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A three-phase optimal power flow applied to the planning of unbalanced distribution networks

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ABSTRACT

This paper models a three-phase optimal power flow applied to distribution networks. The objective function is to minimize electrical losses, the restrictions of which are the maximum and minimum levels of active and reactive power supplied the voltage magnitudes, and taps of voltage regulators with consideration of the mutual impedances of cables. In order to gain numerical stability, the voltage phasor is represented by the rectangular form. The optimization problem is solved by the Interior Points Method version Primal–Dual, whose importance to the planning of distribution networks is tested using the IEEE-123 system bus.

Introduction

The advent of Smart Grids has affected the planning and operation of distribution networks, making them more innovative, branched, smart, and unbalanced. These features require intensive use of information technology, communications, instrumentation, control and the development of new mathematical formulations to operate these intelligent distribution networks.

The planning and operational analyses must evolve beyond the traditional tools of power flow. This is because now there might be contraflows of power through the wires, changes in the voltage profile caused by the insertion of distributed generation, growth of load and voltage imbalance that requires tap adjustments of the voltage regulators and the distribution transformers in order to control the magnitudes of voltage beyond the reactive control.

The main tools available for the analysis of electrical networks are applied to single-phase loads developed for transmission systems, such as the Newton–Raphson method and its variants. However, they do not have adequate performance for radial distribution networks owing to issues of dominance and ill conditioning of the nodal admittance matrix [1].So, some dedicated and efficient methods for determining a solution for the single load flow problem in radial distribution networks are available in the literature. These methods are divided into two main categories: the method of Current Sum or Power Sum, known as "Front and Backwards Sweepings"; and methods based on the "Implicit Nodal Impedance" [2]. The first category is recommended mainly for purely radial systems and it comprises two versions: one in terms of currents [3], and the other based on power [4]. The second category includes methods based on the implicit nodal impedance matrix and they are more applicable to branched systems [5].

In terms of three-phase analysis, [6] presents a three-phase power flow that is an extension of mono-phase version of [3], that includes three-phase lines, loads and capacitors; [7] presents a model based on three-phase current injections using rectangular form (it does not include modeling of transformers, capacitors and voltage regulators). In [8], the topological characteristics of the network relating the three phase current injections of the buses with the flow of currents through the branches are modeled. This work is applied only to radial networks and it does not include modeling of transformers, capacitors and voltage regulators. The mutual coupling of the transmission lines of a three-phase and radial network is also considered in [8], which uses the "process of backward" to meet the current flows and the "process of forward" to calculate the voltages.

In [9], a critical assessment regarding the performance of the formulations of power flow applied to three-phase systems using an iterative method of Newton–Raphson is presented, which used the polar and rectangular forms. According to this work, for ill-conditioned systems, balanced or not, the polar method did not converge, whereas the rectangular methods and injection currents converged in all cases analyzed.

The work [10] presents the formulation of a three-phase power flow problem using sequence components with results as fast and robust as conventional Newton–Raphson method.

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Moreover, experiments with conventional optimal power flow (using single load) applied to extensive and ill-conditioned distribution networks have shown good results when using the voltage in rectangular form, as reported in [7,11].

Usually, studies reporting on analyses of three-phase distribution systems use conventional load flows. However, strategies to control the voltage and reduce the losses are important in three-phase networks with large numbers of unbalanced loads because the voltage along the feeder also becomes unbalanced, increasing losses and seriously impairing the regulation of voltage. For example, some operational procedures of distribution networks recommend that the unbalance voltage between the phases should be at most 2% (when voltage > 1 kV). Thus, adjustments of the taps of voltage regulators and distribution transformers for each phase also must be considered in order to control it.

Furthermore, the increased connection of distributed generation requires effective coordination of the various types of distributed energy, transport and use, which requires an improvement of the systems network analysis in order to achieve a safe state of operation. So, it must be made an effective control of the demand (through management or load shedding), control of the distributed generation, control of the flows through the lines, control of the voltage profile (allocation and taps' adjustment of voltage regulators and transformer distribution), control of the reactive control (allocation and setting of capacitor bank). These new grid can be adjusted using a three-phase OPF considering unbalanced load and mutual coupling.

Thereby, it must also be modeled the three-phase load, the three-phase capacitors, the three-phase voltage regulators and three-phase distribution transformers to properly optimize their adjustments, besides the conventional variables of a power flow to distribution networks.

The literature presents the following Three-Phase Optimal Power Flow (TOPF):

- Ying-Yi and Fu-Ming [12], solved by Newton–Raphson method and applied for three-phase transmission systems;
- Bruno et al. [13] that presents a solution to an unbalanced optimal power flow applied to Smart Grids operating in real time, which is able to perform load shedding. It was solved based on quasi-Newton method, which, to avoid heavy computational burden, does not require the analytical evaluation of first and second derivatives of the equivalent unconstrained problem. In this work, the power balance equations is solved by a three-phase power flow;
- Paudyal et al. [14] that developed a TOPF model with discrete operations as capacitors switching actions and taps adjustments during a day. How commercial solvers did not well solve the proposed problem, the integer values are relaxed and converted into a nonlinear programming solved by GAMS and using the MINUS solver;
- Dall'Anese et al. [15] that proposed an OPF applied to unbalanced microgrid solved by semidefinite programming relaxation technique advocated to obtain a convex problem that has the potential to find the globally optimal solution;
- Araujo et al. [16] that proposed a three-phase optimal power-flow solution using the Primal–Dual Interior Point Method and the three-phase current injection method in rectangular coordinates.

Despite the effectiveness of the TOPF formulations already proposed in the literature, this work chose to use the Interior Point Method (IPM), as also [16], to solve it because this technique is well-established in the literature, is a robust mathematical technique widely applied to single-phase OPF and with good application to real systems (for example, a system of 3000 buses converges using few seconds although it does not guarantee global solution).

Moreover, to skirt problems of bad conditioning of extensive radial distribution networks, it was chosen to represent voltage phasor in rectangular form, which presents good results to three-phase power flow [7], mono-phase optimal power flow [16] and three-phase optimal power flow [16].

Taking into account: [9,11,16] that model the voltage using the rectangular form; [5] that presents classical models of three-phase capacitors, voltage regulators and distribution transformers; [11,16] that use the robustness of the Interior Points Method Primal–Dual version, this work proposes a three-phase optimal power flow based on power injections in rectangular form, differently of [16] which is based on current injections in rectangular form.

The proposed formulation, based on power injections and using the classical models of capacitors, voltage regulators and distribution transformers, does not present the mathematical advantages of the formulation presented in [16], which has the possibilities to represent different types of connections loads and any types of transformers without need of additional calculations. But, the proposed formulation in this work is easily implementable because it uses the well establish equations of the power balance equations on rectangular form of the mono-phase studies, which are replicated three times, one for each phase, and connected by the bus admittance matrix with mutual impedance. This simple strategy can provide valuable information to a planner of an unbalanced load.

The proposed formulation, has the following considerations: the representation of the voltage is in rectangular form; three-phase primary feeder; three, bi and single lateral branches; voltage regulators with adjustments of taps; banks of capacitors; three, bi and single loads; and mutual impedance of the branches.

The objective function of the TOPF is the minimization of losses. The active and reactive power balance equations, and the voltage limits and taps adjustment of voltage regulators are made for all the three phases simultaneously, which are interconnect by the mutual impedance.

This fast implementable and easy formulation can be used to support decision of planning and operation of the distribution network. For example, it can be used to assess the problem of allocation of capacitor banks and voltage regulators as described in traditional single-phase [17] problems, and also the problem of planning the switching of automatic capacitors [18], but now using the TOPF that considers the load unbalance and mutual coupling.

In this work, the proposed formulation (TOPF) will be used to evaluate the importance of it when adjusting taps of voltage regulators and bank of capacitors.

This work is organized in four different sections. Firstly, the elements of a three-phase distribution network are described. Then, the representation of the mutual impedances inside the admittance matrix and the formulation of proposed three-phase optimal power flow are set. Finally, the results and conclusions are presented for a 123 bus system.

Distribution systems

Unlike transmission networks, distribution networks have predominantly a radial topology, unbalanced connections, and different types of loads and lines [19]. Thus, despite the modeling used are well known, it is necessary to remember the three-phase model of line, transformer, capacitor, voltage regulator and load to understand how they are formulated and organized by the proposed formulation. The models selected are the simplest, for example, they include only star no-grounded without the neutral conductor (medium voltage level).