ADVANTAGE

Advanced Communications and Information processing in smart grid systems

MARIE CURIE ACTIONS -7th FRAMEWORK PROGRAMME

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WP3 D.3.1

State of the Art in Micro Grids and Definition of Application Scenarios and Research Problems

Abstract:	This deliverable describes the initial literature review and research directions for WP3 of the ADVANTAGE project. This WP will focus on the topic of microgrids, which are distributed clusters of power generation and loads. The first topic to be studied will consider how distributed microgrids can provide demand response functionality to tackle problems in the wider grid network. The second topic relates to intelligent control of microgrids to integrate renewable energy sources into the wider network. Finally, novel communication or bus signaling methods which use properties of the power waveform itself in very simple microgrid configurations will be evaluated.
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1 INTRODUCTION TO WORK PACKAGE THREE: MICRO GRIDS

The evolution of the traditional power grid towards smart grids involves the grid decentralization into microgrids. A microgrid is a cluster of generators (typically from renewable energy resources), storage systems and loads, which is capable of operating independently (i.e., in an islanded mode) and connected to the rest of the grid. Microgrids allow for easier incorporation of distributed energy resources, like wind and solar power generators, as well as more robust and stable operation.

As a small scale electrical network, reliable and efficient microgrid operation involves issues typical for the traditional power grid, but also challenges that did not exist previously. The latter are due to (i) the unstable and unpredictable nature of the renewable energy resources, (ii) the decentralization of the grid structure and (iii) the introduction of the ancillary services and new market incentives.

The work in this WP deals with these novel aspects of microgrid operation, embodied in (currently) three ESR PhD projects:

(1) Smart Demand Response from Industrial & Commercial Microgrids (Gautham Krishnadas, ESR6),

(2) Facilitating Integration of Distributed Photo Voltaic Farms (Ruben Lliuyac, ESR7),

(3) Advanced Bus Signalling Methods in Micro Grids (Marko Angjelichinoski, ESR9).

The aim of the project "Smart Demand Response from Industrial & Commercial Microgrids" is to explore the possibilities of implementing demand response services in industrial and commercial microgrids, which include provision of short term operating reserves, frequency response, wind following, etc. These services are typically realized by tuning the operation of distributed energy resources according to price fluctuations and/or other market incentives.

The project "Facilitating Integration of Distributed Photo Voltaic Farms" deals with the control aspects of the microgrids in the grid-connected and islanded mode, as well as in the transient mode of operation. These control aspects can be divided in primary control that deals with stable operation, secondary control that maintains frequency and voltage at their nominal values, and tertiary control that ensures optimal operation.

Finally, the project "Advanced Bus Signalling Methods in Micro Grids" explores the possibilities of transferring information among microgrid elements using the electrical interfaces and bus interconnections. The motivation is to avoid using separate communication networks and/or devices, and instead rely on the existing electrical equipment. The candidate scenarios in which power bus signalling can be used are exchanges of short messages related to the state of charge of the distributed storages, or voltage and frequency levels, which could be used in microgrid control algorithms.

2. SMART DEMAND RESPONSE FROM INDUSTRIAL & COMMERCIAL MICROGRIDS

2.1 INTRODUCTION

Microgrids include cluster of distributed energy resources (DERs) such as distributed generation (DG), storage units and flexible loads which are grid connected. Industrial and commercial microgrids comprise DG units based on combined heat and power (CHP) systems, diesel generators, photovoltaics; storage possibilities within pumped water reservoirs, thermal/cold stores, electric vehicles; flexible loads such as air-conditioners, greenhouse grow-lights, among many others [1-2]. Demand response refers to changes in normal operation of DERs induced by price signals or incentives from the electricity market. These changes represent decrease/increase of generation/consumption and help maintain supply-demand balance in the electricity grid [3-4].

Due to their flexible, distributed and remotely-controllable nature, microgrids can participate in demand response services such as providing short term operating reserves (STOR), frequency response, wind following, triad management, etc. Industrial and commercial microgrids within greenhouses, data centers, landfill sites etc. are involved in grid balancing services due to possibility of increased revenue without compromising their own site specific energy requirements. This is diagrammatically represented in Figure 1. Conventional demand response mechanisms, however, have not yet exploited the absolute potential of microgrids in providing these services and also maximising revenue for the owners.

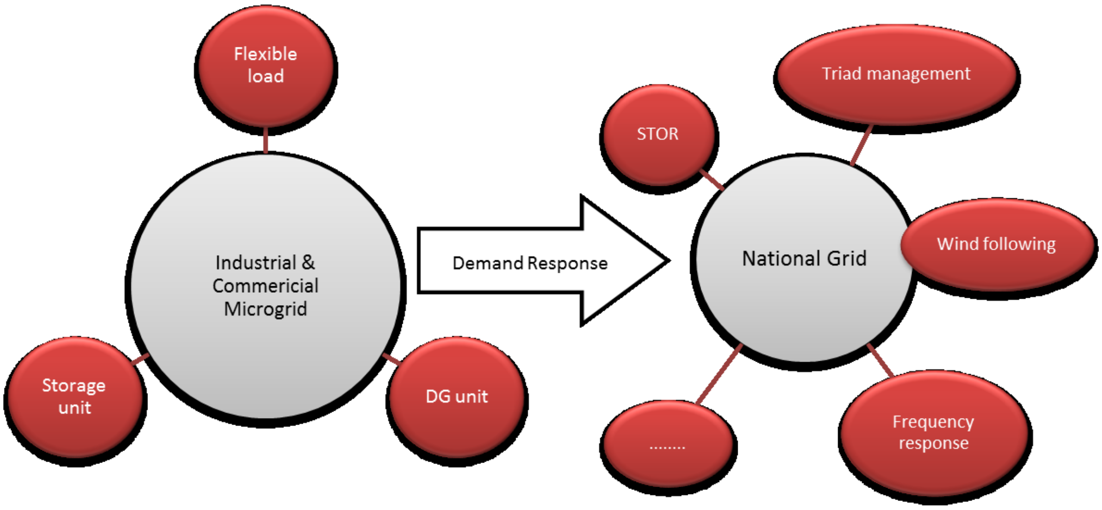

Figure 1: Demand response from industrial and commercial microgrids

2.2 SMART DEMAND RESPONSE METHODS

Studies on smart demand response methods such as fine-tuned forecasting of DER availability, aggregation, real-time manipulation of DERs, profit maximization, risk reduction, etc. for industrial and commercial sites are found in the literature. While this literature does not always focus on microgrids, the techniques employed motivate the present research.

Mohagheghi and Raji [3] in their research states that demand response from industrial processes requires a more sophisticated approach due to production constraints, inventory constraints, maintenance schedules, crew management, etc. Hence an intelligent fuzzy logic system to curtail load in the site based on operational constraints of the industrial site in near-real time was developed. Such an approach expands the potential of industrial process units in grid balancing services.

Alipour et al. [6] in their study of demand response from commercial and industrial combined heat and power (CHP) units considers electricity price and demand as stochastic processes. These variables are forecasted in a differential autoregressive moving average (ARMA) model, while profit maximization and risk minimisation are taken into account in order to generate operational schedules for the units in grid balancing services.

Riveros et al. [7] focused on day ahead scheduling of aggregated micro-CHP units based on electricity price and demand for system balancing services. In addition, optimization using a model predictive control method is employed to reschedule the operation of aggregator so as to compensate the total system imbalance in near real-time and obtain extra revenue.

Sun and Li [8] developed a dynamic power control model for effective real-time electricity demand response for a typical manufacturing system under a Markov Decision Process framework. This analytical model identified the optimal energy control actions and estimated the potential capacity of demand reduction based on online information of typical manufacturing systems during the period of demand response event without compromising system production.

3. FACILITATING INTEGRATION OF DISTRIBUTED GENERATION

3.1 INTRODUCTION

Variable energy resource (VER) generation such as wind and solar are widely spread in many power systems all over the world. The level of VER penetration is so significant for many countries that it can be accounted over 25% of the installed capacity in some cases [9]. Moreover, their penetration are expected to be still increasing by 3.2%/year on average due to technological advances and favorable policy incentives [10]. A lot of VER penetration are located into distribution networks as distributed generation (DG). In 2012, 39% of the total capacity addition was invested in DG installations, and that trend is expected to continue [11].

In the integration of DGs into distribution networks there are many challenges from the point of view of planning, operation and control [12]-[13]. The microgrid concept aims to simplify the solution for the integration of large penetration of DG by decentralizing the operation and control from the main grid to the microgrids. A microgrid can be defined as a cluster of DGs, storage systems and loads (lately loads tend to be controllable). The operation of a microgrid depends on the type of technologies of DGs, storage systems and loads, but also on the condition of the microgrid whether it is in grid-connected or stand-alone mode with respect to the host grid.

So far, when a microgrid is disconnected from the host grid (due to faults, maintenances, etc.) all DGs within the microgrid are disconnected due to the inexistence of a proper frequency control that can handle generation and consumption balance during autonomous operation. Thus, renewable generation are wasted. During grid- connected mode it is desired to control the active and reactive power flow between the microgrid and the host grid in order to improve the energy management in the whole system. However, the transition between the two modes must be handled properly in both directions: connection or disconnection from the host grid. Therefore, implementing control strategies for microgrids will support the integration of DG into the grid, exploit the production of renewable energy and make more efficient use of electricity.

Control strategies have to be able to deal with frequency/voltage regulation for the two operating modes, power flow control between microgrid and main grid, proper power distribution between DGs, and optimal power management for microgrids in both modes [14].

3.2 HIERARCHICAL CONTROL OF A MICROGRID

The control structure adopted in this work is based on hierarchical approach which consist of three levels namely primary, secondary, and tertiary [14]-[18]. Primary control is responsible to stabilize frequency and voltage and control the distribution of active and reactive power among DGs. Secondary control deals with the restoration of frequency and voltage to their nominal values. Finally, tertiary control ensures optimal operation in both operating modes.

3.2.1 ZERO-LEVEL CONTROL

DGs are usually connected to the grid through power electronic interfaces that include DC/AC converters. These converters can be operated in two modes: current source inverter (CSI) or voltage source inverter (VSI).

In CSI mode, the inverter supplies a given active and reactive power reference points. Active power set point is subject to power availability from the primary resource (wind, sun, etc.), while reactive power is predefined either locally or through a central control [19]. In VSI mode, the inverter seeks to control predefined frequency and voltage, which is the reason it is usually connected to a storage systems. When a VSI is connected to the host grid, where frequency and voltage are fixed, VSI can supply desired active and reactive power [20]. Nevertheless, it is usual to have a converter in CSI mode when it is in grid-connected mode, while VSI are more needed in stand-alone mode to keep the frequency and voltage in a microgrid [16]. Both modes of operation are based on inner control loops, also referred to as zero- level control.

3.2.2 PRIMARY CONTROL

In order to avoid circulating current when more than one VSI are operating in parallel two strategies have been adopted [21]:

Active Load Sharing

This method was first thought for paralleling UPS units that operate close to each other [21]. The strategy consist on making the output current of each converter to be equal or at least proportional to its nominal power rating. Current reference point is determinate through different approaches such as centralized [22], [23], master-slave [20], average load sharing [24], [25]. In a microgrid, where its elements might be separated by several kilometers, using this method might require large communication infrastructure through all the grid which makes this application unfeasible for some cases. To overcome this problem, droop characteristic method was proposed.

Droop Characteristic

The droop control method is based on local measurements, then it does not require communication infrastructure between DGs. The idea of this method is to control power distribution among different DGs within a microgrid by emulating the droop control characteristic of a synchronous generator. The grid impedance influences on the droop control method by its inductive and resistive components.

High voltage networks are inductive, medium voltage is a mix between inductive and resistive, while low voltage are mainly resistive.

First, if resistive component is neglected and only inductive is taken into account, frequency decrease with the increase of output active power, and voltage amplitude decrease with increase of reactive output power. This principle can be integrated in a VSI by using the following mathematical formulation [17]:

$$f = f^* - k_P(P - P^*)$$

$$E = E^* - k_Q(Q - Q^*)$$

Where f and E are the frequency and voltage amplitude of the VSI's output, f^* and E^* are their references, P and Q are active and reactive power delivered, P^* and Q^* are their references, and k_P and k_Q are the droop coefficients which are based on the converter power rating and maximum voltage and frequency deviation. Nevertheless, these coefficients can also be optimal designed by using some heuristic techniques such as particle swarm optimization or genetic algorithms [18].

On the contrary, if only resistive component is taken into account, the frequency decrease with the increase of output reactive power, and voltage amplitude decrease with increase of active output power. This can be expressed as:

$$E = E^* - k_P(P - P^*)$$

$$f = f^* + k_Q(Q - Q^*)$$

In the general case, that is taken into account both resistive and inductive components, the droop control can be modified by using park transformation [17], then it can be written as:

$$f = f^* - k_P\frac{X}{Z}(P - P^*) + k_Q\frac{R}{Z}(Q - Q^*)$$

$$E = E^* - k_P\frac{R}{Z}(P - P^*) - k_Q\frac{X}{Z}(Q - Q^*)$$

Where R and X are the resistive and reactive component of the Thevenin equivalent impedance from the VSI's eyes.

As it has seen above, conventional f-P and v-Q droop control strategies cannot be applied to medium-low voltage level, where the resistive component cannot be neglected. Potential solutions have been discussed in the literature to overcome this issue. The virtual power method consists of an orthogonal linear transformation matrix which transfer active and reactive power (P, Q) to a new reference frame (P', Q') where resistive and inductive components are decoupled [26]-[27]. A similar method was present using frequency and voltage frame transformation [28]-[29]. Overviews of some of the aforementioned methods are presented in [14], [18]. However, an outstanding solution is the introduction of the called "virtual impedance" within the primary control [30], [31]. The virtual impedance's function is to regulate power sharing among different VSI by modifying their voltage references as the next equation shows [17]:

$$v_{ref} = v^*{}_{ref} - Z_v i_{grid}$$

It is important to point out that the value of Z_v should be larger than the actual line impedance so that its effect ensure inductive behavior within the inner control loops [19].

3.2.3 SECONDARY CONTROL

The secondary control is a centralized control related to each microgrid. This control level is expected to restore frequency and voltage to their nominal values once primary control was happening, thus, the dynamic response of secondary control is slower than for primary. In the secondary control structure, frequency and voltage output of VSI unit are compared with the corresponding references values, w^* and E^*, respectively (in grid-connected mode these references are set by the main grid). Controllers process their input signals as follows [17]:

$$\Delta w = k_{Pw}(w^* - w) + k_{Iw} \int (w^* - w)dt + \Delta w_s$$

$$\Delta E = k_{PE}(E^* - E) + k_{IE} \int (E^* - E)dt$$

The coefficients k_{Pw}, k_{Iw}, k_{PE} and k_{IE} are the controller´s parameters and, Δw_s is a synchronization term that is zero during stand-alone operation, while during synchronization to the main grid it provides an additional input to the secondary control in order to facilitate the synchronization process. The introduction of participation factors (pf_0, pf_1, .. pf_n) will allow the desired distribution of power among the DGs.

3.2.4 TERTIARY CONTROL

Tertiary control is responsible for the economical and reliable operation of the microgrid, it is also referred as energy management system (EMS), whose purpose is to find the optimal generation schedule for available DG units for both operating modes.

In grid-connected mode the concern lay on maximizing revenues by finding optimal set-points of DGs according the requirement of the main grid, bids and market prices [32]. Normally, wind and solar generation power within the microgrid are totally used, whereas mismatches within the microgrid are supplied by the main grid. Some works have proposed unit commitment (UC) for a microgrid operating in stand –alone mode, where stochastic techniques were used to deal with intermittent nature from non-dispatchable generators [32]-[34].

When the microgrid is in grid-connected mode, the power are controlled by adjusting the frequency and voltage amplitude, inputs of the secondary control, through PI controller based on next expressions. The coefficients k_{Pw}, k_{Iw}, k_{PE} and k_{IE} are the controller´s parameters. Whereas, in stand-alone operation the generation dispatch is result of UC process.

$$w^* = k_{PP}\left(P_{ref} - P\right) + k_{IP} \int (P_{ref} - P)dt$$

$$E^* = k_{PQ}\left(Q_{ref} - Q\right) + k_{IQ} \int (Q_{ref} - Q)dt$$

4. ADVANCED BUS SIGNALLING METHODS IN MICROGRIDS

4.1 BACKGROUND

As discussed, the notion of control is central in MGs [35]-[39] because the power exchange between DERs, loads and the main grid should be balanced and the overall operation of the MG should be optimized and stable. The coordinated control can be achieved by various techniques ranging from a centralized to a fully decentralized and distributed solutions [40]. The control mechanisms in MG are usually combination of both and are organized in a layered, hierarchical structure [41] as discussed in the previous section.

Recently, there is increasing interest in designing control solutions where the feedback of the control loop is not enabled with external communication links. Example of such systems are small MGs where the deployment of communication network might prove to be inefficient in terms of cost, implementation complexity and overall system stability. It is therefore more practical to try to use the MG itself to enable coordination and information exchange capabilities. In light of this, the main question would be: can we use the existing power switches and other equipment in the MG in order to convey data messages for control and coordination?

A straightforward solution would be to use Power Line Communications (PLC) to inject information signals in the MG using the existing power lines [42]. Although eliminating the need for using external communication network, the PLC concept still requires installation of additional communication hardware (such as modems) in the MG. In recent work, another interesting and promising approach has emerged, namely the bus signalling method [43][44]. The main idea is to exploit the variations of the common bus parameters (voltage/frequency). These parameters vary dynamically with different MG entities, thus providing inherent coordination signals between these entities. The bus signalling method can be implemented in the power electronic interfaces using Digital Signal Processing (DSP), thus virtually providing “modemless” communication facility to the MG.

4.2 STATE-OF-THE-ART IN BUS SIGNALLING SOLUTIONS

In summary, the bus signalling methods can be systematized with respect to the type of MG system they are designed for. Different MG systems use different bus parameters for bus signalling. In particular, for DC MGs the common bus parameter is the voltage level, and for AC MGs, the frequency is the common bus parameter that can be varied to communicate control information in the MG.

The bus signalling method was initially introduced in [43] for low voltage DC MGs. The basic implementation consists of assigning different voltage thresholds to different nodes in the MG (such as renewables, non-renewables, and loads for load shading) so they can react as the bus voltage varies. The voltage thresholds are assigned uniformly by including some local voltage estimation error margin. For each voltage threshold, the operating mode of each MG node changes. As defined in [43], the sources can be either off or discharge and the storages can go off, charge or discharge. Although this is the earliest paper on bus signalling, it still remains one of the most comprehensive works on the topic, offering insights for various different generalization and extension opportunities.

Several recent papers [45][46] focus on bus signalling in DC MGs using the same technical approach as in [43], i.e. through assigning voltage thresholds. The authors in [45] use the bus signalling methods for single bus MG systems with modular photovoltaic cells and battery storage. The system can operate in either grid-connected or islanded mode through modular, bi-directional DC/AC converters.

The authors assign different thresholds to the MG, so that each threshold represents different operational state of the MG. Each state on the other hand, is a combination of different operating modes for each MG node. In each state there is at least one MG node whose power electronic interface operates in constant voltage regime and controls the voltage of the MG bus to the predefined value for the specific state. The transition from one state to other is performed by monitoring the bus voltage and detecting its changes which signals a change in the conditions of the MG (either load change or battery State-of-Charge change or even weather conditions change) so a transition is necessary to address these changes in a more optimal manner. The same voltage bus threshold assignment philosophy is applied in [46] where each node (either battery or RES) can locally switch between different modes depending on the voltage changes. The difference in this paper is in the calculation of the droop gain (i.e. virtual resistance for DC MGs) which is based on fuzzy logic to enable more optimal charging strategy for the ESS with multiple batteries and to enforce convergence of the State-of-Charge for all batteries to a common value in normal mode of operation.

There are other papers that use the same idea of assigning voltage thresholds to the MG bus, but the detection of the threshold is either performed remotely, in a central, supervisory entity which triggers state transitions using signalling through external communication network [47], or the detection is performed locally but the state transition signalling is performed using PLC [48]. The latter approach is seen by the respective authors as more reliable variation of the bus signalling method since it still uses the same MG bus for signalling, but provides more flexibility in terms of reliability and control data rate.

The bus signalling method has also been successfully adapted and applied to AC MGs using the bus frequency as a signalling medium [49][50][51]. In [49] the authors observe a simple AC MG with RES and single node ESS and assign different operating frequency thresholds depending exclusively on the State-of-Charge of the battery. The motivation lies in the common fact that when the battery approaches high State-of-Charge, it becomes dangerous to continue to charge it because it might damage the battery. The paper also uses adaptive P-ω droop characteristic to put both the battery and the RES in different modes. Similarly, [50][51] observe simple AC MG system with battery bank as ESS and PV panels as RES. [51] extends [50] and assigns two different frequency thresholds for each battery through which it signals the State-of-Charge of the battery; upper threshold to indicate that the battery is nearly full and lower threshold to indicate that the battery is nearly empty. The frequency variations are used as mode change triggers for each node. Interestingly, because the frequency signalling produces a deviation in the operating bus frequency, this paper employs secondary control to cancel the deviations and restore the deviated frequency to the nominal, using low bandwidth communication links. Since the focus is on distributed coordination, the presence of these links is superficial, and further investigation is required to explore the possibility for their complete removal and enabling secondary control frequency deviation cancelation only through bus signalling.

From the previous discussion and the work presented in the referred papers, several main conclusions can be drawn:

- The operating states of the MGs are determined by a higher level energy management entity. These high level controls usually operate on a much slower time scale, providing updates occasionally. Thus, in the existing work, the states, the mapping between MG state and MG nodes' modes, the bus parameters thresholds and the transition between the states are fixed and predefined a priori. Moreover, in the current implementations, the bus signalling does not support continuous MG node state signalling and only supports simple almost binary signalling. There is little to no flexibility for the bus signalling to be used for other purposes like local observation information exchange for distributed MG optimization etc. One of the main targets of this project is to alleviate this issue through design of more flexible and intelligent bus signalling solutions.

- Most of the changes in the MG are usually made in the power electronic interfaces which excludes the requirement for additional equipment in the MG and provides robust and reliable alternative to classical NCS solutions.
- Altering the bus parameters through primary control modification also alters the dynamic performance of the system and affects its stability properties. Thus, it is very important to address the stability requirements and to enforce the bus signalling strategies to operate in a stable region. Some authors have already observed the possibilities to provide better energy management in the MG by investigating the allowable droop modification region. The stability concerns become a central element in this project since map the physicality of the underlying power system and provide us the space in which we are allowed to intervene.

Evidently, there is need to provide adequate alternatives to address some of the issues mentioned above.

5. KEY RESEARCH OBJECTIVES FOR WORK PACKAGE

The research objectives for WP3 in the ADVANTAGE project will be organized into three major directions.

The research aims to develop solutions for microgrid operation in the distribution network on a large scale. For that, exploring the potential, limitations and methods of smart demand response from operational industrial and commercial microgrids as well as modelling microgrids networks and enable control methods to support system stability and optimal operation are required. Furthermore, communication systems enabling technologies, play key role for a reliable real time operation. Therefore, the key research objectives can be summarized as follows:

- Identify industrial & commercial microgrids with DERs such as DG, storage units, flexible loads.
- Collect and analyse process information, in-house energy requirements, climatic influences on performance, historic generation/consumption data, etc.
- Develop smart demand response methods for grid balancing services from these microgrids.
- Test the accuracy of developed methods in ongoing grid balancing services.
- Validate the developed methods and motivate further research.
- Design a novel control scheme for frequency regulation in a microgrid under different scenarios.
- Evaluation of methods to tackle problems such as active and reactive power control.
- Improve the performance of the frequency control upon sudden change in loads within a microgrid.
- Development of analytical modelling tool of the MG that uses bus signaling.

- Design of novel communication protocol(s) for information exchange using bus signaling.
- Extension of the bus signalling method for distributed energy management in MGs.
- Integration of the bus signalling method with wireless systems for clusters of MGs.
- Extending the bus signalling beyond MGs, in medium and high voltage power networks.
- Build use cases and Microgrid models that employ advanced control architectures and use bus signalling for status update, rather than external communication network.

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