediate recombination on strategy parameters, normally will be a useful choice (Back T, Hammel U, 1994).

With mutation, innovation element is introduced with the generation of variations in the individuals. It is important to first mutate the strategy variable, because it is used to mutate the object variable. It can be seen that mutation is a two-stage operation:

$$\delta_i'^{j} = \delta_i^{j} \exp(\tau' N(0,1) + \tau N(0,1 \qquad (1)$$

$$x_i'^j = x_i^j + \delta_i'^j N(0,1 \tag{2}$$

Where i= 1,…,λ and j=1,…,k. *N*(0,1) represents a normal distributed random number with zero mean and variance 1. The factors τ and τ' are defined as "learning rates" and are proposed as

$$\tau = \left(\sqrt{2\sqrt{k}}\right)^{-1} \tag{3}$$

$$\tau' = \left(\sqrt{2k}\right)^{-1} \tag{4}$$

Where k is the dimension of problem in hand.

When the mutation and recombination operators are applied, the μ best parents should be selected according to their objective function. In most cases, the (μ, λ) strategy is faster and more realistic, since no individual may survive forever. As this strategy accepts deterioration from one generation to the next, it causes the algorithm to evade from local solutions.

4. Problem Formulation

4.1 FACTS Devices Models

The FACTS device models considered in this research are shown in Fig. 2.

The TCSC is modeled as a variable reactance series with transmission line (see Fig. 2.a). The range of values that TCSC can take, is a function of the line reactance, with a maximum value of 0.8 X_L (Lai LL, Ma JT, 1996). Therefore, the equivalent reactance of line considering the existence of TCSC is given by:

$$X_{Leq} = (1 - k)X_L \tag{5}$$

Where $0 \leq k \leq 0.8$

SVC is modeled as a reactive power source that can exchange (inject or absorb) reactive power with the bus connected. (see Fig. 2.b). The acceptable values for SVC are between -100 MVA and 100 MVA.

For UPFC, two different models are used in papers, one is coupled model which for using it, modification of jacobian matrix should be done and is so difficult, and the second model is decoupled model, which modification of jacobian matrix is not required in it (Niaki N, Iravani MR, 1996), (Kim TH, and Seo GC, 1998) and in comparison to the coupled model is easier, So in this paper, the decoupled model is used (see Fig. 2.c).

It is important to say that UPFC can control active and reactive power of transmission line only in its controllable area.

Assuming that UPFC is lossless, this equation should be considered.

$$P_{u1} + P_{u2} = 0 \tag{6}$$

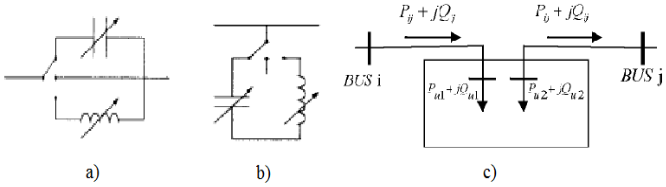

Fig.2. Models of FACTS devices: a) TCSC, b) SVC, c) UPFC

4.2 Proposed ES-based Algorithm

In ES algorithm, an individual is represented as a group of FACTS devices. Each FACTS device is characterized by its location, type and setting. These three parameters constitute the decision variables of algorithm. For each decision variable, a different mutation rate is applied.

The initial population is generated by random. The fitness value is obtained from the evaluation of the current FACTS configuration via the fitness function.

The fitness function is calculated according to the following (Santiago M, Maldonado R, 2006).

$$F = C_1(S - S_{max})^2 + C_2(V - V_{max})^2 \tag{7}$$

Where C_1 and C_2 are weighting factors, S_{max} and V_{max} are limit of apparent power and voltage of transmission line respectively.

Fitness function penalizes configurations which result in over or under-voltage in buses or overload in transmission lines. (An over or under-voltage condition at a bus means that the voltage of that bus is less than 0.95 pu or more than 1.05 pu). The fitness value is then calculated for each individual of the initial population. If no parent has a fitness value of zero, a new generation is created by recombination and mutation. In the recombination process, two parents are randomly selected and discrete or intermediate recombination is applied depending on the kind of variable been recombined.

After recombination, mutation is applied to each individual. Each decision variable has its own mutation rate. The parents for the next generation are selected using the (μ, λ) strategy, where the μ best individuals are selected from the offsprings only. Individuals with lower fitness value which maximize the loadability will be selected as parents for the next generation. The evolution process will continue until an individual having zero fitness value is found or a maximum number of iterations is reached. When an individual with zero fitness value is found, the load factor is increased and the optimization process starts all over again. Starting from an initial load, the load factor will be increased as long as FACTS configuration allows the system to operate in a secure state. In this paper, the value of loads are increased in the same proportion.

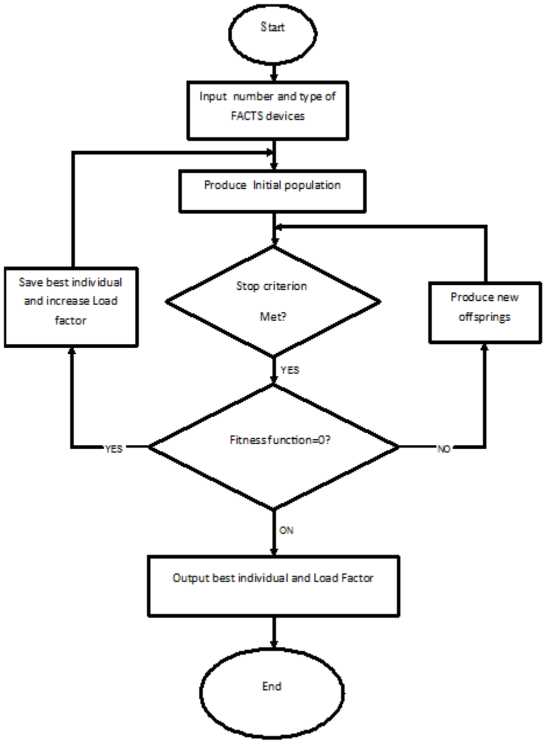

Fig.3. Flowchart of method

5. Simulations and Results

The main goal of the above-mentioned methodology is to locate a certain number of FACTS devices in a power system so that the loadability of the system is maximized. The algorithm was implemented using the Matlab programming language. The power flow simulations were carried out using MATPOWER simulator (Zimmerman RD, 1997).

Simulations were implemented on IEEE 30-bus test system. The single-line diagram of the network is depicted in Fig. 5. For each case study, simulations were executed for different number of FACTS devices to be located on the test system

Due to probabilistic property of evolutionary algorithms, the results reported here corresponds to the average obtained from 80 trial runs.

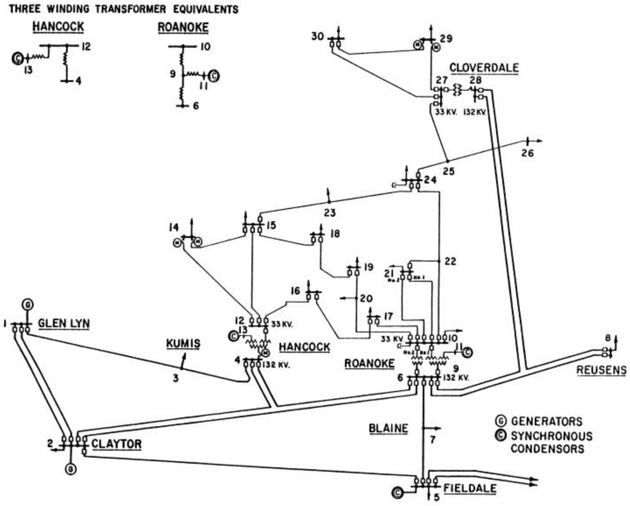

Fig. 4. IEEE 30-bus Test system

A total of three different case studies were considered, In the first case study, only one type of FACTS device was considered, in case II, two different type of FACTS devices were used and in the last case, all types of FACTS devices were considered simultaneously.

Case 1: Simulation with only one Type of FACTS Devices

The results show that UPFC has the best performance and after it, SVC and TCSC have lower ranks (see Fig.5). The load factor values shown in the figure indicate how much the loadability of the system can be improved in comparison to the base case (without FACTS devices), while keeping the power system in a secure state.

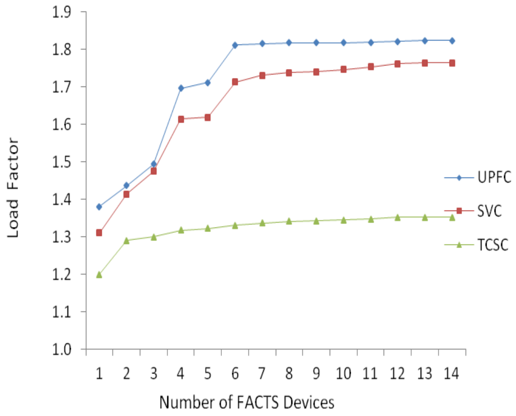

Fig.5. Maximum load factor with one type FACTS device

Case 2: Simulation with two Different Types of FACTS Devices

The results show that the pair of SVC- UPFC has the best performance and after it, TCSC- UPFC and TCSC- SVC, respectively (see Fig. 6)

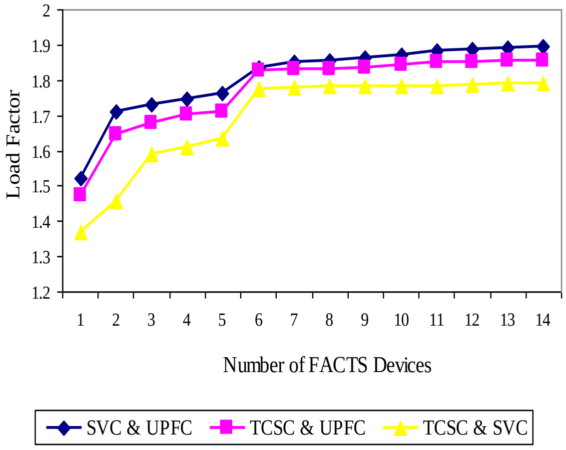

Fig. 6. Maximum load factor with two types FACTS devices

Case 3: Simulation with all Three Types of FACTS Devices

Results show that, this case has the best performance (see Fig. 7). This result is probably due to the synergistic effect created by having different types of devices adjusting their corresponding parameters simultaneously.

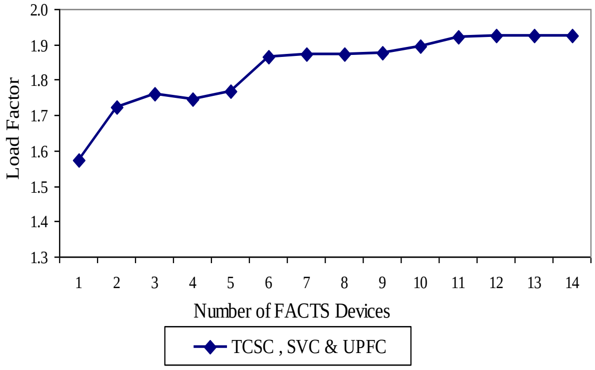

Fig.7. Maximum load factor with three different types FACTS

Overally, the results demonstrate that for all case studies, the system loadability can be increased by properly locating FACTS devices. The results rank the performance of different configurations of FACTS devices from the best to the worst. The simultaneous presence of TCSC, SVC and UPFC is the best, and after it, SVC-UPFC, TCSC-UPFC, UPFC only, TCSC-SVC, SVC only and TCSC only have lower ranks respectively (see Fig. 8). A very important result is that the simultaneous use of all types of FACTS devices provides the best overall loadability in transmission system. In addition, as it was found in previous researches (Gerbex S, et al, 2001) there is always a maximum number of devices beyond which the loadability of the network cannot be increased. Table I shows maximum load factor attainable in each of above cases.

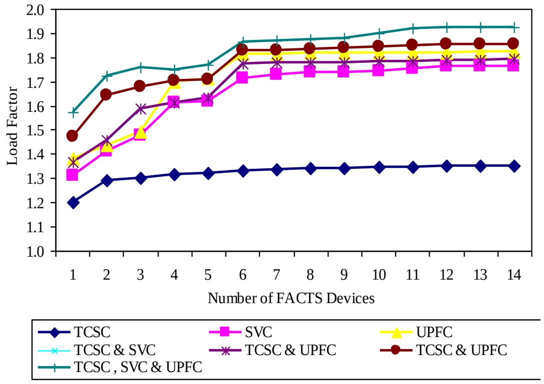

Fig. 8. Maximum load factor for all case studies

Table 1. Maximum Load Factor Attainable in Each Case

FACTs Devices	Maximum Load Factor
TCSC	1.352
SVC	1.764
UPFC	1.823
TCSC&SVC	1.792
TCS&UPFC	1.854
SVC&UPFC	1.895
TCSC,SVC&UPFC	1.926

6. Conclusions

In this research, Multi-type FACTS optimization problem has been solved using one of heuristic algorithms called evolution strategies. In all case studies considered, by locating FACTS device properly, the loadability of system increases, also there is always a maximum number of FACTS devices beyond which the system loadability cannot be increased any further. When only one type of FACTS devices is used, the UPFC has the best performance and after it, SVC and TCSC respectively. Using two different types of FACTS devices , the pair of SVC-UPFC has the best performance and after it, TCSC-UPFC and TCSC- SVC, respectively. Simultaneous use of these three FACTS devices is the best option. The results obtained, also show Evolution strategies are effective in solving power system problems.

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