Electric Power Systems Research 111 (2014) 169–176

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Contributions to thermal constraints management in radial active distribution systems

Ilya Bilibin [1], Florin Capitanescu *

Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, 4 rue Alphonse Weicker, L-2721, Luxembourg

ARTICLE INFO

Article history:
Received 28 August 2013
Received in revised form 14 January 2014
Accepted 11 February 2014
Available online 15 March 2014

Keywords:
Active distribution system
Congestion management
Distributed generation
Network reconfiguration
Optimal power flow
Smart grid

ABSTRACT

This paper deals with centralized thermal overload management in active radial distribution systems that host a significant amount of distributed generation (DG). We investigate the benefits of using remotely controlled switches to reduce the amount of curtailed DG to remove overload. To this end we extend an existing optimization model to the problem of minimizing the non-firm DG curtailment to remove overload. We discuss the pros and cons of the various overload management goals given the particular features of radial distribution grids and propose, wherever possible, the use of a power flow tracing-based procedure to select the non-firm generators that should participate in overload removal. Although the approach focuses on overload removal it also inhibits violation of operational constraints such as voltage limits that may occur due to network reconfiguration. We prove the interest and feasibility of our approach in four distribution networks.

1. Introduction

In order to meet the more stringent environmental constraints, many distribution systems (DSs) host increasing amounts of distributed generation (DG) (e.g. wind, photovoltaic, etc.) [1,2]. This may lead to a significant increase in reverse power flows and thereby to thermal and/or voltage constraints among other operational issues. Medium voltage distribution systems are generally either (and mostly) voltage constrained or thermally constrained. Voltage (raise) constraints generally arise in very long rural networks, whereas thermal constraints [3–5] in lines/cables/transformers may prevail in networks with short lines or with relatively large nominal voltage (e.g. 20–33 kV).

There are two philosophies for determining the allowed DG penetration level in a DS [1]: *passive* DSs and *active* DSs. The former paradigm is based on the "fit-and-forget" principle (i.e. a new DG is accommodated only if this does not lead to operational constraints violation under worst operating scenario). This approach is very conservative and may prevent achieving the required green energy target and harvesting DG benefits (e.g. reduction of: investments in new assets, losses, load peaks, etc.). *Active* DS concept is a way to significantly increase DG penetration by managing DG output and other control means through *centralized* [4–6] or *distributed* [7] control schemes.

In this work we focus on thermally constrained *active* DSs in which we assume a *centralized* management of thermal constraints.

Several approaches have been devoted to the overload management in active DSs such as: (time-series) optimal power flow (OPF) [6,4], constraint programming [5], sensitivity-based [7], etc. OPF [8] is an essential tool to manage constraints in both transmission [9] and distribution systems [6,4]. In DSs it provides optimal DG curtailment to remove constraints according to a given goal (e.g. minimizing either the MW curtailed or the curtailment cost [10]) or DG connection agreements (e.g. last-in, first-off [4]). However, these approaches do not consider network switching as an option.

The *main contribution* of this work is to investigate the benefits of relying on remotely controlled switches to reduce the DG curtailment. This leads to pose a mixed integer nonlinear programming (MINLP) problem. To reduce the computational burden of MINLP problem [12], the latter can be reformulated, for radial DSs, as a more tractable equivalent mixed integer quadratically constrained (MIQC) problem, as demonstrated in [13] for power losses minimization by means of network reconfiguration. In this work we further extend the model in [13] to the problem of overload management and extend significantly our previous approach [14]. Another contributions of the paper are: an analysis of the pros and

* Corresponding author. Tel.: +352 466644 5345; fax: +352 466644 5669.
E-mail addresses: ilya.bilibin@uni.lu (I. Bilibin), fcapitanescu@yahoo.com (F. Capitanescu).
[1] Tel.: +352 466644 5345; fax: +352 466644 5669.

http://dx.doi.org/10.1016/j.epsr.2014.02.018
0378-7796/

cons of constraint management goals, and a power flow tracing scheme to select only the DG units that are truly responsible for overload as candidate for curtailment in OPF.

The rest of the paper is organized as follows. Section 2 discusses the main features of the overload management scheme. Section 3 presents the mathematical model of the optimization approach. Section 4 provides numerical results with the method and Section 5 concludes.

2. Features of the proposed approach

2.1. Regulatory framework

In most distribution systems (e.g. in Europe), in order to ensure fair access and competition between DG units, electricity market and distribution system operation are unbundled; hence the distribution system operator (DSO) cannot own DG [10]. The DG access to the grid relies on DG connection agreements [10] (e.g. "last-in, first-off" principle in U.K. [4]). In this framework, according to the DG connection agreement, one can distinguish between "firm" DG units (generators that cannot be curtailed to remove grid constraints as they invested in grid reinforcement; these DG units are accommodated based on a worst-case scenario) and "non-firm" DG units (generators that accepted to be occasionally curtailed as overload occurs because the lost revenue is deemed more advantageous economically than grid reinforcement option) [4]. As this unbundling may lead to poor operation performances of the DS and or limited DG penetration level, DSO-owned DG frameworks are advocated [16]. Furthermore, regulation may also differ in whether the owners of curtailed non-firm DG units receive a compensation to cover the lost revenue (if this is the case then the DSO looks for minimizing the payments toward the owners of curtailed DG units [10]; otherwise the DSO seeks to minimize the overall DG curtailed energy).

We conclude that most regulatory frameworks differ basically in two respects: the choice of non-firm DG units participating in curtailment and the optimization goal. Bearing this in mind we devise in Section 3 an optimization approach for overload management which is *versatile* enough to be applicable in various regulatory frameworks (e.g. by properly choosing the objective function, some variables and some constraints), including both non-dispatchable and dispatchable DG [15].

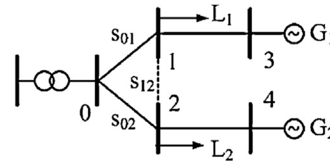

Fig. 1. Illustrative 5-bus distribution network.

2.2. Illustrating the benefits of remotely controlled switches option

The benefits of remotely switching in terms of curtailed energy saving are briefly illustrated by running our optimizer for 24-h generation/load patterns on the 5-bus system shown in Fig. 1 (the data set of this test case are provided in Appendix A). Sectionalizing switches s_{01} and s_{02} and tie switch s_{12} are remotely controlled. G1 is a photovoltaic unit and G2 is a wind unit. The thermal limits of lines 0-1 and 0-2 prevent larger power injections into the upper voltage grid and hence hosting larger amounts of DG.

Fig. 2 shows the unconstrained generators profiles (with dotted line), the constrained generators profiles with only DG curtailment as control option (with dashed line), and the constrained generators profiles with remotely controlled switches as additional control option (with continuous line). The gray areas represent the energy saved thanks to switching actions, provided in Table 1, clearly highlighting the value of this control means. These gains are obtained by redirecting the output of G2 through lines 1-2 and 0-1 when the load L1 is high and generation G1 is small as well as by redirecting the output of G1 through lines 1-2 and 0-2 when the load L2 is high and generation G2 is small. Switches status change occur at hours 6, 13, and 17.

2.3. Analysis of possible choices for the objective function

From the perspective of maximizing the amount of non-firm DG accommodated in the DS (or equivalently minimizing their curtailment) and offering incentives for a fair competition regarding the connection access of DG units to the grid, we assess the pros and cons of three objectives: the norm L_1 (1), a weighted linear objective L_{1w} (2), and the norm L_2 (3):

$$L_1 = \min \sum_{i \in G} (P_{gi}^0 - P_{gi}), \tag{1}$$

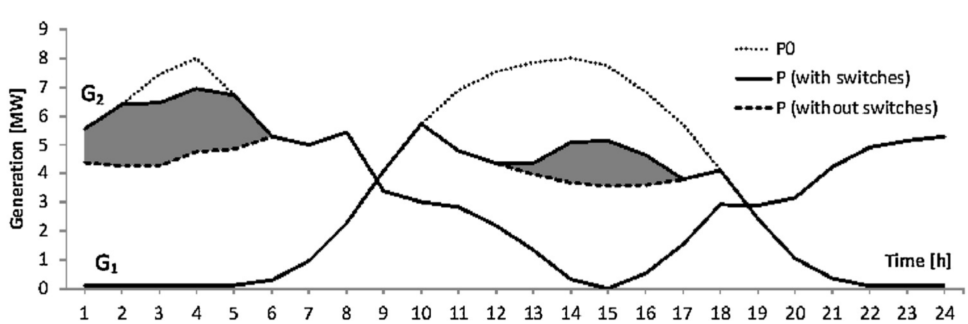

Fig. 2. Energy savings thanks to switching actions.

Table 1
Hourly status of remotely controlled switches.

Switch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
s_{01}	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
s_{02}	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1
s_{12}	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0