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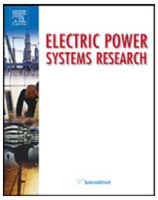

An iterative method for controlling reactive power flow in boundary transformers

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ABSTRACT

This paper presents an operational tool designed to help the system operator to control the reactive power flow in transmission–subtransmission boundary transformers. The main objective is to determine the minimum number of control actions necessary to ensure that reactive power flows in transmission/subtransmission transformers remain within limits. The proposed iterative procedure combines the use of a linear programming problem and a load flow tool. The linear programming assumes a linear behaviour between dependent and control variables around an operating point, modelled with sensitivities. Experimental results regarding IEEE systems are provided comparing the performance of the proposed approach with that of a conventional optimal power flow.

1. Introduction

The management of voltages and reactive power flows in large-scale systems has acquired greater importance nowadays, both in terms of planning and operation of electric power systems [1–3]. This issue has become very critical in the last decade due to the lack of reactive power resources together with a growing demand. Some issues that have contributed to increase such a lack of inversion in reactive power sources are the need for better utilization of existing facilities or the increasing cost of energy.

Reactive power management policies remain insufficiently developed in the new paradigm of competitive electricity markets, mainly due to the local nature of the problem and the complexity of developing a competitive market for the provision of reactive power [4]. Thus, voltage and reactive power control are usually classified as ancillary services, which are necessary for the efficient and economical provision of active power [5]. The characteristic of this ancillary service has been thoroughly treated in Refs. [5–11].

The following three issues are crucial in establishing a proper management of reactive power as an ancillary service: (a) reactive power constraints for all agents connected to the transmission network, typically expressed as a function of the power factor; (b) reactive power actually demanded, which must fall within the acceptable range; and (c) payment for the service, penalties and possible incentives. These aspects are applicable to the agents participating in this ancillary service: generators, transmission service providers and consumers. Most of deregulated power systems [12] also extend these issues to distribution network utilities, as they are considered to be large consumers connected to the bulk transmission network. This implies specific constraints for any transformer connecting a distribution network to the transmission network (boundary transformers), as well as the application of other criteria mentioned above. In this way, NERC establishes these specific rules as a set of recommendations [13], and, in a recent study [14], CIGRE also underscores the importance of reaching similar objectives in the management of reactive power in power systems.

In this scenario, the system operator (SO) must control transmission network voltages and reactive power flows taking into account the constraints imposed on boundary transformers. The most extended way to perform this task is not based on the use of an optimization tool but a set of manual, heuristic decisions. This method to control voltages and reactive power flows is completely inadequate nowadays as is only based on the operator experience and off-line predictions, which often do not correspond to the real changing operating conditions.

This actual situation demands appropriate tools that simplify the SO task of deciding the type and number of control variables on which to act, as well as the magnitude of each action to be taken for each specific case in order to perform an adequate real-time system control. In that sense, the aim of this paper is to develop an operational tool that will serve as an aid to SOs. As a novelty, new constraints associated to the reactive power flow in transmission/subtransmission boundary transformers will be considered.

The paper is organized as follows: Section 2 describes a general Optimal Power Flow (OPF) that can be used to solve the posed control problem. Section 3 presents an alternative operational tool to deal with the new control problem. In Section 4, the new methodology is tested on two networks, the 24-bus and the 118-bus IEEE systems. The resulting solutions are compared against those obtained with the general OPF defined in Section 2. Finally, Section

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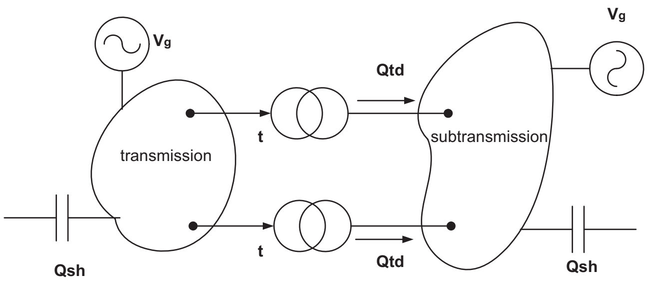

Fig. 1. Boundary transformers between transmission and subtransmission areas.

5 summarises the most important conclusions from the developed work.

2. General formulation

Fig. 1 shows a schematic diagram of a typical power system. There are two areas, well distinguished according to theirs voltage levels: transmission and subtransmission. Both systems are connected by transformers which make up the border. These transformers will be called boundary transformers. Each area has different controls to operate the corresponding network.

The control of the reactive power flow in boundary transformers can be formulated as an OPF problem, where limitations on such reactive power flows are incorporated as a new constraint,

$$\begin{array}{l} \min f(X,U) \\ \text{subject to} \\ \quad h(X,U)=0 \\ \quad V^{\min} \le V \le V^{\max} \\ \quad t^{\min} \le t \le t^{\max} \\ \quad Q^{\min} \le Q_g \le Q^{\max} \\ \quad Q_{td}^{\min} \le Q_{td} \le Q_{td}^{\max} \\ \quad Q_f^{\min} \le Q_f \le Q_f^{\max} \end{array} \tag{1}$$

where

- $f(X, U)$ is the objective function
- $X = [\,\theta_{n-1} \quad V_{PQ} \quad Q_g \quad P_{Slack}\,]^t$, vector of dependent variables, with:
  - ○ θ_{n-1}, voltage phases in all nodes except the Slack bus;
  - ○ V_{PQ}, voltage at PQ nodes
  - ○ Q_g, reactive power of generation nodes;
  - ○ P_{Slack}, active power of the Slack bus;
- $U = \left[\,t \quad Q_{sh} \quad V_g\,\right]^t$, is the set of control variables available to the SO:
  - ○ t, tap position of OLTC transformers;
  - ○ Q_{sh}, reactive power of shunt devices. Alternatively, the susceptance B_{sh} can be used instead of Q_{sh};
  - ○ V_g, generators scheduled voltage;
- $h(X, U) = 0$, network equations
- Q_{td} are the reactive power flows in boundary transformers which must be kept within limits. These are dependent variables
- Q_f are the reactive power flows in transformers and lines near their ratings.

As the changes in reactive power flows in boundary transformers can significantly affect the reactive power flows in the rest of the network, as a consequence of the redistribution of the reactive power flows across the network, small overloads might appear in lines or transformers that were previously near their operating limits. Therefore, constraints on the reactive power flow on problematic lines and transformers must be included in the formulation.

The solution of (1) provides optimal values for control variables, U, that ensure that all technical and operational constrains are satisfied, and the value of the objective function, $f(X, U)$, is minimized. It is well known that this type of OPF problems is highly nonlinear due mainly to the reactive power equations. Additionally, the new constrains increase even more such complexity.

Note that, as we are not considering emergency states of the system (i.e., states that present variables beyond operational limits) but scenarios in which the system is in normal state [20] but optimality criteria are violated (in this case, a criterion imposed by the regulation itself), the control actions included in the proposed formulation are either continuous (e.g., voltage set-point of generators) or with small discrete steps (e.g., LTC ratio, capacitor banks). Control variables with large discrete steps (i.e., binary variables such as network switching, connection of initially non-dispatched generators, connection/disconnection of large reactors, or even line disconnection) are only used to correct voltage problems in emergency states, and, consequently, are out of the scope of the proposed tool.

The proposed formulation only considers operator control actions used in the voltage and reactive power control problem, being the impact of these control actions on the active power practically negligible. In fact, the active power generated only changes due to the variation in active power losses as a result of the operator actions to control the reactive power flows. In this sense, in the model considered, the changes in active power are assumed by the slack generator, the rest of generators being unaffected.

3. Proposed methodology

Against the previous general OPF, this section presents a more practical and complete tool aimed to help SOs to control reactive power flows in boundary transmission–subtransmission transformers. This tool automatically determines the necessary control actions in order to correct reactive power flows out of limits. The flow chart of the proposed iterative operational tool is shown in Fig. 2. A description of the main steps follows:

- ○ The application starts from an initial state obtained from a load flow (LF).
- ○ Then reactive power flows in boundary transformers are checked with respect to theirs allowed operation limits. If all of them are in limits the application ends. Otherwise control actions are demanded.
- ○ Control actions are computed by using a linear programming module. This module will be developed in Section 3.1.
- ○ The values of control variables are updated with the required control actions.
- ○ The new system state is computed from an exact LF.
- ○ The new reactive power flows are assessed. If there are reactive power flows violating the operational limits, the process starts again. Otherwise, it finishes.

After applying this iterative procedure, the general problem is solved.

The linear optimization module that constitutes the application core is based on two main aspects:

(1) First, it is well known that the existing relationship between the dependent and control variables is quite linear around a given operation point. This behaviour allows the use of a sensitivity matrix $[S_{ij}]$ to relate dependent and control variables. Two sub matrixes constitute $[S_{ij}]$. The first one correlates the nodal dependent variables, X, to the control variables, U, $S_{X,U}$. This matrix can