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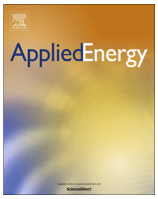

Flat tie-line power scheduling control of grid-connected hybrid microgrids

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HIGHLIGHTS

- Propose a concept called flat tie-line power scheduling.
- Can integrate power ramp-rate limitation and power smoothing functionalities.
- Select proper operation modes and achieve seamless transfer between them.
- Perform power curtailment functionality.
- Ensure constant power injected into the grid with in a determined dispatch period.

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ABSTRACT

In future active distribution networks (ADNs), microgrids (MGs) may have the possibility to control the power dispatched to the ADN by coordinating the output power of their multiple renewable generation units and energy storage units (ESUs). In this way, each MG may support the active distribution network, while promoting the penetration of renewable energy sources in a rational way. In this paper, we propose a tie-line power flow control of a hybrid MG, including photovoltaic (PV) generator, small wind turbines (WT), and ESUs.

Firstly, the structure of the hybrid PV/WT/ESU MG is presented. In this power architecture, the battery is directly connected to the PV side through a DC/DC converter, thus reducing the number of conversions. Secondly, a hierarchical control is proposed to coordinate all those elements of the MG, making the tie-line power flow constant for a period of time, e.g. 15 min. Also, a method to calculate the tie-line power flow to be exchanged between the MG and the ADN is explored, and a power ramp rate is given between different dispatch intervals. Finally, a simulation model of the hybrid MG is built and tested. Simulation results show that the proposed hierarchical control strategy can select the proper operational mode and achieve seamless transfer between different modes. It also presents power curtailment functionality when the difference between the WT/PV output power and tie-line exchanged power flow is too large.

1. Introduction

The high penetration of wind and solar distributed generation in microgrids (MGs) may cause fluctuations in the tie-line power flow and may affect considerably the electrical distribution system operation. Therefore, large-scale distributed renewable energy generation units have been integrated with energy storage units (ESUs) to form electrical MGs [1]. At the same time, with the development of concepts like Energy Internet or active distribution networks (ADN), it is expected that more distributed generation (DG) and MGs will be interconnected in the next future [2–6]. Therefore, in order to facilitate the next ADN's operation, it is necessary to effectively schedule, dispatch, manage, and control MGs or MG aggregators [7].

A lot of work has been done in islanded MG control, aiming to balance active power (P) and reactive power (Q) between

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Abbreviations: WT, Wind turbine; PV, photovoltaic; ESUs, energy storage units; MGs, microgrids; DG, distributed generation; MPPT, maximum power point tracking; ADN, active distribution networks; P, active power; Q, reactive power; DFIG, doubly-fed induction generator; EMS, energy management system.

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Nomenclature

Parameter	Description
C	Usable capacity of the battery [Ah]
$D_{\mathrm{dutycycle}}$	Duty cycle of the DC/DC converter [%]
I_{bat}	Battery current [A]
I_{Cmin}	Maximum charge current of the battery [A]
I_{Dmax}	Maximum discharge current of the battery [A]
K_{β}	A proportional coefficient of pitch control [-]
P_B	Active power of ESU [W]
P_{gl}	Output power of MG [W]
P_{inv}	Output active power of PV-inverter [W]
P_{mpp}	Maximum output power of PV at certain irradiation [W]
P_{PV}	Active power of PV [W]
P_r	Active power of DFIG rotor-side [W]
P_{REF}	Active power reference of PV-inverter [W]
P_s	Active power of DFIG stator-side [W]
P_T	Average power during the dispatching time T [W]
P_T^*	Output power reference of MG during T [W]
P_W	Active power of WT [W]
P_{w}^*	Power reference of WT [W]
$P_{\mathrm{wmax}*}$	Maximum power at a certain wind speed [W]
Q_{REF}	Reactive power reference of PV-inverter [var]
SoC	State of charge of the battery
$SoC(0)$	Initial SoC of the battery [%]
T	Dispatching time [s]
v	Wind speed [m/s]
V_{bat}	Battery voltage [V]
V_{DClink}	DC bus voltage of the PV array [V]
$\upsilon_{\max}$	Maximum (cut-out) wind speed [m/s]
$\upsilon_{\min}$	Minimum (cut-in) wind speed [m/s]
V_{mpp}	Maximum power point voltage of the PV array at certain irradiation [V]
V_{OC}	Open circuit voltage of the PV array [V]
V_{th}	Threshold battery voltage [V]
W_{PV}	Electric energy generated by the PV array [W·s]
τ_{β}	Time constant of the pitch actuator [s]
β	Pitch angle of the WT [°]
β^*	Pitch angle reference of the WT [°]

generations and loads, thus making MGs to operate as a controlled voltage source. In Guerrero et al. [8–11], Marzband et al. [9], Vandoorn et al. [10], and Kim and Kwasinski [11], hierarchical controls of islanded MGs based on droop controlled voltage sources are proposed, which can be interesting when connecting a number of ESUs in an islanded MG. However, in case of grid-connected MGs, the control aim is to make them operate as controlled current sources that should be as much dispatchable as possible. Those MGs are expected to include high level of penetration of renewable resources, such as photovoltaics (PV) and wind turbines (WT), which may lead to severe problems, such as frequency oscillations, voltage instabilities or power line overloading. In order to deal with those problems, it is important to control the power flow of the tie-line that connects each MG to the electrical distribution grid. The tie-line power flow can be controlled by means of different concepts, named: peak-shaving, power ramp-rate limitation, and power smoothing.

The first concept, called peak shaving, is shown in Fig. 1(a). It is used in MGs to reduce the need for back-up generators and the large peaks of power delivered to the main grid. An illustrative example can be found in [12], in which a MG energy management strategy with demand response is proposed to provide peak shaving performance. Peak shaving can be performed by using different storage technologies, and can improve demand response, being economically profitable for some technologies [13]. Other technologies, such as solar combined cooling and power systems can be also used for peak shaving purposes, but they are limited cases in hot climate areas [14].

The second concept, called power ramp-rate limitation, is shown in Fig. 1(b). It consists of limiting the maximum slew-rate of the power caused by the fast variations solar irradiance and wind speed. These fast slew-rates may affect the stability of the main grid, especially in weak-grid/high-impedance situations [15]. The effect of cloud-passing in PV systems output power is studied in [16], and high power-rates are analyzed, which may affect the grid performance. In this sense, the use of ESUs together with PV/WT is suggested to reduce the maximum power ramp-rate. Some examples about it can be found in La Ola island PV plant, in which the power ramp-rate was measured to be more than 60% of the rated capacity per minute, being desirable to lower it down to 30%. In other cases, it has been lowered down to 50% [17]. Furthermore, in networks with high renewable energy penetration like Puerto Rico, authorities have limited the ramp-rates of the PV generators to 10% output power change per minute [18].

The third concept called power smoothing, shown in Fig. 1(c), makes MGs smoothly integrated into the electrical distribution grid [19]. This concept consists of smoothing the output power of a DG or MG [20]. In the literature, several ways to implement power-smoothing can be found. One way is, for instance, to use heat pumps. In [21], a regulation method of stabilizing the power fluctuation of MG tie-line by using the heat pump load start/stop is proposed. In another work, [2], a coordinated control strategy of a MG by using a combination of a battery and an electric-controlled heat pump load as a virtual-ESU to limit the MG tie-line power fluctuations is proposed. In that work, by setting two different time-constants of two Butterworth filters applied to the virtual-ESU and the battery, the high-frequency and low-frequency components of the MG tie-line power fluctuation are effectively suppressed [22,23]. Alternatively, in [3], the use of composed energy storages to smooth the output power fluctuations of a hybrid PV/WT/ESU MG in different time periods is presented. Further, in [24], the characteristics and the mathematical models of a hybrid MG are analyzed, and a charge/discharge optimization control of the storage is proposed to smooth the output power fluctuation. Alternatively, in order to reduce the output power fluctuations and to compensate reactive power of a PV/WT/ESU hybrid generation system, an optimal power control combining online rolling-horizon optimization and active real-time control is proposed in [25].

However, the aforementioned previous works still present a number of problems such as low-frequency power-flow fluctuations and lack of controllability. In order to solve these problems and to facilitate the management and dispatch of the future distribution grid, this paper proposes a concept called flat tie-line power scheduling, shown in Fig. 1(d). It consists on controlling every MG to act as generator/load, thus maintaining the tie-line power flow as constant/flat as possible during a determined period of time. This concept is also able to integrate the previous ones, i.e. peak shaving, power ramp-rate limitation, and power smoothing. A comparison between these state-of-the-art concepts and the proposed flat tie-line power scheduling concept, in relation with the needed qualitative size of the storage, is shown in Table 1. By using the proposed concept, a hybrid MG, including PV, WT and ESUs, can be controlled in a hierarchical way to coordinate all those elements making the tie-line power flow constant for a period of

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