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Multi-objective optimal reactive power flow including voltage security and demand profile classification

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Abstract

This paper proposes a method to optimize reactive power flow (ORPF) with regard to multiple objectives while maintaining system voltage security across a time-domain. Compromise programming is employed in the ORPF formulation, which is designed to minimize both losses and payment for the reactive power service in the framework of the UK daily balancing market. In coordination with ORPF, continuation power flow (CPF) is applied to evaluate and maintain the voltage security margin of the system. Prior to the optimisation procedure, the related control parameters can be grouped with the aid of a load classification method in order to simplify the control actions. During the optimisation, through the application of both ORPF and CPF, multi-objective optimisation can be achieved with voltage security at an acceptable level. The Ward and Hale 6-bus system and a 60-bus UK test system are presented to illustrate the application of the proposed modeling framework.

Keywords: Control action; Demand profile classification; Multi-objective; Reactive power control; Transition-optimisation; Voltage security

1. Introduction

As a consequence of the global restructuring of electricity industries over the last decade, a wide range of reactive power markets and pricing mechanisms have been proposed and adopted [1]. With regard to the UK power system, National Grid (NG) provides a balancing market in which the reactive power service is provided [2]. In the market, successful generators sign bilateral contracts with NG for the provision of reactive power, while those unselected generators that can be required to provide reactive power service will receive a default payment that is less than the payment made by the market agreement [2,3].

NG, as a buyer of reactive power service from those generators, has an incentive to keep such expenditure at a minimum level. Furthermore, as the owner of transmission network, NG also needs to lower the operation cost. In order to achieve those targets, a compromise-programming concept is employed to minimize both losses and payments based on the daily load curve as presented in [3].

However, to achieve the 24-h optimisation of real losses and payments requires excessive calculation [4]. Thus, to speed up the calculation process and to simplify the control actions, it is necessary to divide the load curve into several intervals. In each interval control actions are performed only once. Recently [5–7] the problem has been formulated in a transition-optimised fashion. In [5], six typical operating points are chosen to represent the daily load pattern. However, such six points may be inadequate to represent the whole daily load if the load varies more significantly in one day. In [7], an adaptive limit method was proposed that could perform effectively by using two statistical measurements when partitioning the load profile. The number of groups of the intervals is calculated at the end of classification. However, being a commercial organisation, NG is likely to want to decide the times of the control actions a day in advance. To meet this goal, this paper proposes a method to partition continuous load points into a certain number of groups according to the characteristics of the

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Nomenclature

D	demand bus
$f1$	functional form of the objective to minimize loss
$f2$	functional form of the objective to minimize total payment
$f_1^* f_2^*$	ideal solutions of the objectives in the independent optimisation
g	generator bus
i	node number
L	a set of load points in a continuous period
L_i	a member of a set of load points
N_g, N_d	number of the generator buses and the demand buses
P, Q	active and Reactive power injection
S_{ij}^f, S_{ij}^t	apparent power flow of the 'from' and 'to' bus
T	tap-changer
T_{fixed}	fixed value decided after load classification for tap-changer
V	voltage of the bus
$V_{\min}$	minimum voltage of the system
θ	phase angle of the bus
σ	step-size in CPF
k_1, k_2, k_3	constants
P_i^e, P_i^a	payment for the lead and lag reactive power services in a settlement period duration
N	number of the load points

forecasted load profile. For example, at the beginning of each interval, corresponding tap-ratios and shunt reactors will be selected and will remain constant for the whole interval [8]. Alternatively, generator voltages can be continuously controlled within an interval. Thus, unnecessary control actions can be avoided, and the required number of control actions taking place in a day can be optimised.

Meanwhile, being the system operator, it is the responsibility of NG to keep the system secure from voltage collapse. In previous studies, optimisation techniques have been applied to solve the problem by incorporating the voltage stability constraints to the OPF formulations [9,10]. However, such techniques increase complexity of the model, thus causing more difficulty with regard to computational progress. So instead, CPF is applied to evaluate the security margin [11–15].

In this paper, a two level master-slave algorithm is proposed to optimise multiple objectives over a day ahead time horizon while maintaining the voltage security of the system. The master level is used to divide the daily load curve into several intervals and to reduce the depreciation cost via the control of corresponding tap-ratios and shunt reactors; alternatively the slave level is used to solve the multi-objective problem via the control of generator voltages with fixed tap-ratios and shunt reactors at each Settlement Period Duration (SPD). Also in the slave level, CPF is incorporated into the optimisation process in order to maintain the voltage security of the system.

The remainder of the paper will introduce the master and the slave levels respectively, then demonstrate the algorithmic technique with a Ward and Hale 6-bus system and a 60-bus UK based system, and finally draw conclusions based on the results and analysis.

2. Master level – load classification

In order to demonstrate the classification process a daily load curve representative of the UK demand [16] has been employed as illustrated in Fig. 1. During the 24-h period the peak demand appears at approximately 19:00 h whilst the lowest value appears at approximately 04:00 h. Furthermore, there is little variation in the load curve for the period 09:00 to 17:00 hours and considerable variation for the remaining periods. Therefore, the proposed classification method aims to partition the curve into several segments in the time domain according to these characteristics. The setting of discrete control variables such as transformer tap-ratios and shunt reactors will be prohibited within each segment.

2.1. Scattering and variability measurements

The tolerance associated with partitioning in the classification method is based on both scattering and variability analysis of the load points associated with a daily demand curve. Therefore, starting from 00:00 h, as long as subsequent load points are within the tolerance, such points can be grouped into one segment. In order to judge whether those points are within tolerance, two statistical measurements are used; standard deviation and range.

The standard deviation represents the degree of spreading within a group of load points. However, if a skew point occurs the standard deviation method may not reflect the characteristics of such load points accurately. In order to solve this problem the range that represents the difference between the highest and the lowest values is employed as an additional measurement. The statistical formulations for both measurements can be presented as follows;

2.1.1. The standard deviation

$$S = \sqrt{\frac{\sum_{i=1}^{n}(L_i - \overline{L})^2}{n}} \tag{1}$$

where