Energy 36 (2011) 3579–3589

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Reactive power price clearing using multi-objective optimization

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ARTICLE INFO

Article history:
Received 3 September 2010
Received in revised form
23 February 2011
Accepted 26 March 2011

Keywords:
Ancillary services
Electricity markets
Reactive power management
Load modeling
Genetic algorithms
Multi-objective optimization

ABSTRACT

This paper presents a new multi-objective optimization based reactive power price clearing (RPPC) mechanism, considering voltage stability. Use of realistic voltage dependent load models is important in power system analysis and optimization. The influence of the same on RPPC is investigated in this paper. Investigations have also been carried out to ascertain the effectiveness of objectives such as, Total Payment Function (TPF), Loss Minimization (LM), Load Served (LS) and Voltage Stability Enhancement Index (VSEI). The unsuitability of LM/TPF minimization as independent or joint objective(s) for this problem, due to load served reduction is emphasized. The effect of loading condition on judicious combination of these objectives is further probed. The multi-objective RPPC problem is solved using Strength Pareto Evolutionary Algorithm (SPEA). Some of the results are also compared with the Multi-Objective Particle Swarm Optimization (MOPSO). The utility of the proposed approach is demonstrated through detailed investigation on IEEE 30 bus system considering base and stressed cases with constant and voltage dependent load modeling.

1. Introduction

In a deregulated power system environment, one of the basic responsibilities of the Independent System Operator (ISO), is to maintain system reliability and security, by acquiring ancillary services such as reactive power support, spinning reserves, energy balancing and frequency regulation. The North American Electric Reliability Council (NERC), along with the Electric Power Research Institute (EPRI), have published a joint report in which 12 different services have been formally defined as ancillary services [1]. Out of these, voltage support or the reactive power support, is termed as one of the important ancillary services. Sufficient reactive power support needs to be provided in the system, in order to maintain the power flow through transmission lines and the voltage within limits.

Since, market design treats pricing of ancillary services separately, separate market/mechanism is required for reactive power [1]. The main objective of optimal reactive power dispatch has always been minimization of the total transmission losses, subject to system operational constraints [2–4]. A two step approach for reactive power procurement by ISO is proposed in [5]. It determines the marginal benefit of each reactive bid, with respect to the system losses. Using this, it seeks to maximize a Societal Advantage Function (SAF), formulated by incorporating the price bid offers. In [6], a method for reactive power market design and clearing is developed for uniform price auction model, to competitively determine the prices of different components of reactive power service, namely: availability, operation and opportunity. Method of allocating the costs of reactive power, using circuit theory and Y-Bus matrix is presented in [7]. In [8], a methodology to allocate reactive power costs in a deregulated market is described. In this method, reactive power supply service is decomposed into voltage regulation and reactive power spinning reserve. A method for long term procurement market for reactive power, considering security, is proposed in [9]. In [10], a new reactive power market clearing scheme is proposed. It considers generators, transmission system elements such as reactive power sources and transformers. The latter are remunerated, based upon their action of tap shifting, while participating in the market. In [11], a new day-ahead reactive power market clearing considering uncertainty of generating units in the form of system contingencies by the stochastic model is presented. Optimal Power Flow (OPF) based security constrained real power market clearing approaches are discussed in [12–15].

The objectives of cost based approach for reactive power pricing are to minimize the costs of the reactive power, and the system active power loss. A methodology for cost based pricing structure of the reactive power support from generator is proposed in [16,17]. Drawbacks of the cost-based approach are presented in [18]. In [19], a day-ahead reactive power market clearing, based on multiple objectives, is proposed. In the deregulated environment, in pursuit

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doi:10.1016/j.energy.2011.03.070

of profit, the power producer has the incentive to sell active power as much as possible. Enough reactive power support enables a generator to sale active power. Inadequacy of the same may preclude sale of active power due to system security constraints (e.g., the voltage stability limits). So, it is essential to establish a mechanism for the financial compensation of the reactive power ancillary service. The requirement of locally producing reactive power on one hand, and the extreme dependence of system stability to reactive power on the other hand, may encourage the reactive power producers to benefit from the situation and maximize their own profit. In other words, market power is a serious challenge. Must run index based method is proposed in [20], to measure the market power held by reactive power suppliers, by virtue of their strategic locations in the system. The market regulator is responsible for devising regulatory mechanisms that strike a balance between providing adequate incentives to generators to supply reactive power, while also overseeing and preventing their abuse of the market power.

Most of the reported work on reactive power as ancillary service focuses either on developing suitable pricing methods that effectively reflect the cost of reactive power production, or proposing appropriate models for optimal reactive power procurement, and/or dispatch. These models usually aim to achieve a certain objective (e.g., reactive power production cost minimization or social welfare maximization) using OPF based models. An important requirement that has not been addressed in most of the existing models, is the inclusion of voltage dependent load modeling in the reactive power price clearing (RPPC).

Reactive optimization problems often involve multiple, conflicting objectives. In a single-objective optimization, there exists a global optimum. The multi-objective case, however, has no optimal solution clearly defined, but rather entails a set of solutions, called the pareto optimal front [21]. The goal of multi-objective strategies is to generate a set of non-dominated solutions, as an approximation to this front. However, the majority of problems of this kind cannot be solved exactly, because they have very large and highly complex search spaces. In recent years, metaheuristics have become important tools for solving multi-objective problems encountered in industry [22]. Multi-objective evolutionary algorithm for achieving economic dispatch, considering the environmental impacts, is explained in [23]. A multi-objective optimal operation management problem considering minimizing total energy losses, total energy cost, total pollutant emission produced by sources, and deviation of bus voltages as objectives is solved in [24]. In [25], a multi-objective reactive power dispatch problem is formulated by taking into account the active losses, reactive compensation device cost and the voltage deviation penalty functions. In [26], a multi-objective congestion management problem incorporating voltage and transient stability limits is proposed.

In the light of the above, this paper proposes a new reactive power price clearing mechanism, that uses more realistic voltage dependent load models instead of constant power models. It then shows that loss minimization (LM) and total payment function (TPF) minimization, individually or jointly, lead to reduction of the load served. The paper then suggests that, multi-objective optimization is essential to do justice to such a complex problem. The importance of using multiple objectives like, total payment function (TPF) minimization, loss minimization (LM), voltage stability enhancement index (VSEI) minimization and load served maximization (LSM) is highlighted. The paper also emphasizes the need for selecting judiciously, a combination of the objectives best suited for a given operating condition. In this work, Strength Pareto Evolutionary Algorithm (SPEA) is selected as one suitable multi-objective algorithm. Some of the results obtained with SPEA are also compared with Multi-Objective Particle Swarm Optimization (MOPSO) for validation. In order to focus on the main contributions, issues like security and impact of market power of reactive sources are not considered in this paper.

This paper is organized as follows: Section 2 describes the reactive power market structure. Section 3 presents design of the RPPC scheme. Sections 4 presents description about multi-objective optimization. Section 5 presents results and discussion. Finally, Section 6 summarizes the contributions.

2. Reactive power market structure

In this paper, reactive power provided by generators is treated as ancillary service and is eligible for payment. Fig. 1 shows the synchronous generator capability curve, consisting of three segments. These segments reflect field current heating, armature current heating and under-excitation limits. The power flow equations and the relationships of three segments of capability curve are nonlinear. The reactive power market is a single buyer market with system operator as the only buyer. The demand of reactive power depends on system structure, security requirements, etc.

2.1. Reactive power bid structure

The generators bid to provide reactive power support [6]. These bids consist of a capacity component (price per MVAr and quantity of offer), which is paid in advance for their readiness to produce/absorb reactive power. A utilization component (MVArh price curve) is paid for reactive power actually dispatched in real time. Compensation payment component (LOC) of a generator is computed based on its real power schedule, capability chart and other considerations [6]. Different components of reactive power offer structure are explained next.

2.1.1. Expected payment function (EPF)

The payment to the generators providing reactive power services consists of various costs depending upon their operating regions. The EPF is a mathematical formulation of cost components of the generator's expectation of payment towards capacity, utilization and compensation components. The EPF of a generator, as a function of the amount of generator reactive power production, is presented in Fig. 2 [6].

2.1.2. Cost of loss

This is one of the components of EPF. The field and armature losses of a generator increase with the increase in reactive power, in both lagging and leading power factor zones. In the under-

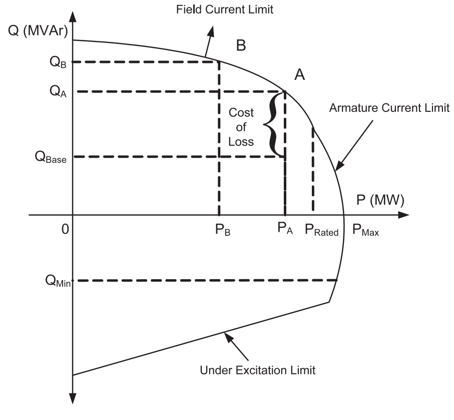

Fig. 1. Synchronous generator capability curve.