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Optimal siting and sizing of UPFC using evolutionary algorithms

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ABSTRACT

This paper addresses an application of evolutionary algorithms to optimal siting and sizing of UPFC which are formulated as single and multiobjective optimization problems. The decision variables such as optimal location, both line and distance of UPFC from the sending end, control parameters of UPFC and system reactive power reserves are considered in the optimization process. Minimization of total costs including installation cost of UPFC and enhancement of the loadability limit are considered as objectives. To reduce the complexity in modeling and the number of variables and constraints, transformer model of UPFC is used for simulation purposes. CMAES and NSGA-II algorithms are used for optimal siting and sizing of UPFC on IEEE 14 and 30 bus test systems. NSGA-II algorithm is tested on IEEE 118 bus system to prove the versatility of the algorithm when applied to large systems. To validate the results of transformer model of UPFC for optimal siting and sizing, results using other models are considered. In single objective optimization problem, CMAES algorithm with transformer model yields better results when compared to other UPFC models. The statistical results conducted on 20 independent trials of CMAES algorithm authenticate the results obtained. For validating the results of NSGA-II with transformer model for optimal siting and sizing of UPFC, the reference Pareto front generated using multiple run CMAES algorithm by minimizing weighted objective is considered. In multiobjective optimization problem, the similarity between the generated Pareto front and the reference Pareto front validates the results obtained.

Introduction

The capacity of transmission lines is becoming the main bottleneck of the existing transmission network. The loadability of transmission lines is increased due to the surge in loads. Larger amounts of power are being conveyed over the interconnections to important load centers. Consequently, some utilities maximize the import of power by keeping the tie lines at 90% to their security limit. This leads to an uneven distribution of electricity leading to congestion in some transmission lines while some other lines are underutilized.

To utilize the existing transmission lines more reliably and efficiently, the load demands are to be met satisfying the stability criterion. Flexible AC Transmission systems (FACTS) provide the right solution to the above problem. FACTS devices are high current power electronic devices mainly used for controlling various steady state problems such as voltage regulation, power flow and transfer capability more effectively.

One of the popular FACTs device UPFC's main strength lies in its ability to regulate active and reactive power simultaneously. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement in the same device. To achieve such functionality, it is equally important to determine the appropriate location for installation of UPFC. The effectiveness of UPFC varies when it is installed in different locations. Placement of UPFC in an optimal location is decided based on the various performance indices. Due to the high cost of UPFC, it is important to decide their optimal placement to meet the desired objective [6,13].

In the last decade, several optimization algorithms have been used for the determination of optimal location of UPFC for minimizing/maximizing various objectives while satisfying various constraints. Various models of UPFC such as uncoupled model, voltage source model, current injection model and transformer model are used in simulation studies [11,23,3].

An attempt is made to locate UPFC using evolutionary programming based load flow algorithm using voltage source model [26]. The optimal location of FACTS devices for the installation cost

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along with production cost is reported using current injection model [24]. Also, real power flow performance index is used to identify the optimal location in open power markets. The optimal location of UPFC for maximizing loadability using genetic algorithm with decoupled model of UPFC is discussed [4]. Perturbed particle swarm optimization is employed to identify the optimal location and control parameter settings of UPFC using decoupled model for enhancing system security under deregulated environment [19]. Sensitivity analysis is used to screen the location of UPFC for minimum power generation cost using transformer model of UPFC [23]. This technique requires only one OPF to obtain UPFC sensitivities for all possible transmission lines.

The optimal location of UPFC by minimizing combined generation cost and UPFC installation cost is formulated as an optimization problem and solved using continuation power flow technique with uncoupled model [1]. Decoupled model of UPFC operation for the minimization of power production and delivery costs is discussed [16,17]. The optimal location of UPFC by considering combined loss minimization, cost minimization and loadability maximization using PSO with power injection model of UPFC is reported [5]. PSO is used to identify the optimal location of UPFC for minimizing the installation cost of UPFC and maximizing the system loadability using combination of static voltage compensator (SVC) and Thyristor controlled series compensator (TCSC) [21]. Use of Fuzzy Evolutionary Programming for optimal location of UPFC devices with the objectives of minimizing the total operating cost and improving the voltage profile is reported [25]. Application of immune algorithm to find optimal location of UPFC to achieve minimum operating costs in open power market is reported using uncoupled model [22]. CMAES algorithm is used to solve the optimal reactive power dispatch by combined minimization of real power loss and maximization of the voltage stability using voltage source model [15]. Optimal location and parameter setting of UPFC for power system security enhancement is obtained using differential evolution algorithm using current source model [14,18].

In all the previous work, for simulating UPFC, uncoupled model, voltage source model and current injection model have been employed. These models require the calculation of Jacobian matrix in each iteration and this increase the computation time. Even though injection model and uncoupled model can be easily incorporated into steady state load flow or optimization problems there are some disadvantages as discussed below.

The control variables in these models depend on its input and output currents and voltages. Both the models require adding two additional buses to the OPF or load flow formulation. Inclusion of real power balance equation of UPFC is a necessity while using these models. Four additional equality conditions are to be added to the existing constraints for each UPFC. Addition of fictitious nodes is necessary while using these models for optimal power flow analysis.

To overcome the above problems, transformer model of UPFC has been proposed [23]. Modeling of power system network with UPFC is easier with transformer model as only passive elements are used in modeling. The number of variables involved while using transformer model is less when compared to other models. This feature reduces the complexity of the problem. Further the size of the admittance matrix remains a constant even with the inclusion of UPFC.

Recently, PDIP algorithm has been employed to identify the promising locations of UPFC based on marginal values of cost in wind integrated conversion systems with transformer model [2]. However, this technique has severe limitations (i) need of continuous and differential objective functions (ii) easy convergence to local minima (iii) difficulty in handling discrete variables. To overcome these limitations, an attempt has been made in this paper to determine the optimal location and control parameters of UPFC with transformer model using evolutionary algorithms namely CMAES algorithm and NSGA-II algorithm for single objective and multiobjective problems respectively.

This paper is organized as follows. Section 'Transformer model of UPFC' describes the transformer model of UPFC. Section 'Optimal location of UPFC' represents the mathematical formulation of the optimal power flow problem. Section 'Evolutionary algorithms' describes the evolutionary algorithms used in solving the optimization problem. In Section 'Implementation of algorithms', implementation of the optimal location of UPFC for minimum total cost and maximum loadability for the CMAES and NSGA-II algorithms are described. Section 'Results and discussions' discusses the numerical results. Section 'Conclusion' carries the final conclusion.

Transformer model of UPFC

With its unique capability to control real and reactive power flows on a transmission line simultaneously as well as to regulate the voltage at the bus where it is connected, UPFC creates a tremendous impact on the quality of power system stability.

The conservation of real power and providing reactive power by the UPFC helps in modeling the UPFC as a transformer with a shunt branch as shown in the Fig. 1.The advantage of this model is that the variables of UPFC namely the transformer turns ratio (T) and variable shunt susceptance (ρ) are independent of UPFC input and output voltages and currents.

The UPFC variable $\bar{\mathbf{T}}$ in this model is defined as

$$\bar{\mathbf{T}} = \mathbf{T}e^{\mathbf{j}\phi} \tag{1}$$

where T is the transformer turns ratio, Φ the phase shifting angle, and ρ the variable shunt susceptance.

The UPFC input and output voltage, current relationships, real power balance equations are well explained by Seungwon An et al. [23]. The number of independent variables in the earlier models are four namely V_{sh} (shunt inverter voltage), Φ_{sh} (angle of the shunt converter), V_{sc} (series inverter voltage) and Φ_{sc} (angle of the series inverter) whereas in the transformer model of UPFC, 3 control variables namely T, Φ and ρ are involved. This reduces the complexity of the problem when transformer model of UPFC is employed. Inclusion of real power balance equation is not necessary for this model. In other models, four additional equality constraints are also need to be included to represent the UPFC characteristics whereas in the transformer model of UPFC there is no necessity for additional constraints.

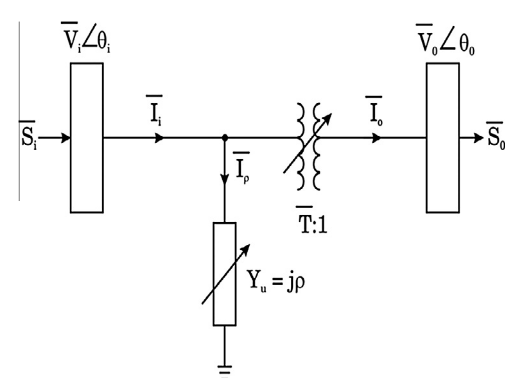

Fig. 1. Transformer model of UPFC.