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Published in:

Proceedings of the International Conference on Electrical Machines and Systems, ICEMS 2014

DOI (link to publication from Publisher):

[10.1109/ICEMS.2014.7013977](https://doi.org/10.1109/ICEMS.2014.7013977)

Publication date:

2014

Document Version

Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Hu, J., Zhu, J., & Guerrero, J. M. (2014). Model predictive control of smart microgrids. In Proceedings of the International Conference on Electrical Machines and Systems, ICEMS 2014 (pp. 2815 - 2820). IEEE Press.
DOI: 10.1109/ICEMS.2014.7013977

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Model Predictive Control in Next Microgrid Control Architectures

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Abstract — The exploitation of renewable energy and the development of intelligent electricity network have become the main concerns worldwide. This paper aims to integrate renewable energy sources, local loads, and energy storage devices into smart microgrids. It proposes a new microgrid configuration required to realise high-performance of distributed generations and will realise innovative control techniques utilising model predictive control (MPC) to assist in coordinating the plethora of generation and load combinations, thus enable the effective exploitation of the clean renewable energy sources and provide high quality electricity for customers.

I. INTRODUCTION

As the global warming is progressing, while the worldwide electricity demand is continuously rising a new way of conceiving the electricity systems is needed. A huge amount of energy is lost when transporting electricity from the generation areas to the consumption areas, which are normally fairway each other. The idea of generate/store energy near to the consumption areas may reduce these losses, making also the energy generation/storage more coherent with the geographical and natural resources. Further this is a way to grow together with the city or the rural areas, since all the energy chain should be taking into account in every step of growth. This energy system is defined as a microgrid. A microgrid is a small-scale energy grid which contains distributed generators (ideally based on renewable energy), energy storage systems and loads; sometime microgrids are defined as electrical distribution networks but they need also to be conceived as a hybrid thermal-electrical system. This way efficiency of the system can be improved; being also possible to increase the controllability, since energy can be seen as a global issue, rather than particular ways of energy such as electricity or heat. Furthermore, a microgrid definition is not related to the size, but to the functionality, it can be seen as a compact controlled system that can operate autonomously in such a way that it can be islanded, connected to the grid, or even connected to other microgrids forming *microgrid clusters*.

This new concept has attracted much attention in both academic and industry communities around the world in the last few years. Further, the future smart grid is an electricity network that can intelligently integrate generators, consumers and those that do both – in order to efficiently deliver

sustainable, economic and secure electricity supplies [1]. It is expected to emerge as a well-planned plug-and-play integration of small microgrids, which are clusters of distributed generation units (DGs) and local loads that can offer many advantages to the current power grid in terms of power autonomy and the ability to incorporate renewable and non-renewable energy sources [2], [3]. In this sense, the first step towards the smart grid should start at the bottom of the chain, in the microgrid system.

Due to the intermittent nature of wind and solar energy sources, however, the low quality electricity, low efficiency, and the negative impact on the main power system have become major challenges. In addition, the complexity of such a power system including several kinds of energy sources, energy storage systems and loads, has brought in difficulties in the appropriate control of these DGs to achieve optimal power flow and maintain high power quality.

In a microgrid system, the power converters are the essential component to achieve various control objectives. From the perspective of the energy sources, the power converters should be controlled to capture the maximum real power and inject the excess into the utility. From the utility/grid perspective, smart converter technologies can be used to provide ancillary services such as low-voltage ride-through (LVRT), automatic provisioning, curtailment, and grid support in situations of voltage dips or swells [4]. In this sense, advanced techniques of microgrids including DGs, loads, and energy storage system (ESS) for power flow optimization are desired.

Consequently, these generation techniques must be successfully integrated to provide low-emission energy and reduce the burden on the existing electricity grid. Nevertheless, most of the research so far focuses on the component level, i.e., a single wind turbine or a solar PV panel. Large-scale grid connection is not achieved because of the low power quality. For the microgrids control, previous works mainly focus on a two-parallel-DG based system, and droop control method is generally used to control the inverters for autonomous power sharing between DGs [5]-[7]. However, it is commonly necessary to combine different kind of DG sources, loads and storage technologies in order to ensure both long-term and

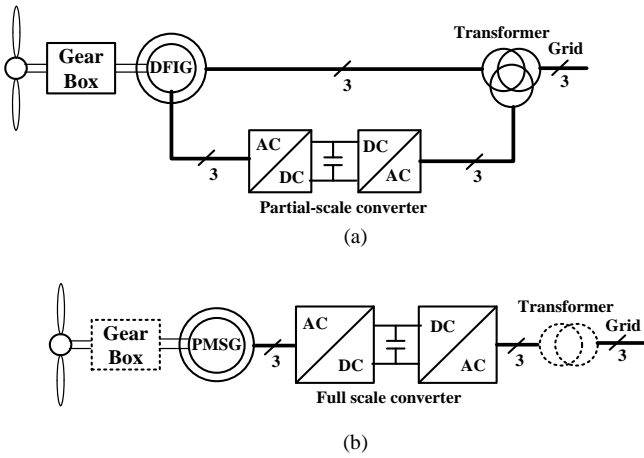


Fig. 1 Commonly used wind power generation configuration. (a) DFIG based wind power system, (b) PMSG based wind power system.

short-term energy storage, and thus smooth the gap between power generation and power consumption within the microgrid. Therefore, advanced techniques of microgrids including DGs, load and ESS for power flow optimization are desired.

Recently hierarchical control that enables the microgrid to operate both in grid-connected and islanded modes was proposed, taking into account different control levels [8]-[10]. Energy management system (EMS) in microgrids is usually thought of as a three-level hierarchical control system. The first control level, often called “primary” or “autonomous” control, consists of a number of local, autonomous controllers. Each controller governs a power electronics converter, and loads with the microgrid. These controllers are the fastest, as they operate in the millisecond range, employing a droop control in islanded mode. A secondary control level employs a low-bandwidth communication to fix the frequency and amplitude of the microgrid’s units, restoring their nominal values. Finally the tertiary control level is related to the control of active and reactive power flow. This level of control is related to EMS and to the optimization of the microgrid resources and is the main subject of this work.

In this paper, in order to effectively integrate renewable power generation units into the grid and achieve high power quality, a new smart microgrid infrastructure is proposed. After that, a new control technique of microgrid using model predictive control (MPC) for the tertiary control level is proposed. This new microgrid configuration and the associated control technique aim to achieve various goals, such as fast and smooth grid connection of renewable and distributed power sources, high quality electricity and ‘grid-friendly’ support, and so on.

II. PROBLEMS IN DISTRIBUTED GENERATIONS

Here, the most common types of DG systems, namely wind power generation and solar photovoltaic (PV) power generation systems, are used as the examples to illustrate the

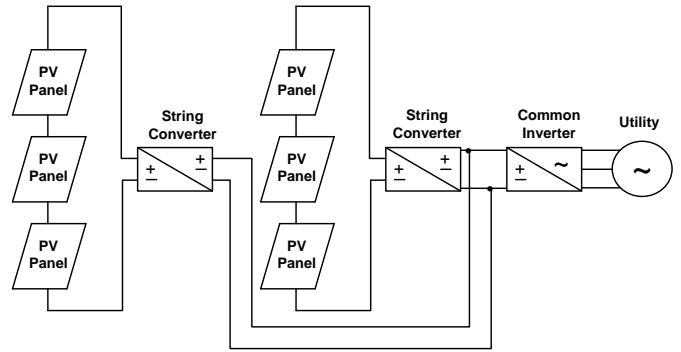


Fig. 2 A typical configuration of PV system.

issues of current DGs. Before the problems of these DGs are identified, their topologies are introduced briefly.

Fig. 1 shows the two most popular configurations of wind power generation systems. The first type is based on doubly-fed induction generators (DFIGs) and the second type is based on permanent magnet synchronous generator (PMSGs). In DFIG based wind power system, the stator of the generator is directly connected to the grid, and a partial-scaled power converter controls the electromagnetic torque, the rotor speed, and thus the rotor frequency. The grid side converter regulates the power factor and maintains the DC link voltage. The DFIG has several advantages including maximum power capture over a wider speed range and decoupled active and reactive power control. It also allows the use of a partially rated converter which reduces the cost [11]. In PMSG based wind power systems, the stator windings are connected to the grid through a full-scale power converter. The induced AC voltage from the stator is first converted to DC voltage through generator-side converter, and then converted back to AC voltage. Advantages of this configuration also include self-excitation, high power factor, and high reliability. Another promising merit of this configuration is gearless, where a heavier direct driven multipole generator is used [12]. In addition, the voltage level of the full-scale power conversion (kV to MV) might be appropriate to connected to the grid transformerlessly.

Solar energy is another renewable source being widely exploited all around the world. For PV system, there is no standard PV topology. Several useful topologies have been studied and applied [13]. Fig. 2 shows a typical configuration of PV system where several strings are interfaced with their own DC-DC converter for voltage boosting and are then connected to a common DC bus. A common DC-AC inverter is often used for grid interfacing. Usually the maximum power point tracking (MPPT) is implemented on the DC-DC converter, while the grid synchronization and power regulation are achieved by the grid-side inverter.

Despite the benefits provided by DGs, there are technical limits in reality on the degree to which DGs can be connected. The main concerns of connecting DGs can be summarized as the following:

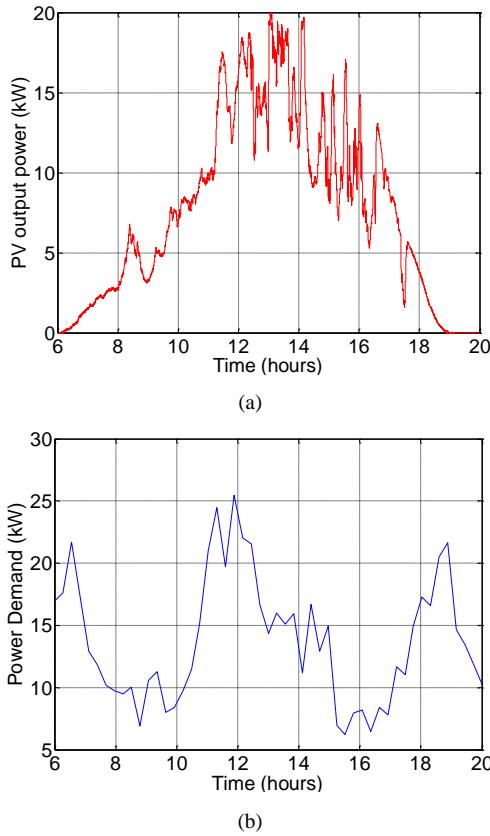


Fig. 3 Characteristics of renewable power generation and load profile in site. (a) Actual power output of PV system during a day, (b) Measured power consumption of a building during a day.

- The power output of the DG is intermittent and the load profile is fluctuated, which would cause negative impacts on the electric appliances
- The steady-state or transient over/under voltages at the point of connection due to sudden connecting or disconnecting a DG
- Possible power quality problems, such as voltage flickers and harmonics,
- Impact on power system dynamics and stability

As shown in Fig. 3, the solar photovoltaic (PV) output increased slowly in the morning and dropped gradually in the afternoon, while the load profile peaked at around 7am, 12pm, and 7pm, respectively. The direct connection of renewable distributed generation (DG) units would pollute the main electricity grid with low quality electrical power due to the intermittent nature of renewable energy sources and the fluctuating load profiles. How to smoothly bridge this power gap between generation and consumption to achieve high quality electricity is a very challenging research task.

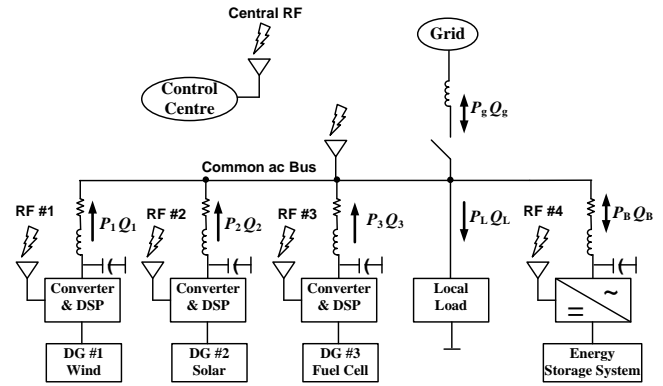


Fig. 4. Proposed smart microgrid configuration

III. PROPOSED SMART MICROGRID SYSTEM

In order to meet the power demand with such a stochastic profile in a microgrid system, it seems that it is impractical to connect the renewable power generation units directly to the loads because the power output of the energy sources themselves are oscillated.

The proposed smart microgrid is shown in Fig. 4. It consists of a wind turbine, a solar PV array, a fuel cell, a battery bank, and a household as the electric load. The wind turbine and the solar PV array are the renewable power generation units. A fuel cell system is used as a backup power generation unit. The battery bank is the energy storage device that can absorb the fluctuation between the power generation and power consumption. All the units are parallel connected to the common AC bus that can be further connected to the main grid through a static transfer switching (STS). In this system, the power converters are the key component to control the power flow.

Current research works focus on the component level. Each distributed generator (DG) is controlled separately without consideration of the power flow optimization and grid requirement. In this work, one of the main innovations is the introduction of an intranet communication network, in parallel with the microgrid AC bus power circuit, plus a microgrid control center. Via the intranet connection, the microgrid control center communicates with the regional control center of the main power grid. Through the intranet, the microgrid control center monitors the state of microgrid system and components (power sources, energy storage units, and loads), and controls the active and reactive power flows between the components within the microgrid to maintain high power quality and efficiency. For the flexible and convenient operation in the intranet, the radio frequency (RF) modules can be used to set up the wireless communication.

From the perspective of the energy sources, the power converters should be controlled to capture the maximum real power and inject the excess into the utility. From the utility/grid perspective, the power electronics interface should be also able to provide reactive power according to the requirement to improve power quality and enhance grid stability. In this sense, advanced techniques of microgrids

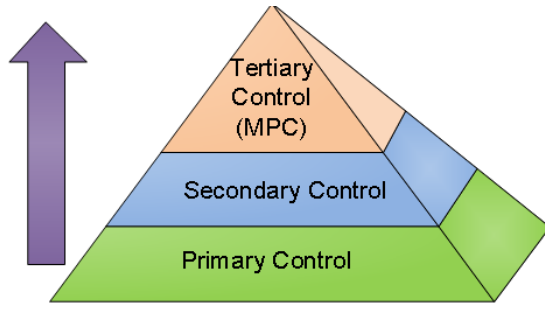


Fig. 5. Hierarchical control levels of a microgrid [8], [9].

including DGs, load and the ESS for power flow optimization are desired. To be specific, the proposed microgrid system integrates the following features:

- Inclusion of DG systems capable of meeting local demand as well as feeding the unused energy back to the electricity grid. Such DGs are known as co-generators and often use renewable sources of energy, such as wind and solar
- Provision of services to a variety of loads, including residential, office and the whole building.
- The control centre will coordinate/dispatch the generators and energy storage devices according to the demands of the local consumption. Therefore, it can smooth the intermittent performance of renewable energy sources and the fluctuating profile of the loads.
- Incorporation of smart sensors capable of measuring a multitude of consumption parameters (e.g. active power, reactive power, voltage, current, demand, and so on) with acceptable precision and accuracy.
- Operation in both grid-connected and islanded modes
- Participation in in the voltage support and power quality improvement for the utility grid.

IV. TERTIARY-LEVEL MODEL PREDICTIVE CONTROL

To bridge the power gap, the key is to optimize the power flows between the DGs, the ESS, and the consumer by controlling the individual power electronic converters properly taking into account the technology used. Generally microgrid controller can be considered as a three-level control system, as depicted in Fig. 5 [8], [9].

- Level 1 (*primary control*): the droop-control method is often use in this level to emulate physical behaviors that makes the system stable and more damped. It can include a virtual impedance control loop to emulate physical output impedance.
- Level 2 (*secondary control*): Ensures that the electrical levels into the MG are within the required values. In addition, it can include a synchronization control loop to seamlessly connect or disconnect the MG to or from the distribution system.

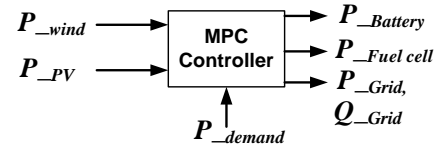


Fig. 6. Schematic illustration of the Tertiary level MPC for microgrids.

- Level 3 (*tertiary control*): this energy-production level controls the power flow between the MG and the grid. This level is related to energy management system (EMS) and to the optimization of the microgrid resources and is the main subject of this work.

In this paper, the tertiary control level is concerned. As the top level of the whole control system of the microgrid, this level of control is related to EMS and to the optimization of the power flow within the microgrid. It determines how much active and reactive powers of each DG should be generated based on the analysis of renewable energy, load demand and the main grid network. Therefore, this control level needs to consider various control constraints in order to achieve a variety of control objectives. MPC is a good candidate to solve this problem, since it integrates optimal control, multivariable processes and it is a flexible control scheme that allows the easy inclusion of system constraints [14]-[16].

MPC has been widely adopted in industry, although there are few works regarding MPC implementation in MGs [17]-[22]. In [17], MPC is used for energy scheduling on a hydrogen-based MG without batteries, while MPC is applied for renewable energy power management with battery storage in a water desalination plant in [18]. Another example is the work of [19], where MPC is performed for a plug-in renewable energy source with battery storage. The electrical power transferred to the network and stored are the control variables that are considered. Also, [20] presented the application of hybrid modeling control for a Photovoltaic-fuel cell power plant.

However, the literatures using MPC for microgrids only focus on one specified energy source, a more complicated system with several renewable energy sources is still under further investigated [21]-[24]. In [25], a MPC scheme is developed for a hydrogen-based microgrid. However, it did not take into account the grid connection from the point of view of the utility grid, and the potential grid supporting capacity of the microgrid is not yet exploited.

In this research, taking the advantages of the model predictive control (MPC) scheme that has been used in power electronics and drives, a new control strategy for microgrids using MPC at the tertiary level is developed. The block diagram of proposed strategy is depicted in Fig. 6. The proposed MPC strategy flexibly includes different constraints in the cost function, based on which the ESS and the fuel cell system modify their behaviors so as to smooth the gap between the power generation and consumption.

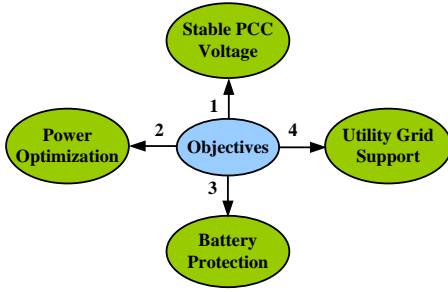


Fig. 7 Control objectives of the tertiary level MPC in microgrids.

The main idea is to minimize a given objective function J defined within a future horizon N , while the problem constraints are satisfied.

Define the power generated as P_{gen} , considering the power demand P_{demand} , the constraints referred to the net power available in the common AC bus can be expressed as

$$P_{net} = P_{gen} - P_{demand} \quad (1)$$

Since the total powers are generated by the PV array, wind turbine, and the fuel cell, therefore, P_{net} can be further calculated as

$$P_{net} = P_{PV} + P_{wind} + P_{FC} - P_{demand} \quad (2)$$

where P_{PV} , P_{wind} , and P_{FC} represent the power generated by the PV, wind turbine, and the fuel cell, respectively. P_{net} , known as the net power, is the available power in the common AC bus, which should be balanced through ESS and the utility grid for energy saving considerations.

The main control objectives of the microgrid system can be illustrated in Fig. 7. To summarize, the main control objectives need to be taken into account in such a smart microgrid system can be described as follows:

- In a microgrid system, the main aim is to supply high-quality power to the loads, regardless of fluctuated load profile and power generation. Therefore, the first objective of the MPC strategy is to establish a stable PCC voltage for the loads, in terms of frequency and amplitude. In other words, power demand from the load should be satisfied with high voltage quality regardless of the intermitted nature of the renewable energy.
- Due to the intermitted nature of the renewable energy sources and the fluctuated load profile, the power generation and consumption are changed every minute, or even every second. Consequently, it is commonly necessary to use energy storage system (ESS) to smooth the gap between power generation and power consumption within the microgrid. For instance, if the power generated by DGs is greater than the load demand, the power will be stored in the ESS and the excess will be injected to the utility grid. On the other hand, if the load demand is greater than the power generated by the DGs, the ESS together with the utility will compensate the unbalance. In a word, the power flow within the microgrid should be optimized.

- Since most of the power outages and disturbances take place in the distribution network, ancillary services for distributed generation systems become a challenging issue to smartly integrate renewable energy sources into the grid. Besides, grid codes from the Transmission System Operators describe the behavior of the energy source, regulating voltage limits and reactive power injection to remain connected and support the grid under fault. Therefore, the microgrid is not only controlled to supply power to the local loads, but also to ride through and support the grid voltage under grid faults. A common method to achieve the grid support is to inject reactive power into the utility grid when grid faults occur.

- Protect the battery bank from deep discharging and overcharging. The manufacturer highly recommends to prevent intensive use of the batteries and also to protect them from a deep discharging or overcharging, with the purposing of expanding the lifetime of these expensive equipment.

- Use the grid connection and fuel-cell with microCHP system only when the renewable sources are unavailable or the load demand is greater than the power generated by the renewable sources and the battery bank.

V. CONCLUSION

This work proposes a new smart microgrid configuration and an innovative power control concept for future grids. The new configuration and the proposed model predictive control approach in the tertiary level of the microgrid control system will enable the grid integration of renewable energy sources with optimized power flow and high flexibility, and thus provide high-quality and reliable electricity to the customers.

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