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Control strategy for AC-DC microgrid with hybrid energy storage under different operating modes

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ABSTRACT

In this paper, a control strategy is proposed for renewable-interfaced hybrid energy storage system (HESS) under grid connected/islanding conditions. A second harmonic based phased locked loop (PLL) is employed for effective synchronization/resynchronization of the microgrid system under contingency conditions. The operation and management of the microgrid system under both these modes are accomplished by an efficient adaptive power management algorithm. A quantitative analysis on the HESS performance is provided in order to investigate the effectiveness of the proposed approach. Further, small signal average models are derived to comment on the system stability. This approach address seamless transfer between the various sub-modes of the system along with additional services such as power quality enhancement and power dispatch between various sources. The effectiveness of the proposed scheme is verified by both simulation and experimental investigations.

1. Introduction

The stochastic nature of renewable energy sources (RES) coupled with the unpredictable changes in the load, demands hybrid energy storage systems (HESS) (such as batteries, supercapacitors etc.,) in the present day microgrids [23,6,16]. The HESS support the renewable energy producers and also system operators by providing many ancillary services [12]. From the control perspective, the hybrid microgrids (RES interfaced HESS) are classified into grid-interfaced and standalone configurations. The stochastic nature of these RESs raise many technical issues while operating in grid-interfaced and islanded modes [6,5,17]. In addition, the transition from one mode to another and vice versa, is an important aspect that need to be considered while design of suitable management schemes for reliable and continuous operation of these hybrid microgrids.

1.1. Literature review

The energy management schemes (EMS) reported in Lu et al. [13] extracts powers from the PV source, battery and supercapacitor, based on the states of each of the individual source. However, the power quality aspects on the ac side have not been addressed in their work. The EMS based on model-predictive control reported in Hredzak et al. [8] is limited to supercapacitor-battery hybrid in a DC microgrid environment by assuming a constant DC link voltage. Moreover, this classical model predictive control relies on a discrete model of the control system and a cost function, making it computationally intensive. Similar performance as obtained in Hredzak et al. [8]is achieved using a much simpler EMS reported in Hredzak et al. [7] making it amenable to be implemented using normal controllers.

The micro grid voltage source converter (VSC) changes its management philosophy based on the connection/disconnection status of the micro grid to the utility grid [15,4]. This mode change in the VSC's management philosophy is decided by islanding detection method. Islanding detection schemes can be divided into distant and native modules. Distant methods rely on communication networks between microgrid and utility [3] leading to high cost along with complexity. On the other hand, native module comprising passive and active methods use local measurements information at the point of common coupling (PCC) [15]. The active islanding techniques intentionally introduce disturbances at the output of the VSC's to find if they affect the voltage, frequency, or impedance parameters, in such case it is assumed that the grid has been disconnected and the VSC is isolated from the load. Moreover, active methods introduce a disruption and force wider

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changes of the parameters after islanding event. Therefore, islanding event can be distinguished even under small power perturbations.

Voltage drifting methods mainly use the under/over voltage information at the PCC and the respective relays initiate the islanding event [20,9]. In few of frequency drifting schemes, the autonomous system is enforced by moving the PCC frequency outside permissible frequency limits. Active frequency drift [22], Sandia frequency shift [19] and imaginary power variation [24] are the some of key frequencies drifting methodologies. On the other hand, several methods have been proposed in the literature by creating perturbations without affecting the stability of the system [2,18,11,10]. However, these methods degrade the power quality of the system.

1.2. Objective of the study

In this paper, a simple unified management philosophy is proposed to provide uninterrupted supply to the load under grid connected and islanded conditions. The proposed scheme uses a harmonic current injection method that detects islanding event without affecting the microgrid stability and also, enhances the power quality.

The main features obtained from the proposed scheme are:

- An effective power flow management at the DC link.
- Improved power quality features at the point of common coupling under grid connected mode due to the attenuation of 2nd harmonic of PCC voltage.
- Allows inherent current limits for both supercapacitor and battery units.
- Seamless mode transfer between different modes.
- The islanding event can be detected in a short time by comparing an exponential raise in second harmonic of PCC voltage with a suitable threshold [as shown in Figs. 4 and 14].

In this paper, system configuration and proposed control strategy are described in Section 2. Quantitative analysis on various functionality is described in Section 3. In Section 4, the stability analysis under various modes is presented. Some of the results and discussion are described in Section 5. Finally, concluding remarks are presented in Section 6.

2. Hybrid AC-DC microgrid configuration and proposed control strategy

The hybrid microgrid mainly consists of AC and DC microgrids connected through controlled power electronic interfaces, as illustrated in Fig. 1. A three-phase four-wire split capacitor VSC topology is used on the AC side to exchange power between the AC and DC microgrids effectively.Non-linear and unbalanced loads are connected on the AC side, in order to test the additional capabilities of the proposed scheme such as harmonic compensation, reactive power support, load balancing and power factor correction under grid connected mode. A circuit breaker (CB) is used to isolate the utility grid from hybrid microgrid under contingency conditions. On the DC grid side, a photovoltaic (PV) system is connected through a boost DC-DC converter topology to extract peak power from the PV panels and HESS is used to balance the average and transient power flow at the DC grid. The AC-DC microgrid system considered in this paper is shown in Fig. 1 with following notations.

- v_B, v_{sc}, v_{dc} and v_g are the battery, supercapacitor, DC link and grid voltages.
- i_B, i_{sc}, i_{ld} and i_{vsc} are the battery, supercapacitor, DC load, and VSC currents.
- C_b, C_{sc}, C_{db}, C_{dsc}, C_{dc} and C_f are the battery, supercapacitor, DC link side battery, DC link side supercapacitor, VSC DC link and VSC filter capacitance's, and L_B, L_{sc}, L_f, R_L and R_{labc} are the battery, supercapacitor, VSC filter inductance of the DC and the AC side loads, respectively.
- S_a, S_b, S_c, S_a', S_b', S_c', S_p, S_{1b}, S_{2b}, S_{1s} and S_{2s} are the control switches of VSC, PV converter, battery converter and supercapacitor converter, respectively.

A control strategy has been proposed in this paper for continuous operation of aforementioned microgrid under different operating modes as shown in Fig. 2. The transient and average powers are separated by a low pass filter and rate-limiter (RTL). These powers are fed to the islanding and grid power management (IPM & GPM) modules. The battery and supercapacitor management priorities are embedded in GPM and ISM modules respectively. The status of selector switches (SS1 & SS2) is decided by the islanding detection (ISD) algorithm and based on this signal the selector switch passes corresponding battery and supercapacitor reference values to control stages. The voltage source converter will change its mode of operation from grid interface/connected to islanding and vice versa based on activating signal from the ISD.

The details of aforementioned functional blocks in grid connected and islanding modes of the AC-DC microgrid are described in the following subsections.

2.1. Energy Storage Unit's Monitoring

The depth of discharge (DoD) status of the energy storage units is computed and monitored using the following mathematical equations [14].

$$DoD_j(t) = DoD_{oj} - \frac{1}{3600 N_{Cj}} \int i_j \, dt \tag{1}$$

where $j = B \; or \; SC$, DoD_o, and N_C are the battery, supercapacitor, initial DoD of energy storage system (ESS) units and nominal capacity respectively. The computed DoDs of the battery and the supercapacitor units are fed to the IPM and GPM modules. Based on the status of the energy storage devices, the power management objectives are defined in these modules.

2.2. Islanding detection method and operating modes

The islanding detection method used in this work is shown in Fig. 3. Under grid connected mode, the voltage at the point of common coupling (PCC) is imposed by the utility grid, and its waveform is not altered by islanding detection algorithm. This grid voltage template is used for generation of VSC reference currents (i_r) under grid connected mode. Whereas, in case of islanding the PCC voltage follows the waveform of current injected by the voltage source converter [21] and the idea of this ISD algorithm is explained as follows,

A small perturbation is generated by modification in the phase signal of the phase locked loop (PLL) as shown in Fig. 3, so that the angle of VSC current reference is changed according to the following,

$$\theta_{vsc} = \theta + K\cos(\theta) \tag{2}$$

$$\cos(\theta_{vsc}) = \cos\{\theta + K\cos(\theta)\} \tag{3}$$

After simplification, the VSC reference current is given as follows,

$$\cos(\theta_{vsc}) \cong \cos(\theta) - \frac{K}{2}\sin(2\theta) \tag{4}$$

The islanding detection method is based on measuring second harmonic of the PCC voltage waveform and corresponding feedback signal (ϑ), control signal under change over from one mode to another are illustrated in Fig. 4. Fig. 4(a) shows the feedback (ϑ) and delayed signals from the ISD algorithm. At $t = t_1$, the grid is switched off. As a result, the feedback signal is more than ϑ_{min} and therefore, ISD algorithm sends activation signal to the CB as shown in Fig. 4(b). At $t = t_2$,