Electrical Power and Energy Systems 81 (2016) 427–443

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A day ahead price sensitive reactive power dispatch with minimum control

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ARTICLE INFO

Article history:
Received 20 September 2014
Received in revised form 31 December 2015
Accepted 25 February 2016
Available online 14 March 2016

Keywords:
Optimal reactive power dispatch
Optimal power flow
Marginal price

ABSTRACT

In this paper, a novel day ahead Price based Optimal Reactive Power Dispatch (PORPD) problem is proposed. The proposed approach aims to find the optimum real and reactive power output of thermal generators and searches for optimal operating schedule for Shunt Capacitors (SC) to minimize total reactive power supply cost. The proposed method is formulated to pay opportunity cost along with VAr supply cost of thermal generators. Moreover, the method recovers the investment cost and pays the operational cost of SC. The investment cost of SC is recovered from the depreciation cost and the operational cost is paid based on real time reactive energy cost. The SC output is made sensitive to reactive energy Marginal Price (MP) and the life span of the device is extended by obeying its operational limitations. The PORPD model is formulated as dynamic optimization problem and solved using Cuckoo Search (CS) algorithm. The program is developed on MATLAB and tested on IEEE 14 and IEEE 30 bus systems under different network complexities; like varying MP and non-linear loads. Moreover, to check the performance of CS algorithm, the results of basic PORPD problem is compared with other methods. Results confirm that the proposed method encourages the ancillary services to maintain a proactive role during higher market pricing hours and provides a guideline for the System Operator (SO) to ensure maximum operational gain for the market participants while maintaining system security.

Introduction

The conventional regulated structure of power industry throughout the world is transforming into a competitive electricity market. Planning and operation of modern power system is primarily based on economic perspective. However, the purpose of attaining only economy may jeopardize many power system components. In this context, maintaining power system reliability and security is a key issue before the power system practitioners and researchers. Ancillary service provider plays an important role in modern power system operation for maintaining system security. Reactive power support is one of the vital components of ancillary services. Without adequate reactive power support, it is not possible to maintain the power flow through the transmission interfaces with acceptable voltages at load buses. Moreover, the requirement of reactive support changes with every change in system topology and other conditions. Thus, optimal allocation of reactive power attracts attention [1,2]. Reactive power compensation and optimization is recognized greatly as a complex problem in power systems [3,4].

The Independent System Operator (ISO) under restructured electricity market coordinates with different reactive power sources and procures reactive power for maintaining system security. It is quite obvious that the cost for providing reactive power services must be remunerated. Therefore, reactive power pricing is gaining popularity and has become a very important issue in modern day power system operation. In deregulated electricity market, all the reactive power ancillary services are entitled to get payment for their support for providing reactive power [5,6]. For example, a VAr compensator is paid for facilitating the plant available for reactive power supply. On the other hand, a thermal generator receives payment for supplying additional reactive power as loss opportunity cost, over and above its committed uses. The reactive power procurement is a complex issue. Here, the ISO has dual objectives; first, to get reactive power from those sources which ensures maximum societal benefits and second, to determine the marginal benefit of bid prices which is acceptable to all market participants [7]. A method of pricing reactive ancillary service is demonstrated in [8], where, the ISO will procure required reactive power and cost involved will be allocated to all consumers impartially. A market based reactive power management issue is discussed in [9] by optimum allocation of reactive power procurement costs among generators and loads.

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http://dx.doi.org/10.1016/j.ijepes.2016.02.035
0142-0615/

Nomenclature

a_o, b_o, c_o	generator reactive power cost coefficients
B_{ij}	line susceptance between bus *i* and *j*
C	total reactive power supply cost for a complete day
C_d	depreciation cost of shunt capacitor
$C_C(Qc)$	reactive power generation cost of shunt capacitor in $
$C_0(Q_{gj})$	opportunity cost of *j*th thermal generator in $
$C_{gq}(Q_g)$	reactive power generation cost of thermal generator in $
$C^k_{gqj}(Q_{gj})$	reactive power generation cost of *j*th thermal generator at *k*th hour in $
$C_{gpj}(S_{gj,max})$	real power generation cost of thermal generator correspond to maximum power level
G_{ij}	line conductance between bus *i* and *j*
IC_{cap}	investment cost of shunt capacitor in $
k	time interval in hours
NB	number of buses present in power system
n_C	number of adjustments per day for shunt capacitors
Nc	number of buses where shunt capacitors are present
n_C^{max}	maximum allowable change for switchable capacitors
Ng	number of thermal generators present in the system
nPQ	number of *PQ* buses
P^k_{gi}	real power generation of *i*th thermal generator at *k*th interval
P^k_{di}	real power demand of *i*th bus at *k*th interval
P^{min}_{gi}	minimum value of real power generation of *i*th generator
P^{max}_{gi}	maximum value of real power generation of *i*th generator
Qc	reactive power generation from shunt capacitor in MVAr
Q_{gj}	reactive power generation of *j*th thermal generator in MVAr
Q_{cap}	capacity of shunt capacitor in MVAr
Q^k_{gi}	reactive power generation of *i*th thermal generator at *k*th interval
Q^k_{di}	reactive power demand of *i*th bus at *k*th interval
Q^{min}_{gi}	minimum reactive power generation of *i*th generator
Q^{max}_{gi}	maximum reactive power generation of *i*th generator
Q^k_C	switchable capacitors output at *k*th interval
Q^{min}_{Ci}	minimum output of *i*th switchable capacitor
Q^{max}_{Ci}	maximum output of *i*th switchable capacitor
S^{max}_{ij}	maximum line MVA flow between bus *i* and *j*
S^k_{ij}	line flow between buses *i* and *j* in MVA at *k*th interval
S_{gjmax}	maximum apparent power of *j*th thermal generator in MVA
$\|V^k_i\|$	voltage magnitude of *i*th bus at *k*th interval
$\|V^{min}_i\|$	minimum voltage magnitude of bus *i*
$\|V^{max}_i\|$	maximum voltage magnitude of bus *i*
θ^k_i	voltage phase angle of *i*th bus at *k*th interval

The importance of real time based pricing of reactive power was felt in early 90s and the approach was developed on Marginal Price (MP) based theory. Siddiqi [10] proposed an Optimal Power Flow (OPF) based model for real time pricing of reactive power. Much of the literatures addressed spot pricing of reactive power [11–15] in the latter stage. Spot price of reactive power at a particular location of electric power system network is calculated based on marginal cost of reactive power at that location. The real time based reactive power pricing is found to be better approach compare to power factor penalty based method [1]. A MP based approach for cost allocation of both real and reactive power is discussed in [15]. Some of the recent literature highlighted other approaches of cost based reactive power dispatch [16–22]; among them, the voltage security consideration is taken into account in [18] as constraint.

Reactive power allocation problem discussed above are formulated based on the current operating condition of power systems and primarily aims to maintain systems security. However, as the networks operating condition varies; the reactive power supply from various VAr sources need to be readjusted. The operating condition keep on varying in different days, months or seasons; therefore, seasonal reactive power planning model under market environment received attention [23]. The problems associated with such long term reactive power market model are: volatility associated with the forecasting of real and reactive power, uncertainty over network configuration and availability of various VAr sources [24,25]. Recently, day ahead reactive power planning model have been proposed by the researchers in [24–28] to improve the operating flexibility of power system networks. A multi-objective reactive power market clearing model is proposed in [26] with the major objectives of minimizing the overall payment towards VAr supply and transmission loss. In the proposed day ahead planning problem, the output of energy market clearing is taken as a potential input to the reactive power market clearing. Authors in [27] proposed a day ahead reactive power market clearing model based on pay as offered (bid) mechanism and compared it with that of market clearing price model. The investigation shows that pay-as-bid based model would benefit more to the local VAr supplier and would improve the overall service reliability for a given power network. A stochastic framework for day ahead reactive power market clearing is proposed in [28] wherein, the uncertainty of VAr generation under contingency is analyzed.

In a day ahead electricity market, the market participants; such as: generators and reactive ancillary service providers, has to declare their availability and capacity to the ISO for next day power system operation [26]. The market operator (ISO) allocates their energy transaction share for next 24 h period, based on the forecasted future operating condition of power system. On this background, in this paper, a day ahead price sensitive reactive power dispatch (PORPD) algorithm is proposed. In the proposed method, the reactive power output of VAr sources like Shunt Capacitors (SC) are made sensitive to the forecasted reactive power marginal price of the locations/buses where they are installed. The maximum number of adjustment possible in a day [29,30] for SC is considered as practical constraint. The problem is formulated as dynamic optimization problem and is tested on IEEE 14 and IEEE 30 bus system. The well known Cuckoo Search (CS) optimization technique [31] is utilized to solve the basic PORPD problem. Since, modern electricity markets are price sensitive and simultaneously work under changing load conditions; the proposed model is further studied under more complex environment; such as, varying Locational Marginal Price (LMP) and non-linear load conditions. Moreover, to check the performance of CS algorithm, the results of basic PORPD problem is compared with two other swarm based optimization techniques [32,33]. Since, swarm optimization techniques are population based and mostly work under random environment; their performances largely depend upon the efficient tuning of control parameters and trial runs. Keeping these facts in mind, in the present work, the parametric analysis is also