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A new multi-objective fuzzy-GA formulation for optimal placement and sizing of shunt FACTS controller

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ABSTRACT

The location and sizing of FACTS controllers for voltage stability enhancement is an important consideration for practical power systems. In this paper, a strategy for placement and sizing of shunt FACTS controller using Fuzzy logic and Real Coded Genetic Algorithm is proposed. A fuzzy performance index based on distance to saddle node bifurcation, voltage profile and capacity of shunt FACTS controller is proposed. The proposed technique can be used to find the most effective location and optimal size of the shunt FACTS devices. The proposed approach has been applied on IEEE 14-bus and IEEE 57-bus test systems. The application results are promising.

1. Introduction

The continual increase in demand for electric power has forced utility companies to operate their systems closer to the limits of instability. This has resulted in stressed operating conditions, with associated problems related to system security. One of the major problems that may associate with such a stressed system is voltage instability or voltage collapse. Voltage stability is the ability of the power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [1]. Many incidents of system blackout due to voltage collapse have been reported worldwide [2,3]. Under stressed condition, one way to save the system from voltage collapse is to provide reactive power support with shunt FACTS controllers at appropriate locations. Placing FACTS devices is the most effective way for utilities to improve the voltage profile and voltage stability margin of the system [4]. However, to obtain good performance from these controllers, proper placement and sizing of these devices is crucial [6–15].

There are several methods proposed in literature for allocation of shunt FACTS devices. A survey on optimal placement of shunt type FACTS devices is presented in [5]. The techniques used for optimal placement of FACTS devices can be broadly classified into index based methods and optimization based methods.

Index based methods such as methods based on modal analysis near point of collapse [6,7], participation factors from modal analysis [8], extended voltage phasors approach [9], *L*-index [10], tangent vector [11], combined hybrid participation factor based on static and dynamic loading margin [12] are proposed for optimal allocation of the FACTS devices. In index based methods, shunt FACTS devices are generally installed in heavily loaded area and at the weakest buses for voltage stability enhancement. On such a basis, the problem of optimal placement of shunt FACTS devices is reduced to a problem of identifying the weakest bus and assigning appropriate VAR capacities to these chosen locations. However, in many cases, placing shunt FACTS devices simply at the weakest bus does not result in optimal reactive power reinforcement for voltage stability enhancement.

In recent years, multi-objective approaches for optimal allocation of shunt FACTS devices have become popular. The intelligent optimization techniques such as Genetic Algorithm (GA) [13,14], Benders decomposition [15], Particle Swarm Optimization (PSO) [16] are used to determine the optimal location and size of the FACTS controller. In these approaches, fitness function based on multiple objectives is maximized. However, the minimum degree of satisfaction among the objectives is not guaranteed in these approaches. It is also difficult to select proper penalty factors or weights used in the fitness function in order to reflect the relative importance of various objectives. In most of the existing methods, the attention has been focused upon real power losses and voltage deviation. Relatively, little effort has been directly involved with voltage stability improvement. However, voltage stability plays a major role in keeping the system operational.

In the light of above, this paper addresses the problem of optimal placement of shunt FACTS devices as a multi-objective optimization in Fuzzy framework. Fuzzy logic technique is applied to

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transform the multi-objective optimization problem into a single Fuzzy performance index and it is maximized using Real Coded GA. The proposed fuzzy-GA method determines optimal location and capacity of shunt FACTS controller which simultaneously maximizes the distance to saddle-node bifurcation (loading margin) and minimizes the bus voltage deviation. The operating and load constraints are also taken into consideration. The effectiveness of the proposed algorithm has been demonstrated by the simulation results of the IEEE 14-bus and IEEE 57-bus test systems.

Rest of the paper is organized as follows: In Section 2, multi-objective formulation for optimal placement and sizing of shunt FACTS controller is described. Fuzzy membership functions for various objectives are given in Section 3. Overview of GA and its implementation is presented in Section 4. Simulation results are presented in Section 5. Finally, conclusions are summarized in Section 6.

2. Multi-objective formulation for placement and sizing of shunt FACTS controller

Shunt FACTS controller like SVC or STATCOM connected at the appropriate location results in prevention of voltage collapse and better voltage profile. The location of shunt FACTS controller should be such that it maximizes the distance to saddle-node bifurcation, i.e., loading margin and minimizes bus voltage deviation from their nominal value with minimum possible capacity of the shunt FACTS controller. The problem for placing shunt FACTS controller can be formulated as a multi-objective problem with the following objectives and constraints.

2.1. Maximum distance to saddle-node bifurcation

Saddle-node bifurcation is the disappearance of system equilibrium as parameters change slowly. A saddle-node bifurcation point of the power flow equations of a power system can provide information regarding the margin of static voltage stability or loading margin at the current operating point of the power system. Loading margin is defined as the distance between the current operating point and the saddle-node bifurcation or voltage collapse point [17]. Saddle-node bifurcation is identified by a zero eigenvalue associated with system Jacobian [18]. Since Saddle-node bifurcation can cause a voltage collapse, it is desirable to maximize the distance between the current operating point and the saddle-node bifurcation point in order to maintain system stability. Thus, the first objective is to maximize the distance to saddle-node bifurcation which can be expressed as

$$\max\ f_1 = \min(eig(J)) \tag{1}$$

where $\min(eig(J))$ is the minimum eigenvalue of the system Jacobian.

2.2. Minimum voltage deviation

Excessively low voltages can lead to an unacceptable service quality and can create voltage instability problems. Shunt FACTS devices connected at the appropriate location play a leading role in improving voltage profile and avoiding the voltage collapse in the power system. Therefore, the second objective is to minimize bus voltage deviation. This objective function can be expressed as

$$\min\ f_2 = \sum_{m=1}^{k} |V_{mref} - V_m| \tag{2}$$

where V_m is the voltage magnitude at bus m, V_{mref} is the nominal voltage of bus m and k is the number of buses for which bus voltage limit is violated. In this work, bus voltage from 0.95 to 1.05 p.u. is considered acceptable. Low value of f_2 indicates flat voltage profile.

2.3. Minimum size of the shunt FACTS device

Due to the high installation cost of FACTS controllers, these controllers should be optimally sized. Thus, third important objective is to have minimum possible size of the shunt FACTS devices. This objective can be expressed as

$$\min\ f_3 = \sum_{i=1}^{sf} C_i \tag{3}$$

where C_i is the capacity of the ith shunt FACTS device in p.u. and sf is the total number of shunt FACTS devices.

During normal operation, power system is required to satisfy some constraints. These constraints are as described below.

2.3.1. Load constraint

The load constraints are the active and reactive power balance equations which can be expressed in a compact form as

$$g(x,u) = 0 \tag{4}$$

where g is the equality constraint representing typical load flow equations. x is a vector of dependant variables consisting of slack bus power P_{G1}, load bus voltages V_L and generator reactive power outputs Q_G, and u is a vector of independent variables consisting of generator voltages V_G, generator real power outputs P_G except the slack bus power P_{G1} and shunt VAR compensations Q_C.

2.3.2. Operational constraint

These constraints can be represented in a compact form as

$$h(x,u) \leqslant 0 \tag{5}$$

where h is the system operating constraint that includes generator voltages, their real and reactive power outputs and shunt VAR compensations. These are restricted by their limits as follows:

$$V_{G_i}^{\min} \leqslant V_{G_i} \leqslant V_{G_i}^{\max}, \quad i = 1,\ldots,\mathrm{NG} \tag{6}$$

$$P_{G_i}^{\min} \leqslant P_{G_i} \leqslant P_{G_i}^{\max}, \quad i = 1,\ldots,\mathrm{NG} \tag{7}$$

$$Q_{G_i}^{\min} \leqslant Q_{G_i} \leqslant Q_{G_i}^{\max}, \quad i = 1,\ldots,\mathrm{NG} \tag{8}$$

$$Q_{C_i}^{\min} \leqslant Q_{C_i} \leqslant Q_{C_i}^{\max}, \quad i = 1,\ldots,\mathrm{NC} \tag{9}$$

where NG and NC are the total number of generators and shunt compensators, respectively.

Considering the objectives and constraints the problem of optimal placement and sizing of shunt compensation can be mathematically formulated as a non linear constrained multi-objective optimization problem as follows:

$$\left.\begin{array}{ll} \max & f_1 = \min(eig(J)) \\ \min & f_2 = \sum_{m=1}^{k} |V_{mref} - V_m| \\ \min & f_3 = \sum_{i=1}^{sf} C_i \\ \text{s.t.} & \\ & g(x,u) = 0 \text{ and} \\ & h(x,u) \leqslant 0 \end{array}\right\} \tag{10}$$

The multi-objective optimization problem (10) is converted into a single objective optimization problem using fuzzy framework. A brief description of fuzzy membership functions used to represent these objectives is presented in the following section.