Switching Performance Optimization for a Hybrid AC/DC Microgrid using an Improved VSG Control Strategy

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***Abstract*—The hybrid AC/DC microgrid gains a great attention in recent years as it can improve the energy efficiency and ensure the reliability of the system. This paper makes an investigation on the operation mode switching performance of an AC/DC combined hybrid microgrid based on a real system at Griffith University, Queensland, Australia. An improved virtual synchronous generator (VSG) control strategy is developed to optimize the switching performance from the grid-tied mode to the islanding mode. The basic VSG principle is described and the improved VSG model is introduced. Based on the improved model, a pre-synchronization method is proposed. Comparison of the microgrid performance between conventional droop control and the improved VSG control is carried out by simulation on Matlab/SIMULINK environment. Simulation results show the advantage of VSG control strategy and the validity of the pre-synchronization method.**

***Index Terms*—Hybrid AC/DC microgrid, switching performance, virtual synchronous generator, pre-synchronization.**

I. Introduction

In recent years, an increasing number of distributed energy resources (DERs) have been put into utilization through microgrids. According to the grid structure and power supply mode, the microgrid can be divided into three forms: namely AC microgrid, DC microgrid and hybrid AC/DC microgrid. In order to reduce the power loss, harmonic current and control difficulty caused by multi-stage AC/DC or DC/AC transformations in a pure AC microgrid or DC microgrid, the hybrid microgrid gains more attention since it is more practical and economical.

A great deal of research has been carried out on hybrid microgrids, ranging from configuration design to coordination control strategy [1-4]. However, the performance during mode transition of a hybrid microgrid is rarely studied. For a hybrid microgrid, the transition from grid-connected mode to islanding mode requires being smooth in case momentary interruption occurs which may cause damages to the devices including loads and power electronic equipment [5]. In order to meet power generation and demand requirements, proper voltage and frequency should be maintained for the microgrid even under the islanded case. An appropriate control method is supposed to be carefully chosen to fulfill the requirements aforementioned. When the islanded microgrid is required to be connected to the utility grid, the voltage and the frequency of the microgrid need to synchronize to the grid in order to ensure a safe grid-connection [6]. Therefore, a proper method for the microgrid to achieve the grid synchronization is necessary.

Authors in [7] made progress on the seamless mode transition for a hybrid AC/DC microgrid system. The system simplifies the switching procedures between the constant power controller and the voltage-frequency controller. However, two different control methods are utilized in the paper, which leads to the complexity of the control strategy. Droop control is a commonly used control strategy for microgrids since it could allow the microgrid to operate under both grid-connected mode and islanding mode [8]. The droop control method of an inverter mimics the primary frequency and voltage regulation characteristic of a synchronous generator. However, the inverter may not be able to restrain the frequency fluctuation in the face of the dynamic change from the grid side. Therefore, the virtual synchronous generator (VSG) concept is proposed to mimic the inertia response characteristic of a synchronous generator [9]. The VSG control is essentially subordinate to droop control [10] while gives better response during mode transition from the grid-connected mode to the stand-alone mode.

In this paper, the performance of a hybrid AC/DC coupled microgrid during the transition from the grid-connected mode to the islanding mode based on a real system at Griffith University is investigated. Case studies under droop control

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and VSG control are carried out and the responses of frequency and AC voltage are compared. In addition, a pre-synchronization method for VSG control method is proposed to ensure a proper transition during the operation mode switching from islanding mode to grid-tied mode.

The other parts of the paper are arranged as follows: Section II describes the real university-based hybrid microgrid system structure as well as the simulation model. Section III introduces the principle of the VSG control strategy. A pre-synchronization method for the hybrid AC/DC microgrid is proposed in Section IV. Case studies of microgrid performance between droop control and VSG control are compared in Section V. Section VI induces the conclusions of this research.

II. SYSTEM DESCRIPTION

The system model prototype used in this paper is a real commercial-use based microgrid system, which is developed at Griffith University, Australia, as shown in Fig. 1. This system contains low voltage distribution systems with renewable energy resource (RES) generation units. Practical loads are from the commercial building N44 on Nathan campus. The N44 building employs 15.5 kW PV panels in order to realize the peak demand shaving function. 60 kWh batteries and 12kW wind turbines will be put into installation to save the power generation from the main grid. In addition, a four-quadrant smart interlinking converter is also planned to be adopted, which may allow for the power generation and consumption of the battery energy storage system (BESS).

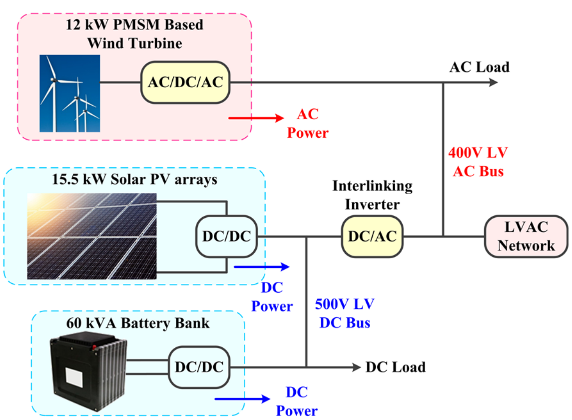

Fig. 1 Hybrid microgrid system configuration of N44 Building, Griffith University

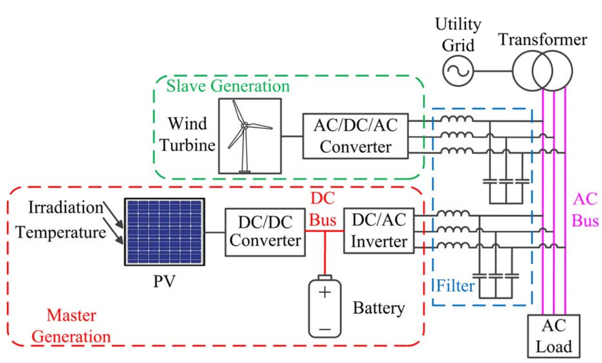

Fig. 2 Simulation model of the hybrid microgrid

A fully developed simulation model comprises of two parts: a DC subgrid including PV and battery; an AC system combining wind turbine with the former subgrid. In the DC subgrid, a PV module with integrated boost converter is included. A lithium-ion BESS model joins the DC bus through a DC/DC converter in order to simulate the real battery bank. The DC microgrid utilizes a bi-directional converter for the connection to the AC bus, which allows a bidirectional power-flow. The DC subgrid with a big capacity can be considered as the main generation unit in this research which operates under the master control strategy (VSG control). The wind turbine is an isolated generation source which is connected to the AC bus directly under a slave control strategy (P-Q control). It always generates the output on the basis of the utility grid or the master generation unit. The simulation model configuration is shown in Fig. 2.

III. BASIC PRINCIPLE OF VSG CONTROL METHOD

The virtual synchronous generator control method aims at mimicking the performance of a conventional synchronous generator (SG). Thus, the RESs and the DERs can easily participate in the regulation of system's frequency and voltage under grid-connected mode. A VSG-based inverter consists of two parts: an external circuit which is known as the power part shown in Fig.3, and an internal controller which is classified as the electric part [9].

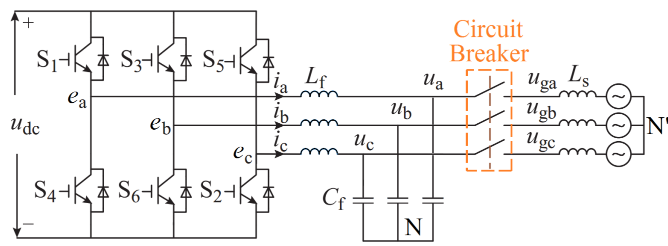

Fig. 3 Power part of a VSG

The DC bus in the power part is required to be constant. Either a DC-bus voltage controller or a battery energy storage could be introduced to achieve such function. The controller is developed based on the mathematical model of a synchronous machine. The frequency control loop obeys the swing equation given by:

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\frac{P_{ref}-P_e}{\omega_n} - D_p\Delta\omega\right) \qquad (1)$$

The voltage control loop can be set according to the following equation [11]:

$$e = \frac{1}{Ks}\left[D_q\left(V_{ref}-e\right) + \left(Q_{ref}-Q_e\right)\right] \qquad (2)$$

where P_{ref} and Q_{ref} are the reference active power and reactive power; P_e and Q_e are the VSC active power and reactive power output; J is the virtual moment of inertia; ω_n is the reference angular frequency; ω is the virtual frequency of the output voltage; $\Delta\omega$ is the difference between ω_n and ω; e is the three-phase back electromotive force (EMF) and V_{ref} is the reference voltage. D_p and D_q are the droop coefficients of the frequency loop and voltage loop respectively, and K is the integrator gain.

The reference active power can be generated from the frequency governor according to the principle of droop control. However, according to [12], the frequency governor may reduce the inertia of the system. Therefore, the frequency control loop can be revised by removing the governor section and setting the active power directly. In addition, the voltage control part may adopt a proportional-integral (PI) regulator in order to keep the voltage stable during transient cases. Therefore, a simplified VSG internal controller is developed as shown in Fig. 4.

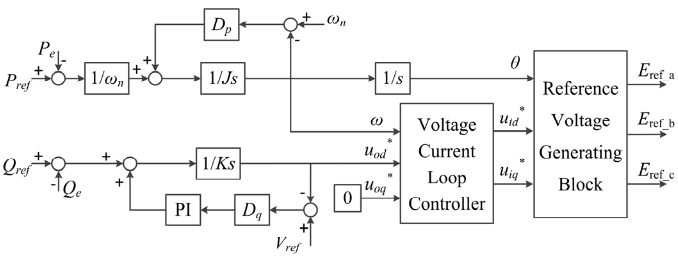

Fig.4 Improved VSG controller

IV. Pre-synchronization method for VSG

The microgrid is required to be islanded following a fault or disturbance on the main grid. According to IEEE Std. 1547 [13], when the grid voltage deviates from 0.88 p.u. to 1.1 p.u. or the grid frequency varies from 49.3 Hz to 50.5 Hz, the grid can be considered as unstable. Until the grid is adjusted to normal, the microgrid is ready for the re-connection to the grid. However, unexpected impacts would happen during the re-connection process if the microgrid's voltage and the grid's voltage are inconsistent. It is necessary to confirm that the microgrid voltage to be at the same level to the utility grid before the connection. Therefore, a pre-synchronization strategy is essential for the microgrid to regulate the voltage to the same stage of the utility grid. A self-synchronize method for the VSG has been proposed to synchronize the inverter with the grid automatically in [14]. However, there is a requirement for the microgrid system to set the reference power output at 0 which means the system would offer no generation during the synchronization process. Such situation is not allowed in several cases such as an uninterruptible power supply system. In this case, a proper pre-synchronization method of the improved VSG controller for the grid-connection purpose is required.

The basic aim of the predictive synchronization method is to regulate the frequency, the amplitude and the phase angle of the output voltage. As the VSG method has already taken these variables under control, appropriate control logic should be embedded. Since the phase angle is proportionally related to angular frequency, once the phase angle is settled, the frequency must be settled as well. Therefore, a revised predictive synchronization method which regulates the phase angle in order to regulate the frequency is proposed as shown in Fig.5. Usually, the microgrid operates under the grid voltage level in order to keep the normal operation of the equipment. In the context, it is not essential for the microgrid to regulate the voltage to the same level of the grid. However, a voltage regulator is still necessary for the synchronization process since the phase-angle regulation can affect the voltage.

Therefore, two PI regulators have been added to the VSG controller configuration. The reference phase angle θ_g and voltage V_g are obtained from the utility grid values. Through the PI controllers, the microgrid output voltage angle θ_m and amplitude V_m track the reference value in order to achieve the synchronization function. When there is a requirement for the microgrid to reconnect to the utility grid, the switches in phase angle regulator and voltage regulator are closed. Either the phase angle or the output voltage has been regulated to the same level with the main grid, the switch should be turned off again. When both values reach the same level to the main grid, the microgrid is ready to connect to the utility grid.

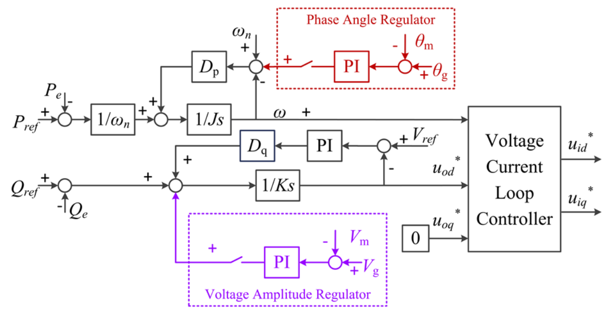

Fig. 5 Improved VSG controller with predictive synchronization method

V. Simulation results

The simulation model is built based on the N44 building system structure mentioned in Section II. Two scenarios simulation studies are carried out in this research: mode switching from grid-tied mode to stand-alone mode; pre-synchronization and grid-connection. For the first case, since the mode switching period is very short, the load can be viewed as constant during such transient situation. During the transition period, the three-phase load is 110 kW/54 kVar according to the actual load of the N44 building. The power reference of the master generation unit is set at 85 kW/54 kVar. Since the wind turbine is operating as a slave generation source, its control strategy is a basic P-Q control method that can be found in [7]. Considering the real situation, the power reference is set at 10 kW/0 kVar. For the second case, the load is reduced to 85 kW/54 kVar in order to make a match with the power generation unit. The hybrid microgrid system could operate normally in this way.

Case A: Mode switching from grid-connection to islanding

The simulation results show the transient performance of the microgrid during mode switching from grid-connected mode to islanding mode under both droop control method and VSG method. The results also verify the pre-synchronization method proposed in this paper. The microgrid is disconnected from the supply network at 4 s. According to Fig. 6, under droop control, the frequency has a variation over 0.2 Hz after the grid-disconnection. Since the load exceeds the generation capacity, the frequency remains at a lower level than rated frequency after the mode transition. However, under VSG control, the frequency drops 0.1 Hz less than droop control and it remains at 50 Hz although there are some negligible ripples. For the AC voltage shown in Fig. 7, the voltage drops down after the grid-disconnection due to the heavy load. There is a sudden voltage drop during the mode transition process, however, the drop is smaller under VSG control and the voltage could go back to be stable directly after the sudden change since there is a virtual inertia inside the system.

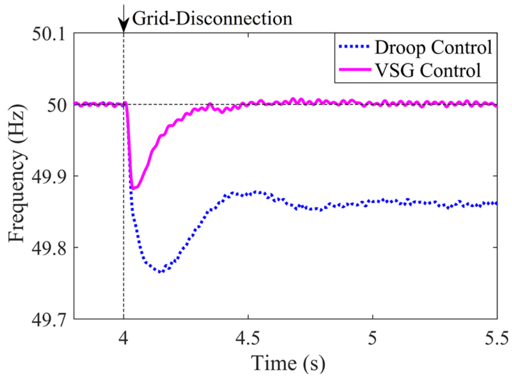

Fig. 6 Microgrid frequency from grid-tied mode to stand-alone mode

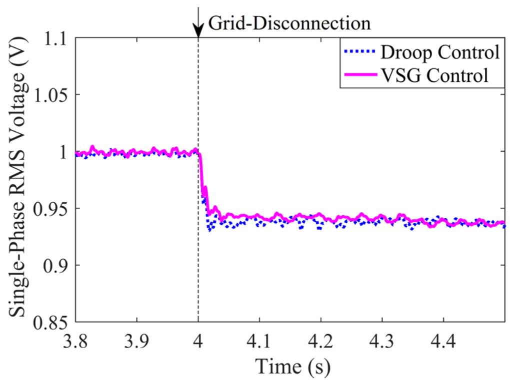

Fig. 7 AC voltage of the microgrid from grid-tied mode to stand-alone mode

Case B: Pre-synchronization and grid-connection

The pre-synchronization method proposed in this paper is also testified. According to Fig. 5, when there is a requirement for the microgrid to connect to the utility grid, the switches in phase angle regulator and voltage regulator both turn on. In the simulation, the pre-synchronization regulators are put into operation at 1.5 s and the microgrid is connected to the grid at 3 s. The whole regulation process lasts for approximately 1 s. The performances of the hybrid microgrid are shown in Fig. 8-Fig. 10. When the pre-synchronization process starts, the phase angle difference is regulated to 0 very soon. Due to the change of the phase angle, the frequency varies during the regulation while the change of the frequency ranges from 49.9 Hz to 50.6 Hz, which is also acceptable. There is a big overshoot occurred in the voltage during the synchronization. However, with the adoption of the voltage amplitude regulator, the voltage can recover to normal value quickly within 0.25 s. The voltage deviates from 0.92 p.u. to 1.12 p.u. After the synchronization regulation, the microgrid is connected to the utility grid at 3 s. According to the figures, the phase angle, the frequency, and the voltage amplitude are all in the same level of the grid. The system achieves a smooth grid-connection without any big impacts on the performance of the overall system. The variation process of the microgrid AC voltage is shown in Fig. 11. The figure presents how the microgrid is synchronized to the main grid. It can be seen that the phase angle can be regulated to the same level within 20 cycles. The entire process is quick without any drastic changes that ensure the normal operation of the equipment within the microgrid.

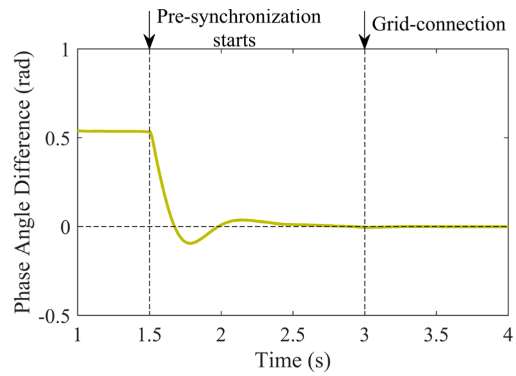

Fig. 8 Phase-angle difference between the grid and the microgrid

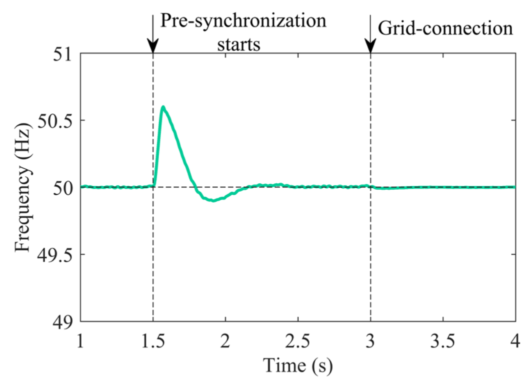

Fig. 9 Microgrid frequency from stand-alone mode to grid-tied mode

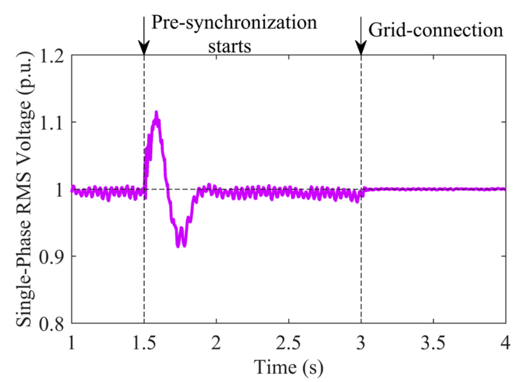

Fig. 10 AC voltage of the microgrid from stand-alone mode to grid-tied mode

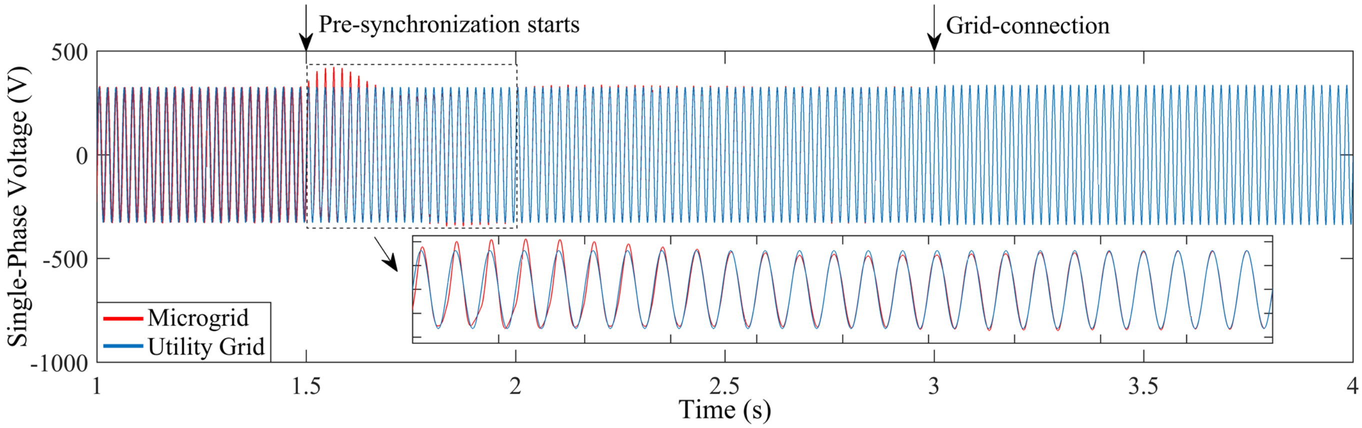

Fig. 11 AC voltage variation during pre-synchronization

VI. CONCLUSIONS

This paper analyses the operation mode switching performance from grid-tied mode to stand-alone mode of a hybrid AC/DC microgrid based in Griffith University, Australia. A comparison of such transient performance during the transition process between the droop control method and the improved VSG control method is carried out. Simulation results show that the system provides better performance under VSG control strategy. In addition, a pre-synchronization method on the basis of the proposed VSG strategy is developed. The simulation results validate the effectiveness of the proposed method. However, the frequency and voltage variation during the pre-synchronization process are a little bit large. Any unexpected situation may change the variation range and cause accidental damages. Therefore, a proper modification of the pre-synchronization method to solve such a problem can be a topic for further research.

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