Renewable Energy xxx (2015) 1–8

Contents lists available at ScienceDirect

Renewable Energy

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

Optimal generation dispatch of distributed generators considering fair contribution to grid voltage control

Chenjie Ma [a,*], Paul Kaufmann [b], J.-Christian Töbermann [a], Martin Braun [a,c]

[a] Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Kassel, Germany
[b] Faculty for Electrical Engineering, Computer Science and Mathematics, University of Paderborn, Germany
[c] Energy Management and Power System Operation Department, University of Kassel, Germany

A R T I C L E I N F O

Article history:
Received 19 March 2015
Received in revised form
16 July 2015
Accepted 28 July 2015
Available online xxx

Keywords:
Distributed generation
Generation dispatch
Real time simulation
Volt/var control
Linear programming

A B S T R A C T

This paper investigates voltage control and generation dispatch of distributed generators (DGs) and how the operation of installed DGs can be optimized in distribution systems. A novel online generation dispatch algorithm for DGs is proposed in this work. This algorithm optimizes the contribution of individual DG units for grid voltage control in terms of costs. The technical advantages of the presented approach are evaluated by comparing the simulation results with various static and local dispatch control strategies, which can be considered currently as state-of-the-art according to technical standards and recent research. Simulation results indicate that the proposed method decreases the total cost for DG, improves the quality of voltage profiles and guarantees for each DG unit the opportunity to provide a fair amount of ancillary service to the grid. Additionally, through a performance test on a real time simulation platform it is concluded that the presented approach is also suitable for large grids in real time operation.

1. Introduction

Due to economic incentives and technological maturity, installations of small and medium sized renewable energy generators have rapidly increased since years. Especially in the rural areas, voltage rise, which is one of the major impacts of DGs, has been challenging conventional planning and operation of distribution systems.

A range of options have been suggested for distribution system operators (DSO) to mitigate critical voltage rise. Measures for grid reinforcement are normally combined with considerable high costs. Alternatively, new regulatory requirements on DGs are introduced, e.g. Refs. [1,2]. According to these grid codes, although equally valid for all systems, the operational set-point of DGs is always configured very conservatively and thus inefficient considering some critical situations which rarely occur, e.g. overvoltage and overloading. In recent studies, local autonomous power control (APC) and voltage droop mechanisms present their technical effectiveness in mitigating large voltage deviations [3,4]. By means of reactive power provisioning and active power curtailment, DGs can actively contribute to grid voltage regulation and increasing hosting capacity of distribution grids. However, applying these APC or voltage droop control strategies, some PV systems, which are located at the end of feeders, have to provide the ancillary service more often than other systems installed at the beginning of feeders. These kind of local control strategies cause therefore an unfair distribution of costs for DG owners due to the involved losses associated with grid voltage support. This situation presents new challenges for improving economy and security of power system operation with consideration of customers' costs.

In this study, we present a new central generation dispatch algorithm for voltage control in distribution systems. It minimizes the total loss for all DG units by optimizing their output set-points; at the same time, it guarantees that all DGs bare the same cost of ancillary service to the grid with respect to their installed capacity. The proposed method is tested with two case studies under high photovoltaic (PV) penetration conditions. Through comparison with the standard regulatory measures and the local control mechanism, the technical and economical effectiveness of the new control algorithm is validated. In addition, the feasibility of this algorithm for online applications is also proved by implementing the algorithm on a large grid model on a real time simulation platform.

* Corresponding author.
E-mail address: chenjie.ma@iwes.fraunhofer.de (C. Ma).

http://dx.doi.org/10.1016/j.renene.2015.07.083
0960-1481/

Please cite this article in press as: C. Ma, et al., Optimal generation dispatch of distributed generators considering fair contribution to grid voltage control, Renewable Energy (2015), http://dx.doi.org/10.1016/j.renene.2015.07.083

Main contributions of this work are:

- This work emphasizes the cost of DG owners for provision of voltage support to the grid. It differs from previous studies, which normally start from the point view of a DSO and aim at operating the whole distribution system optimally with respect to minimization of grid losses and improving voltage profiles. In this work, we assume that the voltage problem caused by power feed-in is also an objective by optimal dispatch of DGs. This optimum denotes the minimum of total cost by all DG owners in the whole system.
- Furthermore, we focus on a fair distribution of costs considering the size (installed capacity) and the location of DGs in the grid. Based on the proposed dispatch algorithm, the same specific costs for all DGs can be achieved without significantly increasing the total costs. Its effectiveness is evaluated on a real LV grid model with measured PV profiles for the investigated grid area. Also, both the offline and real time implementations of this strategy together with the grid simulation model prove the effectiveness and the applicability of our approach.

This paper is outlined as follows. In Section II, a detailed literature review on related work is given. Section III describes the proposed dispatch algorithm, and in Section IV, assumptions and parametrization of the simulation are presented. In Section V, different control strategies are evaluated by comparing the simulation results. Finally, a short conclusion and a discussion about possible future work is given in Section VI.

2. Related work

Voltage control and reactive power dispatch are originally considered as a power system planning problem. They are typically formulated as reactive power planning (RPP) problems in literature mainly at the transmission system level. These publications have the common objective to optimize the voltage profile by control of the reactive power flow. Active power has not been treated as a control subject, because generation is determined by consumption, which is normally not controllable by utilities.

A comprehensive overview on RPP is provided in Ref. [5]. According to this work, strategies for solving this type of optimization problem are differentiated by their definition of objective function, definition of constrains and applied mathematical methods. Traditionally, it is characterized as an optimal power flow problem with the typical objective of grid loss minimization [6–9], mitigating voltage fluctuations [6,8,9], and/or minimizing the total demand of reactive power compensation [10]. Depending on the formulation of the objective function and the constrains, these problems are solved by linear or non-linear programming techniques.

With the presence of DG at distribution level, new tendencies can be identified among recent publications. First, the conventional, worst-case based planning solutions will not efficiently solve the voltage control challenge in distribution systems due to the highly fluctuating nature of renewable energy sources. Thus, the voltage problem needs to be solved also online by grid operation. Some work present online volt/var control (VVC) strategies for voltage control [10,11]. The optimization goal is formulated thereby similar as for RPP. Multi-objective optimization (MO) and heuristic methods for voltage control can be found in Refs. [6,8].

Second, DGs can provide support for control of grid voltages by means of reactive power provision, as it is also suggested by the conventional reactive power dispatch topics. This method is investigated by publications [3,4,10,12]. Besides, active power reduction is also considered as a second option by Refs. [4,9,13]. To sum up, new solutions should be able to equally address both of the possibilities offered by DG in order to achieve the system optimum.

Last, provision of ancillary service also means loss of profit for DG owners. This subject is studied as the reactive power cost allocation (RPA) problem. In the RPA formulation, a special view on individual contribution of DG units to total voltage support is analyzed. By investigating the Jacobian matrix [14] or the modified Y-bus matrix [15], a sensitivity matrix indicating voltage changes at all nodes according to the change of reactive power set-points of individual DG units can be constructed. With help of this sensitivity matrix, costs of reactive power provision can be determined individually for each DG unit. The investigations help to understand the complexity of the generation dispatch problem in distribution systems.

This work aims to minimize the total costs for DG units considering the losses caused by participation in grid voltage support, while ensuring voltage regulation and operational limits of DGs. By utilizing the Jacobian matrix for voltage estimation, the whole problem can be solved linearly. In addition, the proposed algorithm is a joint optimization of active and reactive power set-points with consideration of a fair distribution of individual costs for each DG. As commonly required by central control mechanisms, it is assumed that necessary measurement devices and a communication infrastructure exists in the power system under consideration.

3. Problem formulation

Based on measurements of bus voltage and the maximal current generation potential of each DG unit, the proposed central generation dispatch algorithm optimizes the active and reactive power set-points of generation units at each time interval. In the following, the objective function and the associated boundary conditions are first presented. The work flow of this approach is demonstrated in the second part of this section.

3.1. Cost specification of generation dispatch

In order to mitigate overvoltages in the grid, generation units are requested to absorb reactive power and/or reduce their active power feed-in. Both of these two options cause loss of profit for DG owners. For feed-in energy, DG owners are paid according to either a fixed tariff or a flexible retail price related to spot market. This price is applied for calculating the cost of DG owners. For reactive power provision, DG owners may be compensated by a negotiated price with the DSO. As there is currently no reactive power market existing in Germany, a price charged by a DSO for customers with low power factor is considered as a reference [16]. Therefore, costs of generation dispatch for each DG unit can be specified by combining the cost of reduced feed-in energy and the cost for reactive power provision, which are determined according to Eq. (1):

$$c_i = Price_{EP} \cdot \Delta P_i \cdot dt + Price_{EQ} \cdot \Delta Q_i \cdot dt. \quad (1)$$

c_i stands for total costs of one PV system due to the adjustment of both active and reactive power set-points. $Price_{EP}$ and $Price_{EQ}$ are the specific prices for active and reactive energy in €/kWh and €/kvarh, respectively. ΔP_i and ΔQ_i denote the reduced active power and extra reactive power output of DG comparing to only feed-in of active power. dt equals to the time interval of dispatch control.

3.2. Objective function

The main objective of this central dispatch algorithm aims to