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UPFC Device: Optimal Location and Parameter Setting to Reduce Losses in Electric-Power Systems Using a Genetic-algorithm Method

Mohamed Mezaache[†], Khaled Chikhi, and Cherif Fetha
Department of Electrical Engineering, Batna University, Batna 05000, Algeria

Ensuring the secure operation of power systems has become an important and critical matter during the present time, along with the development of large, complex and load-increasing systems. Security constraints such as the thermal limits of transmission lines and bus-voltage limits must be satisfied under all of a system's operational conditions. An alternative solution to improve the security of a power system is the employment of Flexible Alternating-Current Transmission Systems (FACTS). FACTS devices can reduce the flows of heavily loaded lines, maintain the bus voltages at desired levels, and improve the stability of a power network. The Unified Power Flow Controller (UPFC) is a versatile FACTS device that can independently or simultaneously control the active power, the reactive power and the bus voltage; however, to achieve such functionality, it is very important to determine the optimal location of the UPFC device, with the appropriate parameter setting, in the power system. In this paper, a genetic algorithm (GA) method is applied to determine the optimal location of the UPFC device in a network for the enhancement of the power-system loadability and the minimization of the active power loss in the transmission line. To verify our approach, simulations were performed on the IEEE 14 Bus, 30 Bus, and 57 Bus test systems. The proposed work was implemented in the MATLAB platform.

1. INTRODUCTION

Over recent decades, an emerging transmission technology called FACTS (Flexible Alternating-Current Transmission Systems) has been extensively employed to increase the power-transfer capability of long-distance transmission-line networks as well as for the improvement of the stability of transmission systems [1].

FACTS is an electronics-based power technology that the utility industry uses to deal with power-delivery challenges. A major thrust of FACTS technology is the development of electric-based power systems that provide a dynamic-control capability regarding the power-transfer parameters transmission voltage, line impedance and phase angle [2].

The Unified Power Flow Controller (UPFC) is used for the simultaneous and independent control of the bus voltage and the real and reactive transmission-line power flows. An additional task of the UPFC is the transmission-capacity increase that occurs as a result of power oscillation damping and loss reduction. The effectiveness of the UPFC depends on its optimal location and a proper signal selection in the power-system network.

Genetic algorithms (GAs), which are probabilistic global optimization techniques inspired by a natural-selection process and population genetics theory, provide a general architecture for the solving of complex optimization problems; actually, GAs have been applied widely in almost every field. GAs only need a fitness-function value gradient information is not necessary to guide the GA search direction [3].

This paper proposes the application of a GA method to solve

[†] Author to whom all correspondence should be addressed:
E-mail: mohamedmezaache@gmail.com

the optimal UPFC-location problems for restructured power systems in consideration of the system loadability and loss reduction in the lines; therefore, the presented problem becomes a composite objective optimization problem, whereby the location and rated value of the UPFC must be determined simultaneously.

2. OPERATING PRINCIPLE OF UPFC

2.1 Basic structure of UPFC

A UPFC consists of the following two voltage-sourced converters: one is connected in a shunt and the other is connected in a series. The series converter provides the main function of a UPFC by injecting an AC voltage with a controllable magnitude and phase angle in a series with the transmission line via a series-connected coupling transformer; alternatively, the basic function of the shunt converter is the supply or absorption of the real power that is demanded by the series converter at the common DC link. The shunt converter can also generate or absorb controllable reactive power and provide an independent shunt-reactive compensation for the line. Overall, the UPFC can supply real power in addition to reactive power, meaning that there is no restriction on the relative phase of the injected voltage with respect to the line current [4].

The UPFC structure is described in Fig. 1, whereby the Generator G is connected to the buses m and n, and the converters are connected via a transformer. The structure includes the impedance of the converter such as series impedance Z_{se}, Generator-side impedance Z_G, and load impedance Z_L. The converters are connected by the DC link capacitor C_{dc} with a voltage capacity V_{dc} [5].
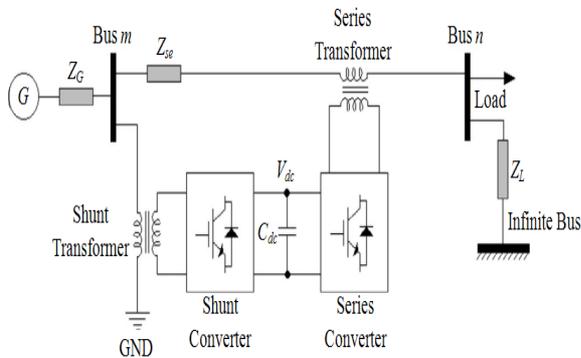

Fig. 1. Structure of UPFC connected in the network.

2.2 Modeling of UPFC

It is therefore possible to simultaneously control all of the parameters that affect the power flow in the transmission line, i.e. voltage, impedance, and phase angle; that is, both the real and the reactive line-power flows and the voltage magnitude can be independently controlled at the UPFC terminals.

The equivalent UPFC circuit is presented in Fig. 2. The series part of a UPFC can be modeled by a controllable voltage source V_{se}, and the shunt part can be modeled by a controllable current source Ish. The voltage magnitude of the output regulates the voltage and the angle Φ_{se} is used for phase regulation. The three controllable parameters of the UPFC are V_{se}, Φ_{se}, and Ish; where V_{se} denotes the magnitude of the voltage with the ranges [0, $V_{se\ max}$] that is injected in the series with the transmission line, Φ_{se} is the phase angle of this voltage with the ranges [0, 2 π], and I_{sh} is the shunt-reactive current
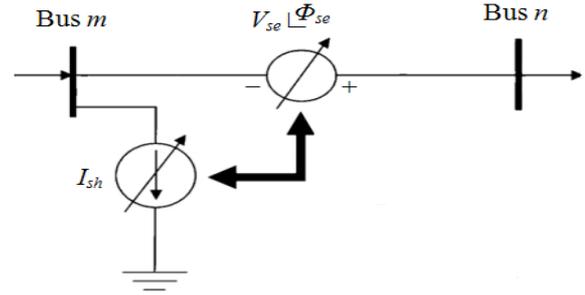

Fig. 2. Equivalent UPFC circuit.

source of the UPFC with the ranges [-I_{shmax}, I_{shmax}] [6].

3. OPTIMAL LOCATION OF UPFC DEVICES

The benefits of the optimal location of UPFC devices in terms of dynamic issues are expressed in this section. Normally, the decision to install a UPFC device often occurs at the planning stage when the system planner needs to accommodate load growth and power-plant integration; therefore, the natural question is, "Do we need to build a line or can we do it with a UPFC device?" We therefore initially focused on the UPFC as a loadability tool.

Regarding the optimal location for a UPFC device, the device must be placed on the bus that is most affected when defects must be identified. With increased-load transmission lines and distribution, voltage instability becomes a serious problem for the planners and managers of a power network. The main challenge of this problem is the refinement of the places where voltage instability could be initiated and gaining an understanding of the problem origin. An effective method (GA) for the refinement of a workspace involves the identification of the low buses (branches) in a system that are most likely to cope with a voltage collapse.

4. GENETIC ALGORITHM FOR OPTIMAL LOCATION OF UPFC DEVICES

GAs are global search techniques that are based on the mechanism of natural selection and genetics. Without any prior knowledge of the objective (fitness) function a GA can search several possible solutions simultaneously. GAs are best suited for complex problems; moreover, they produce high quality solutions.

A GA starts with the random generation of an initial population, followed by reproduction, crossover, and mutation operations that are carried out until the best population is found. A GA is a simple and practical algorithm that can be easily implemented in a power system [7].

The total number of UPFCs that can be inserted in a power system is limited, due to the cost of the devices and the influences on the operating characteristics of the power system. A GA is governed by the following three factors: mutation rate, crossover rate, and population size. A GA is a search process that can be applied to constrained problems; the constraints may be included in the fitness function as added penalty terms.

In this algorithm, the following optimization issues must be noted:

· Location of UPFC: No more than one UPFC can be installed in one branch of power-flow computations.
· Control parameters: The performance of the GA depends on the control parameters such as population size, crossover probability, and mutation probability; therefore, the selection

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of the proper values of the GA parameters has a major effect on the attainment of the optimum solution [3,8].

5. PROBLEM FORMULATION

The aim of optimization is to perform the most effective utilization of the transmission lines. In this respect, the location of the UPFC device is for the maximization of the system loadability while the thermal and voltage constraints are also observed; that is, in terms of branch loading and the voltage levels, the holding power system is in a security state to maximize the power that is transmitted by the power system to the customers.

The objective function is designed to penalize the UPFC configurations that lead to overloaded transmissions lines and over- or under-voltage at buses.

5.1 Penalty factor

To achieve our objective, the load factor λ of the network was increased in an iterative optimization process in accordance with the description of this subsection.

First, the generating powers of the generation buses were modified according to (1), as follows:

$$P_{Gi} = \lambda \times P_{G0i} \tag{1}$$

where P_{G0i} is the initial power generation at bus i and P_{Gi} is the modified power generation.

Then, for the load buses (PQ buses), the active and reactive demands (P_L and Q_L) were modified according to (2), as follows:

$$P_{Li} = \lambda \times P_{L0i} \quad \text{and} \quad Q_{Li} = \lambda \times Q_{L0i} \tag{2}$$

where P_{L0i} and Q_{L0i} are the initial active and reactive load-power values at bus i, and P_{Li} and Q_{Li} are the modified values.

5.2 Objective function

At each iteration, according to (1) and (2), the load factor was increased and the optimization constraints are the following: the verification of the bus-voltage violation and branch loading. When it is no longer possible to satisfy the constraints, the maximum loadability has been reached; in fact, this is a multi-stage greedy algorithm that follows the solving heuristic where the locally optimal choice is made at each stage in the hope of finding a global optimum.

The corresponding objective function that maximizes the power-system loadability could be formalized as follows:

$$F = \max\{\lambda\} \tag{3}$$

To simplify the enforcement of the process constraints while the UPFC devices are placed at random locations, let us define a

fitness function F_t so that the two terms that are targeted separately the first term is line overloading Ove_L, and the second term is related to bus-voltage violations Vio_B are included, as follows:

$$F_t = 2 - \left(\prod_{\text{Line}} Ove_L + \prod_{\text{Bus}} Vio_B \right) \tag{4}$$

$$Ove_L = \begin{cases} 1 & \text{if} \ \ S_l \leq S_{lmax} \\ \exp\left(\mu_l \left| 1 - \dfrac{S_l}{S_{lmax}} \right| \right) & \text{if} \ \ S_l > S_{lmax} \end{cases} \tag{5}$$

$$Vio_B = \begin{cases} 1 & \text{if} \ \ |\Delta V_i| \leq \Delta V_{imax} \\ \exp\left(\mu_i |\Delta V_{imax} - \Delta V_i| \right) & \text{if} \ \ |\Delta V_i| > \Delta V_{imax} \end{cases} \tag{6}$$

where the parameters μ_l and μ_i are constant coefficients; μ_l is the overload penalty factor in line l; the parameter μ_l is calculated for a 20% overload in the line, thereby reducing the Ove_L by half; μ_i is the penalty factor of the voltage violation at bus i; the parameter μ_i is determined so that a voltage difference of 10% at the bus reduces half of the objective function value; S_l is the current apparent power of the line l; S_{lmax} is the maximum value for the apparent power; ΔV_i is the difference between the nominal voltage at bus i and the current voltage; and ΔV_{imax} is the maximum voltage deviation.

If the constraints are fulfilled, then each of the fitness-function terms in Ove_L and Vio_B will be equal to 1 and the value of the fitness function will be equal to zero. Alternatively, if the constraints are not met, the above-defined fitness function penalizes the overloaded branches and over- or under-voltage buses [6].

5.3 Optimization strategy using GA

The number of individuals n_{Ind} is calculated for a population according to the following equation [9]:

$$n_{Ind} = 3 \times n_{UPFC} \times n_{Placement} \tag{7}$$

where n_{UPFC} is the number of simulated UPFC devices and $n_{Placement}$ is the total number of locations for the UPFC devices. The real value of the UPFC device $v_{RealUPFC}$ is calculated with the following relation:

$$v_{RealUPFC} = v_{min} + \left(v_{max} - v_{min} \right) \times v_{UPFC} \tag{8}$$

where v_{min} and v_{max} are the minimum and maximum setting values of the UPFC device, respectively, and v_{UPFC} is its normalized value. The initial load factor is equal to 1.

The parameters of the GA are set as follows: population size = 120, crossover probability = 0.9, and mutation probability = 0.1.

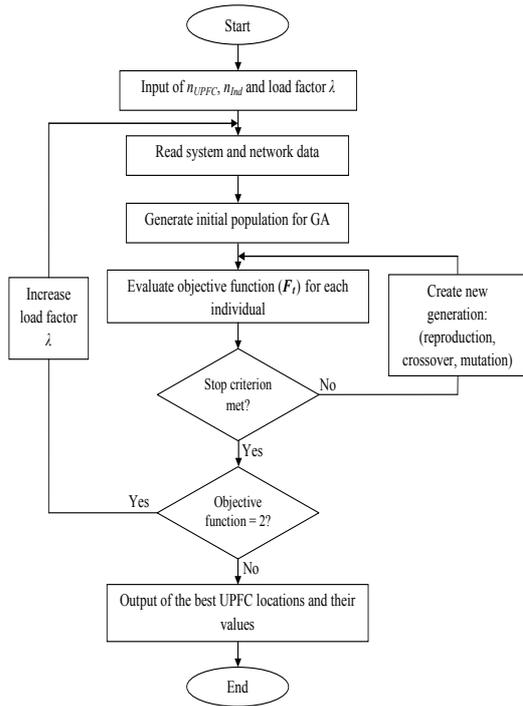The optimization strategy is summarized in Fig. 3.

Fig. 3. Flowchart of optimization according to GA.

6. SIMULATION AND DISCUSSION

To verify the performance of the GA method, a number of UPFC-device combinations were optimally positioned on different IEEE test networks, and the chosen test systems are IEEE 14 Bus, 30 Bus, and 57 Bus.

6.1 Table of results

The allocation results are presented in Table 1.

Table 1. UPFC-device-location results for the selected networks.

Test systems	UPFC numbers	UPFC locations	UPFC values
14 Bus	3	Branche 1	V_{se} = 0.189 p.u. Φ_{se} = 66.153 Degree I_{sh} = 0.084 p.u.
		Branche 9	V_{se} = 0.178 p.u. Φ_{se} = 240.683 Degree I_{sh} = − 0.053 p.u.
		Branche 14	V_{se} = 0.022 p.u. Φ_{se} = 57.468 Degree I_{sh} = 0.023 p.u.
30 Bus	5	Branche 38	V_{se} = 0.165 p.u. Φ_{se} = 187.117 Degree I_{sh} = − 0.079 p.u.
		Branche 41	V_{se} = 0.097 p.u. Φ_{se} = 171.743 Degree I_{sh} = 0.087 p.u.
		Branche 21	V_{se} = 0.122 p.u. Φ_{se} = 303.595 Degree I_{sh} = 0.036 p.u.
		Branche 10	V_{se} = 0.170 p.u. Φ_{se} = 154.694 Degree I_{sh} = − 0.051 p.u.
		Branche 29	V_{se} = 0.170 p.u. Φ_{se} = 15.744 Degree I_{sh} = − 0.008 p.u.
57 Bus	7	Branche 36	V_{se} = 0.118 p.u. Φ_{se} = 75.403 Degree I_{sh} = − 0.056 p.u.
		Branche 42	V_{se} = 0.116 p.u. Φ_{se} = 280.070 Degree I_{sh} = 0.019 p.u.
		Branche 45	V_{se} = 0.025 p.u. Φ_{se} = 147.329 Degree I_{sh} = 0.028 p.u.
		Branche 43	V_{se} = 0.083 p.u. Φ_{se} = 244.550 Degree I_{sh} = − 0.054 p.u.
		Branche 76	V_{se} = 0.035 p.u. Φ_{se} = 292.670 Degree I_{sh} = − 0.068 p.u.
		Branche 33	V_{se} = 0.120 p.u. Φ_{se} = 117.183 Degree I_{sh} = − 0.011 p.u.
		Branche 49	V_{se} = 0.130 p.u. Φ_{se} = 71.970 Degree I_{sh} = 0.019 p.u.

6.2 Figures

We found the figures that show the following variations:

· Influence of UPFC devices on bus voltages
· Total line losses of the power system for different system loadabilities

All of the simulation results from before and after the use of the UPFC devices for the selected test systems are shown in the figures below.

(1) For the 14 Bus test system:

- Total number of locations is 20
- Line losses without UPFC are 64 MW
- Line losses with UPFC are 61 MW

(2) For the 30 Bus test system:

- Total number of locations is 41
- Line losses without UPFC are 10 MW
- Line losses with UPFC are 8 MW

(3) For the 57 Bus test system:

- Total number of locations is 80
- Line losses without UPFC are 391 MW
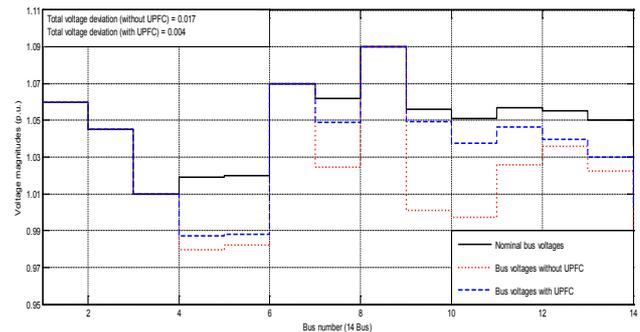- Line losses with UPFC are 149 MW

Fig. 4. Influence of UPFC devices on bus voltages (14 Bus).
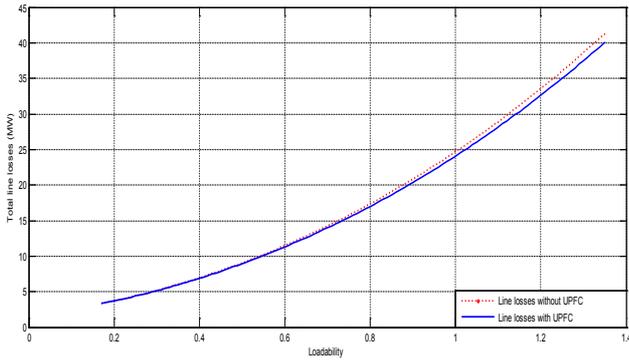
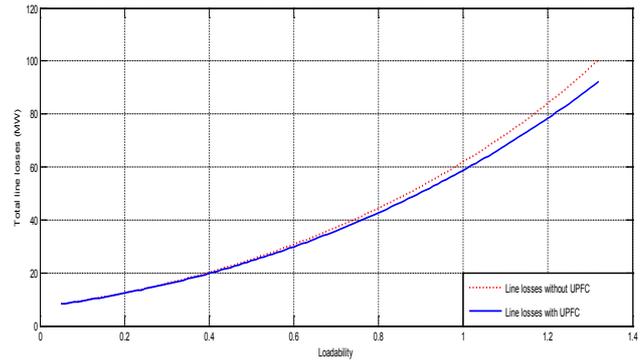Fig. 5. Total line losses of power system for different system loadability (14 Bus).

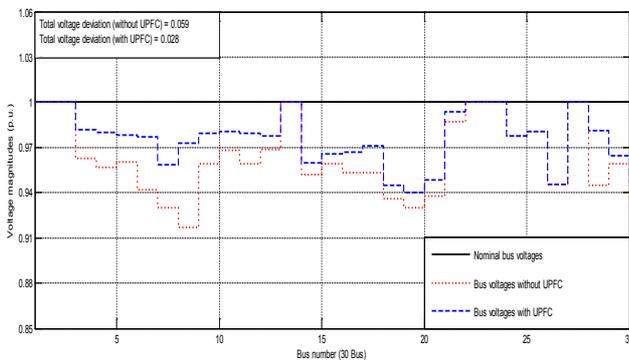Fig. 9. Total line losses of power system for different system loadability (57Bus).

6.3 Interpretation

According to Table 1, the locations of the UPFC devices in the IEEE 14 Bus network show that the most sensitive buses are 1 bus, 9 bus, and 14 bus (these voltage buses have exceeded their lower limits). To avoid this problem, we selected 1 bus, 9 bus, and 14 bus as reinforcement places by installing three UPFC devices at these points.

After the installation of five UPFCs devices at the optimal locations with the corresponding rated values in the 30 Bus test system, we observed an improvement of the system loadability, meaning that a significant reduction of the transmission losses occurred and all of the security constraints had been fulfilled.

For the case study of the 57 Bus test system, the voltage gaits that are presented in Fig. 8 show that, under the same load-capacity conditions, the network without the UPFC has a greater voltage drop in the buses. The results of Fig. 8 confirm the significant influence of the UPFC in the maintenance of the bus voltages within acceptable ranges.

The figures that illustrate the variation of the total line losses according to the load factor show that the appropriate control of the UPFC devices reduces systemic losses. From the obtained results, the efficiency of the UPFC appears clearly on the long networks.

Notably, the limited number of UPFC devices is less than half the number of independent network meshes, and the 57 Bus test network serves as an example (number of branches - number of buses + 1 = 80 - 57 + 1 = 24 UPFC devices) [10].

Fig. 6. Influence of UPFC devices on bus voltages (30 Bus).
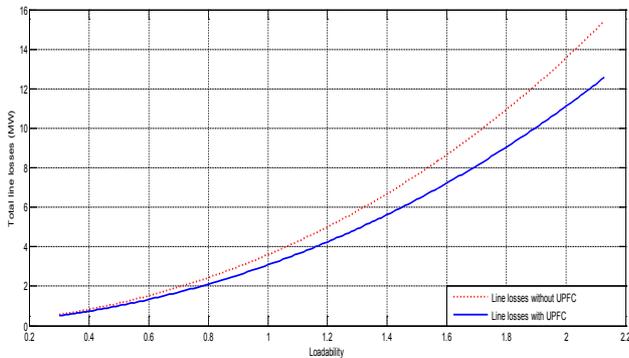
Fig. 7. Total line losses of power system for different system loadability (30 Bus).
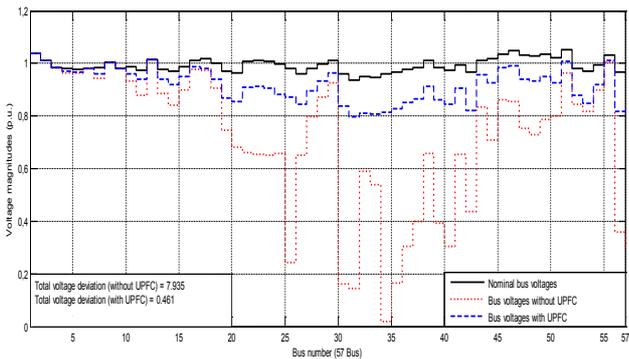
7. CONCLUSIONS

As previously mentioned, FACTS devices are presently considered a competitive solution for the needs of power systems. To date, many studies have proven that the use of FACTS devices can contribute greatly to solutions for the fresh problems that are derived from the liberalization of electricity markets, thereby minimizing the costly capital investments that are required for new lines. Although there are several types of FACTS devices that can be used for the control of the power flow and voltage profile in a power system, the attention of this study is focused mainly on UPFC devices. The proper placement of FACTS devices is very important for the rapid and successful operation of a power system because of the high cost and the circuit complexities.

In this paper, the effectiveness of the optimal location and sizing of UPFC devices to minimize losses is proposed. A UPFC can control the voltage magnitude, voltage phase angle, and impedance. The advantages of the GA method are an effective

Fig. 8. Influence of UPFC devices on bus voltages (57 Bus).

searching ability for the identification of optimum solutions and its accuracy. It has been verified that the use of UPFC devices decreases voltage deviations and minimizes real systemic power losses.

ACKNOWLEDGMENTS

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