A Centralized Optimal Energy Management System for Microgrids

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Abstract—The issue of controlled and reliable integration of distributed energy resources into microgrids and large power grids has recently gained considerable attention. The microgrid concept, which basically corresponds to the coordinated operation of a cluster of loads, distributed generators and energy storage systems, is quite appealing due to its flexibility, controllability and energy management capabilities. In order to provide uninterruptible power supply to the loads, microgrids are expected to operate in both grid-connected and stand-alone modes, and economically meet the demand on an instantaneous basis. The problem of optimal management of the resources in a microgrid is being widely investigated and recent studies have proposed the application of both centralized and distributed control schemes by using multi-agent systems, heuristic methods and optimization algorithms. This paper elaborates on the conceptual design of a centralized energy management system (EMS) and its desirable attributes for a microgrid in stand-alone mode of operation. A number of test protocols are proposed to analyze the performance of the system, as well as the impacts of relevant parameters.

Index Terms—Microgrids, distributed generation, energy management systems, multi-stage optimization.

I. INTRODUCTION

Helped by deregulation processes in the energy sector, and encouraged by the implementation of additional incentive policies, the small-scale distributed energy resources (DER), many of them based on renewable energies, have experienced an unprecedented growth in the last couple of decades. Because of this, important efforts have been made in the energy sector in order to develop appropriate technologies and techniques for the reliable and economic exploitation of the renewable energy sources, and its integration into power systems.

One of the main technical issues to be addressed in the process of integration is the control and management of the non-dispatchable renewable energy sources, like wind and solar energy, which feature somewhat unpredictable behaviour. Another major concern is the assessment of the impact of such sources on the overall grid security and reliability. Also, there is a need for re-engineering the protection schemes at the distribution level, to cope with the bidirectional power flows and take advantage of the fast response of power electronic devices commonly used for the grid connection of distributed energy sources.

Although small autonomic grids have existed for many decades, the concept of microgrid was first introduced in [1], [2] as a solution for the reliable integration of DER and for harnessing their multiple advantages. A microgrid can be described as a cluster of micro-sources, energy storage systems (ESS) and loads that is perceived by the main grid as a single element that can respond to centralized control signals. Special protection, control and energy management systems must be designed for the microgrid operation in order to ensure reliable, secure and economical operation in either grid-connected or stand-alone mode. In particular, the problem of energy management in a microgrid gains more relevance with the presence of highly-variable energy sources, where the update rate of the unit dispatch command should be fast enough to follow the sudden changes of load and non-dispatchable generators, with time constants close to those of the control system.

The problem of energy management in microgrids consists on finding the optimal (or near optimal) unit commitment (UC) and dispatch of the available generators so that certain selected objectives are achieved. A commonly pursued objective for stand-alone mode of operation is to economically supply the local load [3], whereas under grid-connected mode of operation the maximization of profits is typically sought [4]. Additional objectives such as the minimization of greenhouse gas emissions of the microgrid have also been proposed in [3] and [5] by applying heuristic and multi-objective optimization techniques.

With regard to the architecture of the energy management system (EMS), two main approaches have been proposed to date in the technical literature: (i) Centralized EMS (CEMS) and (ii) Distributed EMS (DEMS). The CEMS architecture consists of a central controller provided with the relevant information of every distributed energy resource within the microgrid and the microgrid itself (e.g., cost functions, technical characteristics/limitations, network parameters and mode of operation), as well as the information from forecasting systems (e.g., local load, wind speed, solar radiation) in order to determine an appropriate UC and dispatch of the resources according to the selected objective. On the other hand, DEMS provides a market environment through the use of Multi-Agent Systems (MAS) where each microgrid agent sends buying and/or selling bids to a Central Microgrid Operator (CMO) according to their particular needs and cost structures; the CMO then performs a binding process to determine the operation of the microgrid for the next period. In this case, a separated UC process must be realized to determine the agents that will operate in each particular period. In this paper, the characteristics of the existing EMS.
II. MICROGRID EMS

A few cases of CEMS have been discussed in the literature, taking into account varied microgrid characteristics and configurations. A general framework for the development of CEMS is proposed in [6], while a CEMS for a microgrid composed of hydrogen storage and wind power, utilizing a dynamic linear programming (LP) formulation is presented in [7]. An LP solution technique together with heuristics is proposed in [8] for the implementation of a CEMS for a PV-storage microgrid, while [3] proposes a purely heuristic optimization approach. Different evolutive algorithms for optimization are also applied to the CEMS problem in [9] and [10].

A typical CEMS architecture is shown in Fig. 1, where a central agent collects all the relevant information from the different microgrid actors to perform an optimization and determine the inputs of the control system for the next period. Depending on the particular resources present in the microgrid, the input variables of the CEMS can be:

- Forecasted power output of the non-dispatchable generators for the following N consecutive periods.
- Forecasted local load for the following N consecutive periods.
- State of charge of the ESS.
- Operational limits of dispatchable generators and ESS.
- Security and reliability constraints of the microgrid.
- Interconnection status.
- Main grid energy price forecasting.

Once all the input variables are gathered in the CEMS, a multi-stage optimization is performed in order to determine the optimal dispatch of units according to a defined cost function, over a pre-specified time frame. Output variables of the EMS are the reference values of the control system (e.g., output power and/or terminal voltage) for each dispatchable DER, together with binary decision variables for connecting or disconnecting loads for load shifting. An additional output variable is the UC decision of the dispatchable generators (if required); however, this problem can be solved at a lower frequency than the dispatch, and separately.

The main advantages of the centralized approach are: allowing for a broad observability of the microgrid, and suitability for application of optimization techniques. Some of its disadvantages are: reduced flexibility, as it needs to be modified to incorporate additional generators, and extensive computational requirements to perform the optimization.

B. Distributed (Multi-Agent) EMS

A DEMS based on MAS for microgrids was first proposed in [11] as an alternative for coordinated operation of microgrids in a competitive market environment and with multiple generator owners. The relevant microgrid actors are grouped and represented by different agents that interact in a market environment in order to determine the operation of the microgrid. In this way, consumers, generators, ESS and the main grid participate in the market by sending buying and selling bids to the CMO based on their particular needs, availability, cost functions, technical limitations, expectations and forecasts. The CMO is responsible for the settlement of the microgrid market by matching buying and selling bids maximizing the social welfare, while ensuring the feasibility of the resulting operation plan. A similar MAS approach is also proposed in [12]. Additional agents assigned to different tasks such as load shifting and load curtailment to allow demand side management are proposed in [13] as well.

The MAS-DEMS approach allows almost autonomous operation of the generating units in a microgrid, and reduces the need for manipulation of large amounts of data, thus reducing computation time. Another important advantage of DEMS is its flexibility, as it provides the plug-and-play feature, facilitating the installation and coordination of additional DER in the microgrid. On the other hand, DEMS based on MAS shows disadvantages compared to CEMS when applied to microgrids that require strong cooperation between the different DER in order to operate the system in a secure and reliable way. A typical DEMS model for a microgrid operating in grid-connected mode is shown in Fig. 2.

In the case of isolated microgrids operating in stand-alone mode, the small number of generators in the microgrid and the uneven share of installed power, as well as the lack of a strong
price signal from the main grid, make a DEMS more difficult to implement.

III. TYPICAL MICROGRID CONFIGURATION

Although microgrids can be located close to or within the main grid and be operated in grid-connected mode, the microgrids of interest for this work correspond to isolated, locally-operated systems that can be found in remote locations with accessibility problems, and where the connection to the main grid of electricity is not feasible, either for technical or economical reasons. Thus, the particular microgrid configuration considered here, embodies multiple DER such as wind generators, PV solar arrays, diesel generators, microturbine CHP, Fuel Cell-Electrolyzer ESS, thermal storage, and both electrical and thermal loads. A microgrid with the aforementioned components connected in a typical radial configuration is shown in Fig. 3.

Loads that have a defined energy consumption that can be supplied with certain flexibility over a period of time are referred to as “shiftable loads”, as they can be shifted by the EMS to the most convenient period. A broader description of various microgrid components is provided next.

A. Fuel Cell-Electrolyzer ESS

In order to fully embrace the benefits of renewable energy sources, it is indispensable to have an ESS capable of dealing with intra-day variations of generation. Fuel Cell-Electrolyzer ESS offers interesting benefits for long term energy storage, as it can consume electricity to produce hydrogen, store hydrogen without time limitations, and consume hydrogen to generate electricity, which makes the operation of the system more flexible. Furthermore, these hydrogen conversion processes generate significant amount of heat [16]. However, one of the main drawbacks of this technology is its low round-trip efficiency (energy input-hydrogen-energy output) which is in the range of 30-40% [14], [15], and costs [16]. Constraints on the operation of this ESS are typically the maximum and minimum power output, minimum state-of-charge of the hydrogen tank and ramp rates.

B. Wind Turbines

A wide range of levels of penetration of wind power can be observed in existing microgrids; however, only wind turbines with a significant share of the microgrid peak load are relevant for the operation of the EMS. Different levels of penetration, wind speed profiles and wind turbine characteristics should be considered.

C. Diesel Generator

Mainly due to its flexibility, remote and isolated power systems usually rely on the operation of diesel generators to supply the local load. Although at a very expensive rate in this case, this generator is typically able to supply the peak load on its own, without the need for further energy sources. When considering time frames in the order of minutes, the operation of diesel generators is constrained by their power output limits, power ramp-up and -down rates and start-up time.

D. PV Panels

Together with wind turbines, PV systems are one of the fastest growing renewable energy sources. Although both are based on non-dispatchable energy sources, the PV panels usually have a more easily predicted power production. Different levels of penetration, real solar radiation profiles and PV panel characteristics should be considered.

E. CHP Microturbine

Gas microturbine technology has promising CHP applications within microgrids, as it can achieve overall efficiencies of around 65% when adding a heat recovery cycle.
to the conventional power generation. In small sizes, this technology shows a high operational flexibility, with start-up times of around 3 minutes, and shut-down times of approximately 10 minutes [17]. Its operation is constrained by ramp-up and -down rates, start-up and shut-down times, and minimum power output; additionally, auxiliary power needs to be provided from the grid during the initial part of the turbine warm-up [17].

**F. Thermal Storage**

Heat recovery and storage in form of hot water in isolated accumulator tanks is a simple and efficient way to store thermal energy from CHP plants for intra-day regulation [18], as water offers a good heat recovery capacity per cubic meter, and heat losses can be kept at minimum with a proper tank design. The maximum and minimum storage capacities constrain the operation of the tanks.

**G. Shiftable Loads**

Typically heating and cooling systems can be operated with some flexibility over time, such that the power requirements can be shifted to different times without significant performance degradation. The incorporation of shiftable loads into the microgrid is expected to produce an impact similar to the addition of more energy storage capacity, allowing a more flexible operation of the microgrid.

**IV. PROPOSED EMS ARCHITECTURE**

Depending on whether a microgrid is to be operated in grid-connected or stand-alone mode, the most suitable EMS architecture and objectives may be completely different. As discussed in Section II, the particular characteristics of CEMS make them more suitable for implementation in microgrids operating in stand-alone mode, as they are more likely to provide continuous operation of the system while dealing with variable generation and load, without main grid support. Hence, a in order to perform the coordinated operation of the isolated microgrid described in the previous section, a CEMS architecture is proposed here.

The interaction between the different control modules within the microgrid is illustrated in Fig. 4. The control system block represents the individual control stages of each DER that keep the balance of active power and regulates the voltage in the microgrid. The control system of power-electronics-interfaced (no-inertia) microgrids is typically based on the implementation of droop controllers that emulate the behaviour of synchronous generators against changes in the frequency and voltage of the grid [20], [21].

The proposed EMS embodies two main blocks: a multi-stage Economic Load Dispatch (ELD) block and a UC block. The EMS also requires input from a load and generation forecasting system. The different blocks of the proposed architecture are discussed in some details next.

**A. Generation/Load Forecasting**

The generation and load forecasting system must provide, with two different resolutions, forecasted values of output powers from renewable energy sources and total microgrid load. A high resolution in the order of a few minutes over a horizon of hours is required by the multi-stage ELD block, while a lower resolution in the order of 30-60 minutes over a horizon of tens of hours is required by the UC block.

**B. Multi-Stage Economic Load Dispatch**

The multi-stage ELD performs the calculation of optimal dispatch for DER over a horizon $H_{ELD}$, with a time step $T_{ELD}$, considering a fixed group of on-service units that will be provided by the UC block. The UC block also provides the boundary conditions for the two ESSs at the final time step of the ELD, as it has a more extended visibility of load and generation profile patterns. The ELD calculation is carried out for each time step $T_{ELD}$ so that, although it is calculated over a horizon $H_{ELD}$, only the dispatch calculated for the immediately following time step is used as reference for the control system, and the dispatch for next time steps is updated during the next iteration. Even when the UC and ELD problems can be solved together, they are separated in order to speed-up the ELD calculation and achieve faster update rates for dispatch. As the UC block delivers the ESS state-of-charge boundary conditions with a different time resolution, the multi-stage ELD calculation considers a linear interpolation of the values provided by the UC.

The off-line calculation of the optimal dispatch for each possible demand scenario of a microgrid is discussed in [19], where the optimal dispatch for each condition is stored in a static look-up table or operating chart. However, several drawbacks are identified in this approach regarding the inability to handle variable conditions. In particular, the presence of ESS in the microgrid introduces a time-dependence in the calculation of the optimal dispatch, as the state-of-charge of the ESS at a given time-step will depend on the state-of-charge and dispatch at the previous step; therefore, the optimal dispatch is not solely determined by a particular demand scenario. To manage this time-dependence, a dynamic optimization of the microgrid operation is required.

**C. Unit Commitment**

The UC block calculates the optimal schedule of the DERs over a horizon $H_{UC}$, with a time step $T_{UC}$, and at least $H_{ELD}$ in advance of the next period, such that there is always a defined UC for the ELD calculations. The outputs of this block are the start-up and shut-down decisions for each dispatchable DER in the microgrid, together with the optimal dispatch of units and ESS state-of-charge for each time step, according to the forecasted values.
The coordinated operation of UC and multi-stage ELD blocks, and the overlapping of consecutive ELD calculations is illustrated in Fig. 5, where each vertical line (long lines for UC calculation and short lines for ELD calculation) represents the instant at which calculations take place, and the dotted lines indicate the operating period for which the calculation is being performed. A more detailed time scale of the calculations is depicted in Fig. 6.

V. PERFORMANCE AND CALIBRATION PROCEDURES

A number of procedures to comparatively evaluate the performance and fine-tune the proposed EMS architecture are proposed in this section.

A. Multi-stage ELD horizon vs ESS capacity

The only reason to perform a multi-stage ELD calculation and not a single-stage ELD after the UC is the presence of ESS in the microgrid. As the ESS capacity of the microgrid increases, the link between the operations in consecutive time steps becomes stronger; therefore, a more extended horizon for multi-stage ELD ($H_{ELD}$) must be chosen, slowing-down the calculation process and imposing a lower limit on the time step between consecutive ELD calculations ($T_{ELD}$).

In order to determine the most suitable $H_{ELD}$ for a particular microgrid, a study must be performed to find an optimal balance between the dispatch accuracy and calculation speed. Thus, a low $H_{ELD}$ values would not allow a correct use of the ESS capacity, while high values would increase the calculation times and introduce increasing errors from the forecasting system. This would lead the microgrid operation to deviate from the optimal condition, and therefore would increase the total operating costs. The trade-off in the selection of $H_{ELD}$ is illustrated in Fig. 7.

B. Impact of Forecasting Accuracy

The accuracy of the load and generation forecasting system plays a very important role in the performance of an EMS, as poor forecasting accuracy would lead to deviations from optimal operation of the microgrid. An EMS that strongly relies on the forecasting system outputs is not desirable; moreover, an EMS design should be robust against extended forecasting errors.

To evaluate the robustness of the EMS against forecasting errors, the following three different forecasting scenarios were proposed in [7], which will be adopted in this work: persistence model (worst case), perfect forecasting (best case) and uncertain forecast (realistic case). Although a lower performance is expected from the scenarios without perfect forecasting, the EMS should be able to reduce the loss-of-load risk to acceptable levels. Similarly to the case of large power systems, a trade-off will exist between the acceptable loss-of-load probability of the microgrid, the accuracy of the forecasting method, and the operating costs.

VI. CONCLUSIONS

This paper has presented a brief review of the existing energy management system (EMS) architectures for microgrids, identifying the main advantages of each approach, and has proposed a centralized EMS architecture for implementation on isolated microgrids in stand-alone mode of operation. Some relevant considerations and procedures for the model fine-tuning and performance evaluation have also been presented. Future work will concentrate on the implementation and testing of the proposed architecture.

VII. REFERENCES


**VIII. BIOGRAPHIES**

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