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A distributed minimum losses optimal power flow for islanded microgrids

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ABSTRACT

In this work, the minimum losses optimal power dispatch problem for islanded microgrids with distributed energy resources (DER) is solved by means of a distributed heuristic approach. Optimal power management is performed almost in real time, with a predefined schedule, i.e. every 5 min, and the solution is applied to generators when the current operating solution violates voltage or current constraints or when the current configuration produces too large power losses.

The operating point of both inverter-interfaced generation units as well as rotating production systems can be modified simply using local information. The latter are voltage measurements and power injections or loads data of local and nearby nodes, therefore information processed at each bus derive from communications between adjacent nodes.

The distributed algorithm is iterative but also fast and easy to understand, since it is based on the use of power flow equations. It can be employed for small and medium size networks showing tens of nodes and test results prove that convergence happens in few iterations.

1. Introduction

Distributed generation (DG) and energy efficiency are the basis of the innovative models of power distribution organized in energy districts by particular smart grids (SGs), also known as microgrids (MGs). According to the Department of Energy (United States), MGs are a set of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single entity with respect to the grid and can connect and disconnect from the grid [1]. Thanks to the development of new advances in Information and Communication Technologies (ICT) for power systems, the intelligent integration of the actions of all the connected units (such as generators, consumers and prosumers) is carried out, in order to efficiently deliver economical and secure sustainable supplies of electricity (as the smart grid concept outlined by the 'European smart grid technology platform' in 2006) [2].

The term DER comprises a variety of DG units such as photovoltaic (PV), wind turbines (WTs), and energy storage systems (ESS). Sound management of a MG requires an energy management system (EMS) which controls at the highest level the energy flows, inside the MG and between the latter and the main grid, by adjusting both the energy flowing in or out from the main grid, the dispatchable DER, and the controllable loads based on signals or forecasts on weather and energy prices.

Such EMS, when the MG operates in islanded conditions will no more account for the energy market but for energy production costs and pollution. When the MG is islanded, the optimal power flow (OPF) issue is also quite relevant, since power flows and operational limits must be accounted for, especially if the grid was not originally designed to host a large penetration of RESs or if the size of the system itself is large enough to consider losses a relevant quantity in optimizing the energy management.

Recently, OPF algorithms for smart transmission system, where RESs are integrated, have been proposed, such as the one described in Ref. [3]. However few papers consider the OPF problem for radial distribution systems [4], also involving distributed generators and storage units [5]. Even fewer papers study the issue in MGs [6–9].

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Due to the high computational burden, the centralized OPF problem' solution can become prohibitive in case of medium and large size systems and not so reliable in smaller systems. For real-time networks management, it is in general needed to find a new network operation layout in a few seconds or minutes, so as to promptly re-organize operation following fast load variations and intermittent power generation changes that is typical of renewable-based DG units. Moreover, centralized control architectures are less fault tolerant than decentralized ones. The latter can easily host new nodes and new functionalities without large interventions enabling plug-and-play characteristics.

Distributed algorithms are proposed for transmission systems minimizing production costs [10,11]. The work in Ref. [10], in particular, shows an efficient distributed OPF method suitable for self-optimizing parts of the transmission power system. In each part, a centralized Security Constrained Optimal Power Flow (SCOPF) is solved with constraints over tie-lines connecting to other parts of the power system and the method, iteratively, reaches a convergence. The method offers the novelty of using both power quantities and boundary prices. In Ref. [11], a general framework for distributed economic OPF in transmission power systems is provided, but still employing complex QP solvers that are not easily transferable to cheap distributed microprocessors. Other optimal management distributed algorithms for MGs are devoted to distributed resources management in a market context. In Ref. [12], a distributed algorithm based on the classical symmetrical assignment problem is proposed. In this case, the algorithm solves optimally the negotiation between agents in the MG. No computation is made to minimize power losses during operation. Other distributed algorithms are proposed for energy management in the literature for MGs, in most cases devoted to manage energy resources in the market context. A distributed scheduling strategy for a MG system to minimize the cost of the non-green energy consumption is considered in Ref. [13], where the scheduling problem is formulated as a privacy-constrained linear programming problem. Also in this case, the main aim is the energy market management. In Ref. [14], several distributed algorithms are proposed. However, they are aimed at solving the distributed resource allocation (also loads) problem, facing the decentralized coordination and control of demand response (DR) resources and DERs. Leveraging the dual decomposition, a distributed energy management approach is developed in Ref. [15] for MGs with high penetration of RESs. In this case, the framework is again a liberalized energy market with an aggregator sending power curtailment/increase signals to the distributed energy resources. In Ref. [16], Additive Increase Multiplicative Decrease (AIMD) algorithms are adopted to share the power generation task in an optimized fashion based on minimum production cost among the DERs within a MG. No realistic technical constraints are considered (i.e. power losses are neglected).

Several distributed algorithms can be found in the literature for efficient OPF solution in power systems and in MGs. The PhD dissertation from Cai [17] proposes different distributed multi-agent systems for solving the OPF in microgrids. The simplest does not consider network losses and voltage regulation. In this case, the information flows in parallel and results are obtained in a non-iterative way; therefore, the method is fast and does not show any convergence issues. The same work [17] proposes a multi-agent control for power balance or attaining economic dispatch based on Gauss method for systems with considerable power losses and where voltage regulation is expected. The proposed power flow algorithm makes use of communication time, and updates state information synchronously among agents. However, the convergence is reached after hundreds of iterations and it seems that power losses minimization is not considered within the OPF solution, moreover it cannot be applied directly to islanded microgrids (slack bus showing limited capacity). Finally, the paper in Ref. [18] solves the economic OPF for microgrids in a distributed manner accounting for power balance equations as constraints. In this case, an event-triggered distributed algorithm provides the solution. The latter can be implemented by dynamically adjusting the power set-point of each generator. In this way, the OPF problem can be converted into a sequence of unconstrained problems by adding to the cost function a penalty term that gives a high cost to unfeasible points. Each generator solves an optimization problem and requests information to neighboring states only if necessary (when event triggered). However, the approach does not account for losses and the example shows very limited size.

In Ref. [19], a distributed minimum cost energy management for scheduling of energy resources in a MG is proposed. In the formulation, the optimal operation of MGs takes into account the distribution network infrastructure and associated constraints. The energy management problem is formulated as a minimum production cost issue, where the MG Central Controller (MGCC) and the local controllers jointly compute an optimal schedule. In this case, the energy management problem is thus formulated as the solution of an OPF problem in different times.

Recent works consider distributed computations aimed at optimal reactive power flow management in distribution networks based on dual decomposition [20] and Alternating Direction Method of Multipliers (ADMM) methods [21]. However, there are cases for which the ADMM-based solution of the non-relaxed OPF problem fails to converge [22,23].

The latter works analyze the overall picture of OPF underlining the limits of the two main cathegories of OPF solution methods: those approximating the physical network model and those relaxing the space of solutions and/or control variables. The same works [22,23] recognize also a recently arisen third cathegory called Branch Flow Model methods (BFM) for which the network flows are described by using as variables the currents and the powers of the various network branches, instead of the nodal injections. The work in [23] proposes a distributed OPF that provides exact solution and can only be used for radial systems.

Very few works in MGs literature explicitly analyze the minimum losses issue considering a possible islanded operation and tuning both real and reactive power from generators. The work in [24] offers a nice distributed OPF for grid connected MGs considering smaller partitions, but still remains the problem of defining what is a good partition and moreover also [24] employs commercial solvers hardly usable on industrial microcontrollers.

In Refs. [25] and [26], the entire centralized OPF is formulated as a combination of sub-problems that is solved in a distributed manner by each bus. In particular, [26] proposes a consensus-based distributed OPF algorithm for optimal economic dispatch, which uses consensus algorithm to estimate the optimization variables between neighboring nodes in a given network. Agents at the buses run the algorithm. They own a portion of the power grid representation and solve a local optimization. The agent not only uses the voltage and power variables measured at local level, but also estimates the voltage and power variables coupled with the local power balance constraints. The agents exchange their local data and estimates with neighboring agents to create a correct estimation. To improve the estimation, a consensus filter is used to process the data shared among nearby agents. A penalty function-like method is used to minimize the local objective. However, the number of iterations seems to be quite large (200 iterations for 14 bus system), thus affecting computation time. Moreover, it is not clear when output power from generation buses/storage units should be changed, since there is no prove that all buses reach convergence at the same time. In Ref. [25], by means of an ADMM-based distributed algorithm using closed form solutions to the optimization sub-problems, fast and distributed solutions for real-time feedback control are obtained for balanced radial networks. However