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Optimal power flow in three-phase islanded microgrids with inverter interfaced units

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ABSTRACT

In this paper, the solution of the optimal power flow (OPF) problem for three phase islanded microgrids is studied, the OPF being one of the core functions of the tertiary regulation level for an AC islanded microgrid with a hierarchical control architecture. The study also aims at evaluating the contextual adjustment of the droop parameters used for primary voltage and frequency regulation of inverter interfaced units. The output of the OPF provides an iso-frequential operating point for all the generation units and a set of droop parameters for primary regulation. In this way, secondary regulation can be neglected in the considered hierarchical control structure. The application section provides the solution of the OPF problem over networks of different sizes and a stability analysis of the microgrid system using the optimized droop parameters, thus giving rise to the optimized management of the system with a new hierarchical control architecture.

1. Introduction

Optimal power flow, OPF, in electrical power systems is the problem of identifying the optimal dispatch of generation sources to get technical and economical issues. The problem is typically solved in Distribution Management Systems (DMS), which implement the highest level of the hierarchy of controllers within microgrids [1]. They take care of control functions such as optimized real and reactive power dispatch, voltage regulation, contingency analysis, capability maximization, or reconfiguration. Microgrids, that are small low or medium voltage networks supplying interconnected loads by distributed energy resources, often show unbalanced loads and can work autonomously from the main grid. For this reason, a three phase OPF in islanded distribution systems is needed. The formulation of the problem should also account for the presence of inverter-interfaced units with control laws specifically designed to contrast voltage and frequency deviations when a sudden load variation occurs. Therefore the first issue to be analyzed is the efficient solution of the three phase power flow [2] in islanded three phase unbalanced systems; the formulation of the problem may also put into evidence the droop regulators parameters, so as to account for voltage and frequency deviations within admissible ranges.

In [3], a parametric study on these systems shows the dependency of power losses on the droop parameters, thus it makes sense to consider as part of the solution of the OPF also the set of droop parameters affecting the power injection from grid forming units. In the problem, the other variables are the power injections from PQ generation buses. Besides, according to traditional power flow solution method, a slack bus is needed; the latter is considered as an infinite bus capable of supplying or absorbing whatever real or reactive power flow thus keeping the system frequency and local bus voltage constant. This method for load flow solution is not suitable in islanded microgrids systems having small and comparable capacity generators. In these systems indeed, there is no generator that can be physically regarded as a slack bus. In order to face the problem above, in this paper it is proposed to model inverter interfaced generation units using the control law used for primary voltage and frequency regulation and a suitable power flow calculation method without a slack bus has been proposed in 2009 [2]. Differently from what is commonly done for loads, represented with a constant power model (P, Q), in this formulation, loads

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power depends on voltage and frequency. Constant power model may indeed lead to inconsistent and misleading results about loss reduction and other subsequent calculations on stability [5].

Authors in [2] devise a power flow calculation method for islanded power networks. However, the loads in the study only depend on voltage, not on frequency and the application is devoted to balanced transmission systems. Therefore the proposed model is not suitable for power flow calculations in microgrids, which typically show unbalanced loads. The power flow formulation in three phase unbalanced micro-grid with voltage and frequency dependent load modeling may bring misleading results with traditional methods, such as the Newton Raphson method, due to the presence of sparse matrices. A complete formulation of the problem here discussed can be found in [6], where a new method that can solve this problem called Newton Trust Region Method is proposed. The method is designed by a combination of Newton Raphson Method and Trust Region Method. The paper shows that this new method is a helpful tool to perform accurate steady state studies of islanded microgrids and the solution of a 25 bus test system is achieved after a few iterations. However, the authors do not investigate the dependency between the droop parameters values and the power losses value for each loading condition and do not solve the OPF problem. The OPF in three phase unbalanced systems working in islanded conditions has been dealt with only recently, although some authors have investigated the influence of the network parameters over stability issues affecting the local controllers [4], showing that the selection of droop characteristics requires a thorough investigation of system steady-state and dynamic behavior.

More recently, in [7], the authors use Particle Swarm Optimization to choose the droop parameters and then perform the load flow analysis using the formulation seen in [2]. In the paper however the OPF is not dealt with the three phase load flow formulation. In [8], a methodology for unbalanced three-phase OPF for distribution management system in a smart grid is presented. However, the loads in the study do not depend on voltage and frequency and a traditional power flow solution method for grid connected systems is used.

In [9], it is shown that with P/V droop control, the DG units that are located electrically far from the load centers automatically deliver a lower share of the power. This automatic power-sharing modification can lead to decreased line losses; therefore, there the system shows an overall improved efficiency as compared to the methods focusing on perfect power sharing. Such concept of unequal power sharing is developed in this paper, where droops are optimized based on global objectives such as power losses, the latter being an optimization objective that seems concurrent with dynamic stability of the system.

In this paper, an original formulation and solution approach for the OPF problem in islanded distribution systems is proposed. The methodology is well suited for AC microgrids and can be envisioned as a new hierarchical control structure comprising only two levels: primary and tertiary regulation, the latter also providing iso-frequency operating points for all units and optimized droop parameters for primary regulation. The OPF provides a minimum losses operating point for which voltage drops are limited and power sharing is carried out according to the most adequate physical properties of the infrastructure thus giving rise to increased lifetime of lines and components. Due to the fact that the solution method is based on a numerical approach, the OPF is quite fast and efficient and the operating point can be calculated in times that are comparable to the current secondary regulation level times.

The paper is organized as follows. In Section 2, the modeling of the three-phase system for power flow solution is described. Then the power flow solution for unbalanced three phase microgrids systems using the Trust Region Method is described. Then, Section 3 presents the OPF formulation for losses minimization in closed form. The formulation of the OPF in this first application is devoted to balanced load three phase system in which the only the P-f droop parameters can be optimized, while the Q-V droop parameters cannot. Section 4 shows the attained results and a discussion on the attained results.

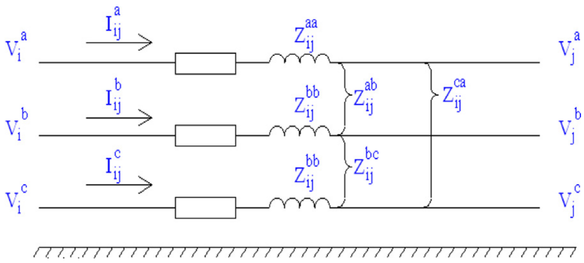

Fig. 1. Model of three phase line.

In the application sections, two test systems different scenarios have been investigated to show:

- the results of the OPFs solution and the results for a small 6 bus system along with the droop parameters attained;
- the results of stability studies carried out over the 6 bus system above.

2. Optimal power flow in islanded AC microgrids

In order to provide a suitable formulation of the OPF problem in islanded AC microgrids also accounting for primary regulation issues, it is required a precise modeling of the system's lines and components.

2.1. Lines and loads modeling

Line modeling [6] in this study is based on the dependency on frequency of lines reactance. Carson's equations are used for a three phase grounded four wire system. With a grid that is well grounded, reactance between the neutral potentials and the ground is assumed to be zero. Applying the Kron's reduction [10] to the impedance matrix modeling the electromagnetic couplings between conductors and the ground, the following compact matrix formulation can be attained, please see Fig. 1 where superscript $-n$ has been omitted:

$$[Z_{ij}^{abc}] = \begin{bmatrix} Z_{ij}^{aa-n} & Z_{ij}^{ab-n} & Z_{ij}^{ac-n} \\ Z_{ij}^{ba-n} & Z_{ij}^{bb-n} & Z_{ij}^{bc-n} \\ Z_{ij}^{ca-n} & Z_{ij}^{cb-n} & Z_{ij}^{cc-n} \end{bmatrix} \tag{1}$$

2.2. Load modeling

The frequency and voltage dependency of the power supplied to the loads can be represented as follows:

$$P_{Li} = P_{0i}|V_i|^{\alpha}(1 + K_{pf}\Delta f) \tag{2}$$

$$Q_{Li} = Q_{0i}|V_i|^{\beta}(1 + K_{qf}\Delta f) \tag{3}$$

where P_{0i} and Q_{0i} are the rated real and reactive power at the operating points respectively; α and β are the coefficients of real and reactive power. The values of α and β are given in [11]. Δf is the frequency deviation $(f - f_0)$; K_{pf} takes the value from 0 to 3.0, and K_{qf} takes the value from −2.0 to 0 [12].