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Optimum Reactive Power Calculation for Reducing Power System Operation Cost

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SUMMARY

Reactive power plays a key role in voltage control and system stability. Various Volt/VAR techniques are utilized in electric power systems to maintain the voltage profile within a defined acceptable range and accordingly provide reliability, stability, and economic benefits. Reactive power has been commonly generated through large-scale synchronous generators or distributed capacitor banks to provide proper transmission and distribution level system management, however, reactive power can be further used as an effective means to reduce total system operation cost. This is to be achieved by adjusting nodal reactive power and accordingly impact the network power flow. The reactive power adjustment is becoming more common as a result of growing distributed energy resources (DERs) with reactive power control capability. The increasing number of inverter-coupled DERs, in particular, provides a unique opportunity to benefit from the reactive power provided by these resources. This paper develops a modified optimal power flow model to determine optimal nodal reactive powers that minimize the system operation cost. The applicability and performance of the proposed model is verified on IEEE 57-bus standard test systems.

KEYWORDS

Reactive power, operation cost, optimal power flow.

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1. INTRODUCTION

Reactive power plays a crucial role in power system stability and voltage control and is considered as an essential ancillary service that supports the power system operation. Reactive power control can also potentially minimize system real power losses and accordingly reduce total system operation cost which is a less investigated problem. Various equipment can be found in power systems to manage reactive power, such as capacitors banks, flexible AC transmission system (FACTS) devices, and static voltage compensators (SVC) to name a few, further managed through various Volt/VAR control techniques [1-3]. The growing proliferation of distributed energy resources (DERs), however, introduces another viable source for reactive power generation which is primarily integrated to distribution grids.

The existing studies on reactive power mostly focus on its control, management and pricing [4-16]. A framework for reactive power management to protect voltage stability at maximum marginal value while keeping real and reactive power at a least-cost dispatch is presented in [4]. Reactive power shortage and the associated voltage violations due to the failures of reactive power sources are considered in [5], where reliability indices are proposed to represent the effect of reactive power shortage on system reliability. The control of real and reactive power exchange between inverter and utility grid using the d-q theory is proposed in [6]. A correction method is proposed in [7] to achieve rapid reactive power control on synchronous generators. A method to calculate the optimum real and reactive power pricing that maximizes social benefit is presented in [8]. A comparison between the provision of reactive power support ancillary service in distribution systems and conventional equipment such as capacitor banks and distributed generation (DG) units based on renewable resources is provided in [9]. Design of a competitive market for reactive power ancillary services is discussed in [10], using a compromise programming approach based on a modified optimal power flow model. A mathematical model for reactive power pricing structure based on various cost components is developed in [11]. The study in [12] suggests a model to evaluate economical price of reactive power. The problem of reactive power ancillary services pricing is addressed and formulated as a joint cost allocation problem in [13]. A new multi-objective optimization method, based on reactive power clearing is proposed in [14], while considering system voltage stability. In [15], the authors investigate the possibility of designing a localized reactive power market. A competitive market for reactive power services in deregulated electricity systems, based on offers from reactive power resources, is presented in [16].

Existing literature investigates various methods of reactive power generation and control, with primary objectives of ensuring voltage stability and improved reliability. The cost optimization problem through reactive power control is however an important topic which needs further investigation and is lacking in the literature. In this paper, the optimal reactive power in all system nodes, which are capable of adjusting reactive power, is determined to minimize the system operation cost. A modified optimal power flow problem is defined and solved to find these optimum values, which is subject to all prevailing operational constraints. The rest of the paper is organized as follows. Section 2 presents the model outline and formulation of the proposed optimum reactive power calculation problem. Numerical simulations to show the performance of the proposed model on standard test systems are provided in Section 3. Section 4 concludes the paper.

2. MODEL OUTLINE AND FORMULATION OF OPTIMUM REACTIVE POWER CALCULATION

The goal of the proposed model is to determine the optimal nodal reactive powers that guarantee a minimum total system operation cost. In other words, the nodal reactive powers are adjusted in a way that the cost of real power generation in the system is minimized. The objective function is defined in (1) as the sum of individual unit costs, each presented as a second order function of its real power generation. P_i represents real power generation of unit i and a, b, and c represent constant cost coefficients. This objective is subject to operational constraints (2)-(10).

$$\min \sum_i \left(a_i P_i^2 + b_i P_i + c_i\right) \tag{1}$$

$$P_i^{\min} \le P_i \le P_i^{\max} \qquad \forall i \in \mathrm{G} \tag{2}$$

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \qquad \forall i \in \mathrm{G} \tag{3}$$

$$PL_{mn} = g_{mn}V_m^2 - V_mV_n\left(g_{mn}cos(\theta_m - \theta_n)\right) - V_mV_n\left(b_{mn}sin(\theta_m - \theta_n)\right) \qquad \forall mn \in L \tag{4}$$

$$QL_{mn} = -b_{mn}V_m^2 - V_mV_n\left(b_{mn}cos(\theta_m - \theta_n)\right) - V_mV_n\left(g_{mn}sin(\theta_m - \theta_n)\right) \qquad \forall mn \in L \tag{5}$$

$$-PL_{mn}^{max} \le PL_{mn} \le PL_{mn}^{max} \qquad \forall mn \in \mathrm{L} \tag{6}$$

$$-QL_{mn}^{max} \le QL_{mn} \le QL_{mn}^{max} \qquad \forall mn \in \mathrm{L} \tag{7}$$

$$\sum\nolimits_{i\in \mathrm{G_m}} P_i + \sum\nolimits_{n\in \mathrm{B_m}} PL_{mn} = PD_m \qquad \forall m \in \mathrm{B} \tag{8}$$

$$\sum\nolimits_{i\in \mathrm{G_m}} Q_i + \sum\nolimits_{n\in \mathrm{B_m}} QL_{mn} = QD_m + QM_m \qquad \forall m \in \mathrm{B} \tag{9}$$

$$V_m^{min} \le V_m \le V_m^{max} \qquad \forall m \in \mathrm{B} \tag{10}$$

$$QM_m^{min} \le QM_m \le QM_m^{max} \qquad \forall m \in \mathrm{B} \tag{11}$$

The limits of real power (P) and reactive power (Q) of synchronous generation unit (i) are shown in in (2)-(3). G represents the set of all generation units. Equations (2) and (3) can be further linked and extended using each unit's capability curve. Synchronous generator's capability curves are provided by manufacturers and used for loading the synchronous generators in different operating loads without exceeding the designed limits. Generally, nominal capacity of a synchronous machine can be indicated by MVA in a specific voltage and power factor (usually 85-90% leading) in which the synchronous machine is able to work continuously without abnormal temperature increment. Real power output of the synchronous machine depends on turbine ability and nominal MVA machine limits. The maximum reactive power capability is associated with operating with lagging power factor and the minimum reactive power capability corresponds to the maximum reactive power the generator may absorb when operating with leading power factor. Lines' real power flow (PL) and reactive power flow (QL) equations are presented in (4) and (5), respectively, based on nodal voltage magnitudes (V), voltage angles (θ), and lines conductance (g) and susceptance (b). m and n are indices for system buses and L is the set of transmission lines. Equations (6) and (7) ensure that lines' real and reactive power flows are limited to their respective capacities. The nodal real and reactive power balance equations (8)-(9) ensure that the sum of nodal real and reactive power injections from generators and the power injected/withdrawn through the lines connected to each node, equals the real load (PD) and reactive load (QD) at that bus. G_m and B_m respectively represent the set of generation units and lines connected to bus m. Nodal voltage magnitudes are also restricted by their respective limits as in (10).

To consider the role of DERs in reactive power generation/consumption, a new variables (QM) is defined and added to the reactive power balance equation. This variable represents the amount of reactive power that DERs contribute to each node, and is restricted by its respective limits as in (11). These limits are determined based on the capability curve and the amount of real power that DERs are producing. It should be noted that in (9) the impact of DERs (connected to the distribution network) is considered in the transmission network, so the employed variable is an aggregate number for all the DERs connected to that specific transmission bus. As this is a free variable in the optimal power flow problem and merely bound by its limits, it will reach an optimal value that minimizes the objective function.

3. NUMERICAL SIMULATIONS

The proposed model is formulated in MATPOWER and applied to the IEEE 57-bus standard test system as shown in Fig. 1. This system consists of seven generators and fifty PQ buses.

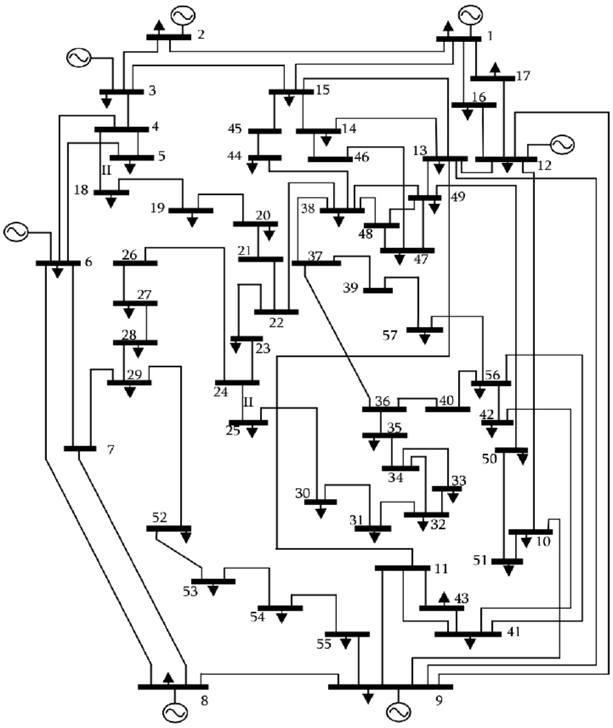

Figure 1: IEEE 57-bus standard system.

The reactive power is initially considered to be fixed and equal to the values provided by the input data. The operation cost in this case is calculated as $41738. To minimize the total operation cost, the reactive power at each bus, individually, is considered to be variable (i.e., a reactive power source is available at that bus) and the optimal reactive power is calculated accordingly. The results of the optimal reactive power in each bus are listed in Table I, and the corresponding costs are shown in Fig. 2. As the results demonstrate, some buses have a large effect on the system operation cost, while others have a relatively smaller effect, showing the criticality of some buses over others in impacting the system operation cost.

As shown in Fig. 2, buses 35, 36, and 40 share the highest effect on the total system operation cost. These results suggest that it would be logical to focus only on a handful of buses in the system for reactive power generation, as these buses may have a larger impact than the sum of many other buses.

Table I. Base vs optimum reactive powers for PQ buses in IEEE 57-bus system

Load bus number	Basic reactive power (MVAR)	Optimum reactive power (MVAR)
4	0	1.77
5	4	2.47
7	0	55.21
16	3	1.13
18	9.8	-5.58
21	0	-4.41
23	2.1	-0.46
25	3.2	0.85
27	0.5	177
29	2.6	-49.34
31	2.90	3.00
33	1.90	1.90
36	0	0.08
40	0	40
42	4.4	4.82
51	5.3	-78.26
52	2.2	-1.68
54	1.4	1.66
57	2	0.27

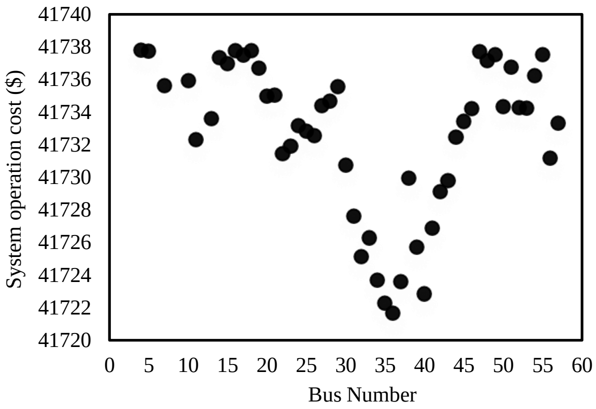

Figure 2: Effect of optimum reactive power of buses on the system operation cost for IEEE 57-bus system.

Table II shows a comparison of total system operation cost for the base case, considering unity power factor for all buses (associated with Q=0), and after finding optimum reactive power. The results indicate that having unity power factor at all buses does not necessarily lead to the minimum system operation cost. A comparison of the costs show that a unity power factor in all buses reduces the cost by around 0.03% while this reduction for the optimum reactive power case is 0.04%. This may seem as a small percentage, however considering the extremely large operation cost of practical systems (in range of millions of dollars daily), this reduction can lead to significant savings.

It is worth mentioning that the required nodal reactive power will be provided by the available DERs and microgrids in the network, therefore the investment and the ownership costs do not need to be considered in the proposed model. Determining the value of these services from a local provider's perspective, however, may need additional studies which will be investigated in a follow on work.

Table II. Total system operation cost for IEEE 57-bus system

Test system	Base case (without applying optimization)	Q=0 in all load buses (unity power factor)	After applying optimization
IEEE 57-Bus System	$41738	$41724	$41721.7

4. CONCLUSIONS

Reactive power has a crucial role in voltage control, and accordingly reliability and stability of power systems. In addition, reactive power is an important factor in reducing system losses. The main purpose of this paper was to find optimum nodal reactive power in a power system such that the total system operation cost is minimized. To this end, a nodal reactive power variable was added to the optimal power flow problem, and the critical buses which showed the highest effect on decreasing the system operation cost were determined. The required reactive power adjustments were considered to be supplied by DERs and microgrids. The proposed model was tested on the IEEE 57-bus standard test system and the obtained results showed that the unity power factor at all buses does not necessarily minimize system operation cost, but the combination of positive and negative reactive powers at various buses in the system would help achieve this objective.

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