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A model predictive control strategy of PV-Battery microgrid under variable power generations and load conditions

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HIGHLIGHTS

- A state of charge (SOC)-oriented charging scheme for battery.
- A model predictive control for interlinking converter.
- Energy management system for stable operation of the PV-Battery microgrid.
- Exploit the microgrid reactive capability for grid support.

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ABSTRACT

Renewable energy sources have been increasingly deployed as distributed generators in remote areas. Meanwhile, fluctuating power generation from renewable energy sources, together with variable power demand, poses challenges in stable and reliable power supply. In this paper, a microgrid with solar photovoltaic (PV) and battery energy storage (BES) is studied. A state of charge (SOC)-oriented charging scheme is developed to control the BES to smooth the PV output. Most importantly, a sophisticated control algorithm, consisting of a model predictive voltage control (MPVC) and a model predictive power control (MPPC), is proposed for the interlinking converter. It enables stable voltage in islanded mode. Also, in grid-connected mode, flexible reactive power can be injected into the main grid for grid support according to the voltage variation level. Finally, by considering the intermittent nature of the PV and the load profile, an energy management system (EMS) is designed to ensure power balance within the system. Case studies are provided to demonstrate the effectiveness of the proposed control strategy.

1. Introduction

With growing concern on the environmental issues and the rapid depletion of traditional fossil fuel, electrical grids tend to be more distributed, intelligent, and flexible with high penetration of renewable energy sources. Electrical and energy engineering now have to face a new scenario in which small distributed power generators and dispersed energy-storage devices have to be integrated together into microgrids [1,2]. In order to successfully integrate renewable distributed energy resources, many technical challenges must be overcome to ensure that the present levels of reliability are not significantly affected, and the potential benefits of distributed generation are fully harnessed [3].

In the control technique development for various microgrids, the energy sources are usually replaced by ideal DC sources by many researchers [4–7]. This is because the simulation of real renewable energy sources by using idea dc sources can simplify the system and hence, facilitate the control strategies development. However, the intermittent nature of the renewable energy sources cannot be ignored in practical microgrids. Under such practical considerations, original control approaches may not work well when demanded power cannot be met by energy sources due to intermittency.

To avoid such occurrence, suitable microgrid configurations and sophisticated control are necessary by considering both varying power generation and consumption. Battery energy storage (BES) plays a significant role in smoothing the renewable energy output [8,9]. It has been promoted as the "game-changer" worldwide in the development of future grids with capability of keeping the power balance and

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maintaining voltages. In [10], a BES system is employed to smooth the PV output and increase the level of the microgrid scalability based on a decentralized control approach. In [11] and [12], the BES is used to stabilize the wind-PV microgrid and supply stable power for the loads. In such microgrid systems, however, the grid-connected operation is not developed. This, to a large extent, limits their applications.

Microgrids with multiple energy sources and ac-dc subgrids that can operate in either grid-tied or autonomous modes have been studied in [13–16]. In such systems, the interlinking converter plays an important role in ensuring power balance. In autonomous mode, the ac/dc interlinking converter is controlled to provide a stable ac voltage and frequency for the ac grid while the dc-bus voltage is maintained by the bidirectional dc-dc converter [13]. In grid-tied mode, the ac/dc interlinking converter is used to maintain a stable dc-bus voltage and to exchange power between the microgrid and the utility [14]. In the literatures mentioned above, conventional multiple feedback loops with proportional-integral-differential (PID) controllers are commonly used to control the interlinking converters [16]. Conventional cascade linear controllers suffer from PID parameters tuning work and low dynamic response, due to their cascaded structures. Besides, complicated coordination transformation and PWM modulation are needed. Also, different control structures are required for grid-tied and autonomous operations.

Even grid-connected operation has also been achieved, another concern is raised from the operation of BES. In most of the research work mentioned above, the BES is kept discharging or being charged with constant rate in grid-connected mode. This is obviously not an appropriate approach as overcharge or overdischarge may occur without considering the state-of-charge (SOC). By using SOC feedback and real-time power allocation, a control strategy was developed for smoothing the fluctuating output of the renewable energy [17]. The SOC can be regulated within a specified range while the BES units are able to share the load consistently. The details about BES operation in grid-connected mode is however not investigated. It is noted that modeling uncertainties and current/voltage sensor bias may cause estimated SOC drift, which in turn, can deteriorate the system performance. To obtain accurate SOC estimation, a variety of closed-loop techniques have been developed. For instance, adaptive filters such as Luenberger observer [18] and Kalman Filter [19] are employed due to their low computational complexity and reasonable accuracy. More recently, a recursive total least squares (RTLS) technique based on Rayleigh quotient minimization is developed to eliminate unexpected sensing noises during SOC estimation [20].

Another aspect that is seldom mentioned in the existing microgrid control is the reactive capacity for grid support. As reactive power can directly regulate the grid voltage, reactive power support is usually provided by capacitor banks, static Var compensators (SVCs) or static synchronous compensators (STATCOMs) in a centralized manner [21,22]. This is the most common method adopted by present grid operators. However, recent research has revealed that localized control can achieve nearly 80% saving in losses when compared to a centralized control [23]. In the future grid, more and more micorgrids are integrated into the distribution network. Therefore, it may be efficient to provide grid support near the consumers by flexibly controlling the reactive powers of the microgrids [24].

To address the issues mentioned above, a model predictive control (MPC) strategy is developed in this paper. Actually some control algorithms of power flow using MPC have been proposed for microgrids to achieve a variety of aims such as minimizing system operating costs [25], economic load dispatch [26], energy storage [27], optimized power flow management [28], to name but a few. These algorithms are designed and implemented only at the system level while the structures of the microgrids and the power converters are not considered. For the first time in ac/dc microgrids consisting of renewable energy sources and energy storage, here the MPC is applied to control the interlinking converter to achieve multiple objectives including stable voltage supply, flexible power regulation and grid support.

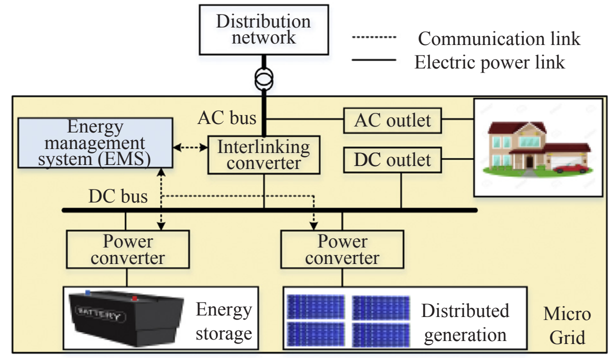

Fig. 1. Proposed hybrid ac/dc microgrid structure.

2. Microgrid configuration and modeling

2.1. Microgrid configuration

Fig. 1 shows the microgrid architecture. A solar PV array is connected to the dc bus through a dc/dc boost converter. A battery as energy storage is connected to the same dc bus via a bidirectional dc/dc converter. The ac and dc buses are interconnected through a bidirectional ac/dc interlinking converter. Variable dc and ac loads are connected to the dc and ac buses, respectively. This hybrid ac/dc microgrid can be further connected to the distribution network through a static transfer switch (STS). The control center collects the real-time data and delivers the control demands through the communication link. The power converters coordinately control the power flow based on an energy management system (EMS) through the electric power link. Even although it is out of the scope of this work, it is worth mentioning that these small micrograms can be interconnected to each other through the distribution network operator (DNO) under the future smart grid framework. The global central controller (GCC) is to coordinately control the microgrids for flexible power sharing [29].

In this microgrid, the mathematical models of the PV, battery and the ac/dc interlinking converter are essential for the control technique development. These models are now well known but for completeness they are quoted below.

2.2. Modeling of PV system

The PV system is shown in Fig. 2. The PV array is connected to the common dc bus through a boost dc-dc converter. The PV array consists of SunPower SPR-305-WHT solar modules. Solar modules are connected in series to form strings that are further connected in parallel as an array. The solar module can be equivalent to a current source in parallel with a diode [30]. Fig. 3 depicts the output characteristics of the PV. Under different solar irradiance, the maximum power points of the power-voltage curves are associated with different output voltages. Also, under certain solar irradiance, the output of the PV panel is

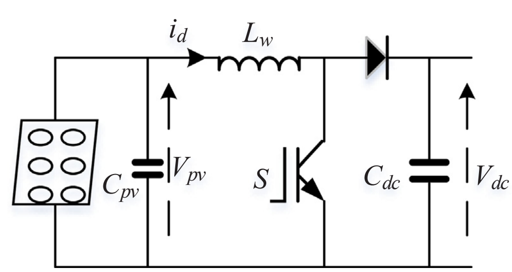

Fig. 2. PV system configuration.