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A review of optimal control techniques applied to the energy management and control of microgrids

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Abstract

This paper presents a literature review on optimal control techniques for energy management and control of microgrids. A classification of references linked with the design and development of optimal energy management systems (EMS) is made, considering mainly the objective functions to be solved and also the optimization techniques used for solving optimal control problems (OCPs) related with reliable operations of microgrids. A hierarchical control architecture for the development of EMS is the most commonly found in literature, which implies the necessity of a telecommunications infrastructure to communicate a distributed control layer with an upper layer, where the optimization of the microgrid operation is done. Typically, this layer is developed at an entity called microgrid central controller (MGCC). A general architecture for optimal EMS is provided and analyzed in detail, as well as its future perspectives.

Keywords: Energy management; microgrids; optimal control

1. Introduction

One of the biggest problems that mankind has to deal with is global warming and all the consequences related to it. Carbon dioxide emissions (CDE) have to be avoided as much as possible for which purpose drastic changes are urgently needed in the way fossil fuels are used. An important contribution in this field is being done by the increasingly use of renewable energy sources (RES) within power systems.

It is therefore important to contribute in topics associated to energy efficiency, which is linked with the concept of the smart grids (SGs). A broad range of definitions and opinions about SGs have emerged in the past decade and it seems as the perception of the future grid is more standardized now, which incorporates bidirectional telecommunication networks, distributed and centralized controllers, distributed generators and manageable loads, in order to offer an increased reliability, security, energy efficiency and a reduced rate of CDE\textsuperscript{1}.

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Microgrids are vital components of SG architectures, which are defined as low voltage (LV) and medium voltage (MV) systems with distributed energy resources (DER), storage devices (SD) and controllable loads (CL), connected to the main power system or isolated. During grid-connected operation of a microgrid it is possible to dispatch DERs active power considering an economic criterion since voltage and frequency regulation is performed at the main grid. In isolated mode it is necessary to control DERs to ensure voltage and frequency stability within the microgrid.

Several contributions on control strategies of microgrids have been made. Planas et al.\(^2\) provides details about the control tasks involved in the microgrids management with a review on the main types of controls proposed in the literature. In reference\(^3\) a comprehensive review about advanced control techniques applied to the microgrid control is presented within the framework of standards IEC/ISO 62264. Additional references\(^4\)\(^5\) present general concepts, architectures and main literature reviews about EMS for microgrids. These references do not consider important issues related to optimal control for developing EMS for managing microgrids, which motivated the literature review to be presented in this paper. This paper presents a literature review on optimal control techniques applied to the energy management and control of microgrids. A categorization of research papers in the area of design and development of optimal EMS found in the literature is presented, considering their objective function and the optimization method used to solve OCPs related with reliable operation of microgrids. The control architecture used in the EMS is hierarchical, which implies the necessity of a telecommunication infrastructure to communicate a distributed control layer with an upper layer, where the optimization of the microgrid operation is done. The entity which performs this operation is the MGCC.

2. Microgrid operation

Due to the high integration of cutting edge technology within a microgrid, it is a challenge to optimally operate in a coordinated way all the variety of devices installed in a microgrid. Fig. 1 shows a hierarchical control scheme for large power systems that has been adequate for the operation of bulk power systems (BPS), and whose details are presented in\(^6\). The operating characteristics of a microgrid are different from those of BPS with smaller generation inertia, variable power generation due to RES integration, low fault currents when islanded, etc. A potential hierarchical control of microgrids is discussed in\(^7\)\(^-\)\(^12\). In this context, the primary control is designed for controlling DG units to add virtual inertias and to control output impedances. Secondary control deals with corrections of steady-state errors in frequency and voltage magnitudes produced by the primary control loop. The tertiary control is conceived for energy management according to different design criteria, such as: microgrid stability, environmental issues, etc.

![Fig. 1. Hierarchical control scheme for power systems](image)

Consequently, to achieve an effective coordination of this hierarchical control scheme, a centralized microgrid control strategy is envisioned in\(^12\)\(^-\)\(^14\), where three controllers are mainly present, as shown in Fig. 2: 1) DER distributed controllers (DC), 2) Microgrid central controller (MGCC), and 3) Distribution management system (DMS).

DCs work at the device level (primary and secondary control) and are designed for a correct operation of every DER. Two levels of inertia in microgrids mean that every DC must be fast and reliable to maintain voltages, frequen-
cies and power flows within acceptable tolerances and to adapt in real time to unknown and variable loads and network conditions. At the MGCC level (tertiary control), the power management of the microgrid is determined based on the information from DERs active power, load demand and storage requirements. A two-way communication between the MGCC and the DCs allows the interchange of power references (set points) sent to the DERs and loads, while each individual DC ensures that the power reference from the central control level is reached. At the DMS level, overall grid demands and stability requirements are met.

Since the MGCC is responsible of the optimization of the microgrid operation, the optimal control techniques to be presented in next section are developed in this entity.

3. Optimal control techniques

Within the framework of environmental and economical issues, and microgrid stability, optimality is directly linked with the minimization of fossil fuels consumption (e.g. diesel generation), management of storage units and loads, and to warranty a reliable operation of the microgrid. An OPC needs to be established in order to include a customized cost function and constraints related to this reference framework. Generally speaking an OPC can be represented by:

$$\min_u f(u)$$
subject to
$$u_L \leq u \leq u_U$$
$$b_L \leq Au \leq b_U$$
$$c_L \leq c(u) \leq c_U$$

where $u$, $u_L$, $u_U \in \mathbb{R}^n$, $f(u) \in \mathbb{R}$; $A \in \mathbb{R}^{m_1 \times n}$; $b_L$, $b_U \in \mathbb{R}^{m_1}$ and $c_L$, $c(u)$, $c_U \in \mathbb{R}^{m_2}$, represent the control variable, upper and lower limits of $u$; cost function, matrix of linear constraints, upper and lower limits of the linear constraints; nonlinear constraints, upper and lower limits of $c(u)$, respectively.

Therefore, the OPC is related with finding the minimum of the real valued function $f(u)$ subject to the defined linear and nonlinear constraints in the continuous-discrete space. The optimal control techniques included in this review for controlling microgrids are classified according to the objective function to be minimized and the optimization method, as show in Fig. 3.
3.1. **Optimal power flow (OPF)**

The OPF problem becomes a challenging task in the microgrid operation, due to the RES variability and non-constant load demand, reverse power flows at the transmission-distribution boundaries, which results in an energy export from the distribution network to the transmission grid. Some papers deal with these issues, see for instance\textsuperscript{14,15}. A telecommunication infrastructure and the use of smart meters (SM) allow fast interchange of local measurements of power consumption and DER active power generation to feed power flow equations for which the main objective is to balance power production within the microgrid and the load demand. A modeling framework for microgrids with different control tasks is presented in\textsuperscript{16} where it is also shown that a set of feasible set points for OPF dispatch in a microgrid has a one-to-one correspondence with a set of reachable steady states by decentralized droop control. Reference\textsuperscript{17} presents a weighted-sum objective function for solving a multiobjective optimization problem within the OPF framework to a microgrid with multiple DG units and battery storage systems (BSS), through a niching evolutionary algorithm (NEA). In\textsuperscript{18}, a centralized controller is proposed which minimizes a quadratic power generation cost function while keeps constant for a frequency reference of the nodes of the grid involved in the minimization function; this result is compared with a distributed controller strategy. In\textsuperscript{19}, a control strategy is proposed for managing stored energy in order to optimize the overall microgrid power consumption at the point of common coupling (PCC) considering constraints imposed by the storage devices, voltage and limits, and power limits. Additional information on OPF techniques are presented in\textsuperscript{20–22}.

3.2. **Load shedding**

Severe power system disturbances can cause the available control actions not sufficient to maintain voltage and frequency stability. To counteract such system’s instability issues, special protective algorithms have been designed based on voltage and frequency limits, e.g. under voltage load shedding (UVLS) and under frequency load shedding (UFLS) schemes, which work in load shedding relays. An uncoordinated and non-optimal load shedding scenario is commonly performed in the system under these circumstances. This fact summed up with the necessity of a control strategy that guarantees a stable operation of a microgrid when it is operating in islanded mode motivates the researches presented in\textsuperscript{23,24}, where centralized load shedding strategies for preventing potential outages are designed.

3.3. **Economic dispatch**

Economic dispatch has been studied for the two operating modes of a microgrid: grid-connected and islanded. Non-autonomous operation optimization, regarding economic aspects is shown in\textsuperscript{25–27} where the main objectives are to maximize the local production of the DER units and the power exchanges with the main grid, while optimizing the cost production of the energy. Isolated operation of the microgrid presents several challenging aspects for optimizing
energy costs reduction, mainly due to the variability of power generated by RES and non-constant load demand, for which case predictors based on different algorithms, e.g. artificial neural networks (ANNs) assist the optimization techniques. Deeper details on economic dispatch for microgrids working in isolated mode are presented in 28–31.

3.4. Demand side management (DSM)

DSM permits energy users of all kinds to act as virtual power plants (VPP). By voluntarily lowering their demand for electricity based on some pricing scheme, these businesses and organizations help stabilize the grid, and they are paid for providing this important service. Utilities and grid operators treat demand response capacity as a dispatchable resource. In 32, an autonomous centralized strategy is proposed for DSM in a microgrid based on a multi-agent system. The microgrid is equipped with smart devices (entities), which obey the DSM strategy for scheduling the connection moments of shiftable devices in order to adjust the load consumption curve to an objective load consumption curve. Reference 33 proposes two different pricing schemes to predict the adoption of DSM in a microgrid through the use of a game-theoretical framework. A similar approach, using a game-theoretic perspective which attracts the participation of the users through economic incentives, is detailed in 34.

3.5. Carbon dioxide emissions reduction

CDE reduction is one of the principal goals of the SG architectures. In this context, apart from guaranteeing a stable operation of the microgrid, whether it is operating grid-connected or isolated, some research papers have prioritized in their cost function of the optimization algorithm and constraints, variables directly linked with CDE to be minimized, as detailed in 35–38.

3.6. Predictive optimization

The model predictive control (MPC) algorithm has the capability of performing a constrained minimization of a customized cost function over a prediction horizon, based on a system model that predicts the future behavior of the system to find an optimal control sequence, which is used for reaching the control objectives. Details on the MPC algorithm can be found in references 39,40. There are some research papers related to the development of EMS for microgrids with MPC 41–46. For instance, in 41,42 a distributed control strategy managed by a supervisor MPC is proposed for manipulating the DERs set points online, which guarantees an optimal energy balance in the microgrid. In 43, a supervisory MPC is designed for optimal power management and control of a hydrogen-based microgrid. Olivares et al. 44 proposes a centralized EMS with MPC, which optimizes the dispatch of the energy in storage units, as well as decomposes the energy management problem into two problems: unit commitment and OPF in order to simplify the optimizer performance.

3.7. MILP

Mixed-integer linear programming (MILP) deals with optimization problems in which only selected variables are integers, while the remaining variables are non-integers. Since the number of DERs to be managed in microgrid architectures is an integer number, MILP fits perfectly for this application. Morais et al. 47 uses MILP to search the optimal operation of a wind turbine (WT), a solar unit, a fuel cell and a battery in a microgrid. In 48,49, a centralized DSM strategy is presented to provide online set points for the DG units, operation modes of a water supply system and control signals for consumers, through the minimization of operational costs while keeping energy balance. A forecasting unit for load and generation prediction assists the EMS. The EMS includes non-linear constraints associated to the modeling of both units, and objective function. These constrains are represented by piecewise linear models, binary variables, etc. The optimization problem is solved using MILP ensuring the near-optimality. Additional information of MILP applied to EMS in microgrids is detailed in 20,50,51.

3.8. Non-classic optimization techniques

Several other optimization techniques for similar purposes are listed below:
4. Discussion

Centralized EMS for microgrid control is a non-standardized control architecture that is maturing thanks to the contributions of the scientific and industry community related to the SGs technology development. Distributed controllers commanding DG units for primary and secondary loop control are of vital importance for a good performance of an EMS, since typically the optimization procedures are developed at this level of the control hierarchy prior to sending online set points to the DCs through the telecommunication infrastructure. A general structure of an EMS for a microgrid with DERs is shown in Fig. 4, where it is remarkable the necessity of a load forecasting unit and a RES power generation predictor to guarantee a reliable energy balance in extended periods (overall under changing weather conditions), an increased RES power production in order to decrease CDE, an adequate energy storage and its usage, as well as competitive prices that allow load scheduling scenarios.

Since a centralized controller is used, an advanced metering infrastructure (AMI) is required in the microgrid. Therefore, it is assumed that every load has an SM. The SM performs instantaneous voltage, current and power measurements, energy measurements, and power quality data, and has communications capability. Operating microgrids around the world demonstrate that this control architecture is suitable for a sustainable, long-term and scalable operation.

5. Conclusions

Despite of the optimization technique used to solve the OPC, a basic requirement of the microgrid control is to assure a proper balance between the power generated within a microgrid and the demand load to avoid instability problems in the microgrid operation. There is a variety of optimization techniques to design an optimal energy management and control system for microgrids, ranging from classic optimization techniques, e.g. minimization of a simplified linear optimal control problem through a least square minimization algorithm to complex, predictive, and multi-objective optimization techniques. From the predictive perspective, MPC is attractive for managing microgrids.
due to its ability to operate based on future behaviors of the system. In problems related with power scheduling, which depend on forecasted values of demand and RES production, the MPC method would be very effective.

Additionally, the increasingly less inertia present in a microgrid should be carefully considered. The objective of the droop control is to compensate for instantaneous mismatch between scheduled power and power demanded by loads. A DG unit can maintain its power generation (constant if possible) whenever a master generation unit or the main grid handles the power mismatch. If two or more DER units participate in grid stabilization and voltage regulation, the frequency-droop and voltage-droop control strategies should be used.

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