A Hybrid AC/DC Microgrid Control System Based on a Virtual Synchronous Generator for Smooth Transient Performances

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ABSTRACT

This paper presents a high-performance control strategy to support an optimised transient performance for a hybrid AC/DC microgrid system based on an improved virtual synchronous generator (VSG). The standard VSG is modified and an improved control strategy is developed. A pre-synchronization controller is embedded within the improved VSG controller for grid-connection use. In addition, this paper builds the small-signal model for the improved VSG controller in order to analyse the system's stability. A controller for the battery energy storage system is developed in order to assist the power output of the hybrid microgrid. The microgrid system is designed in a MATLAB/SIMULINK simulation environment based on the under-construction hybrid AC/DC microgrid system at Griffith University, Australia. A comparative study of droop control, conventional VSG control, and the improved VSG control is carried out under different possible transient cases. The pre-synchronization method is also tested. The simulation results show that the improved VSG control strategy is evidently able to ensure smooth variations in frequency, voltage and active power during transient cases.

Keywords: Hybrid AC/DC microgrid; transient response; virtual synchronous generator; pre-synchronization

1. Introduction

The traditional power grid utilises fossil fuels as its primary sources of energy, which cause carbon dioxide and dust emissions, climate change, and the continuous depletion of fossil fuels [1]. In addition, it has other disadvantages such as a centralised power supply, limited extensibility, and higher costs. In recent years, renewable energy sources

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(RESs) based distributed generation (DG) units have gained the attention of researchers worldwide since they offer several advantages such as high efficiency, environmental-friendliness, flexible extensibility and improved reliability [2]. The distributed energy resources (DER), for example, photovoltaic (PV) systems, wind turbines (WT), battery energy storage (BES), and micro-turbines (MT) are regarded as flexible power sources and are connected directly to the low-voltage network [3].

However, due to the intermittent and uncertain characteristics, the DER units may cause unpredictable problems when connecting to the utility grid or operating independently. For this reason, the microgrid concept is proposed to deal with such problems [4]. The microgrid has drawn a great deal of attention because of its flexibility and efficiency. It can plug-in or plug-out from the utility grid which means it can operate either under a grid-connected condition or as an independent system [5]. The microgrid market is expected to grow at a significant rate between 2015 and 2020, and to become a multi-million-dollar industry [6].

Since the AC power system has existed for a very long time, and common loads are basically AC types, the commonly used microgrid type is also the AC microgrid [7]. However, a trend for connecting DC loads and resources to the AC power systems is growing in order to save energy and reduce carbon credits, which requires a significant number of inverters for DC power to convert to AC power in an AC microgrid. DC-to-DC converters are also essential for some DC generations units to regulate the DC output to the same level to the DC bus (including managing the impact of battery storage systems and EV charging systems). Multi-level conversions can lead to power loss and the degradation of power quality. Therefore, the hybrid microgrid concept is proposed to overcome the defects caused by the individual application of AC microgrids or DC microgrids [8].

The hybrid microgrid system contains both the AC bus and DC bus as well as AC loads and DC loads. It combines the advantages of both the AC and DC microgrids and also avoids their disadvantages, which makes it practical in use and a possible

distribution form in the future [9]. AC loads and generations such as wind turbines and microturbines are connected to the AC bus to build an AC microgrid. DC loads and generations like solar PV and BES units are connected to the DC bus to form a DC microgrid. The DC subgrid can be considered as a unique power generation unit, which is connected to the AC bus through an interlinking inverter [10]. Since the hybrid microgrid provides a solution for the distribution generation system, research on the various aspects of the hybrid AC/DC microgrid has been carried out [11]. However, most of the research concentrates on investigating the performance in a stable operation mode. The performance of a microgrid during mode switching is also important since the microgrid is responsible for the voltage and frequency regulation without the support of the utility grid and so are the transient cases under the islanding mode of a microgrid system.

The smooth-mode transition is important for the reliable and stable operation of microgrids, however, so far, less attention has been paid in the literature to tackle this problem. Lasantha et al. in [12] designed a transition strategy for the switching from the grid-connected mode to the islanding mode since the authors considered this to be the most dangerous case. However, if the microgrid is not synchronised with the utility grid when switching from islanding mode to grid-connected mode, the consequence is also serious which can possibly result in damaging the devices. Chunxia et al. provided a switching controller for operation mode transition based on the multiple Lyapunov robust stability method [13]. The method is proposed for a specific system, which can be further studied and applied to other systems. However, the microgrid system in the paper adopts constant power control for the grid-tied mode and V/f control for the stand-alone mode. The requirement to change the control strategy during mode switching makes the system more complex. These researchers conducted different aspects of study for an islanding situation, but it is an important function for a microgrid to connect to the main grid in order to save energy. An isolated microgrid system should always be with a proper grid synchronisation unit, which is not referred in the

references mentioned above. Amir et al. in [14] proposed a supplementary mechanism for the smooth transition between different operation modes, while two control strategies are adopted for one controller which increases the system's complexity. There is not so much research on other types of transient cases such as load changing or faults. Most of the research concentrates on stability analysis instead of optimisation. Authors in [15] proposed a resistive superconducting fault current limiter in order to optimise the microgrid performance during a fault. This method adds an extra part to the system, which increases the complexity of the system.

Motivated by the previous research on the aforementioned issues, this paper presents an interlinking inverter control strategy for a hybrid AC/DC microgrid, which enables a smooth transient performance during the system's operation condition variation. The hybrid microgrid adopts a master-slave structure for different DER units. In order to reduce the complexity of the system, the microgrid utilises the main voltage and frequency controller since it is capable of making the system operate under both grid-connected mode and stand-alone mode. Droop control mimics the primary voltage and frequency regulation characteristics of a synchronous generator, which gives the inverter an ability to perform as a voltage and frequency supporter [16]. However, since the microgrid generation units mainly depend on inverter or converter energy conversion based on RESs, it lacks the inertia of the traditional utility grid with rotational generators [17]. The system's inertia is an important parameter which could maintain its frequency in case of transient changes in load [18]. With the high penetration of RESs, the inertia of the whole power system reduces, which may lead to a large fluctuation in the rate of change of frequency when the active power is unbalanced in the power system. Also, the steady-state frequency error becomes larger after the primary frequency regulation. Traditional power supply system conducts the inertia regulation before the primary voltage and frequency regulation which could prevent sudden frequency fluctuation during an unexpected change in generation and load patterns. A comparison of the frequency response to the sudden change of the system between the traditional power supply grid and the grid with high penetration of RESs is shown in Fig. 1. According to the figure, the grid-connect inverter should be able to simulate the inertia regulation, primary voltage and frequency regulation of a synchronous generator in order to

ensure the stability of the power system's frequency and voltage amplitude with high penetration of RESs.

Fig. 1. Comparison of the frequency response to the sudden change of the system between the traditional power supply grid and the grid with high penetration of RESs.

The main controller in this paper is reorganised according to the synchronous generator characteristic equations to make the inverter a synchronverter which is also known as a virtual synchronous generator (VSG) [19] in order to maintain the system's inertia. It mimics the primary voltage and frequency regulation characteristics of a synchronous generator, which gives the inverter the ability to perform as a voltage and frequency supporter [20]. This concept was first proposed from the VSYNC project, which only adopts the frequency regulation characteristic of a synchronous generator [21, 22]. Based on this research, researchers in [23] improved the VSG controller by simulating the voltage regulation characteristic of a synchronous generator. Similarly, authors in [24] introduced an algebraic type VSG to simulate the inertia and the output impedance characteristics. All of the three control strategies are on the basis of current control, which is difficult to provide the frequency and voltage support to the system. Qingchang Zhong considered the electromechanical transient and electromagnetic transient characteristics of a synchronous generator and put forward the concept of synchronverter [25, 26]. This method achieved a good equivalent of the VSG and the synchronous generator physically and mathematically. However, the participation of the excitation current greatly increased the control difficulty. Authors in [27] summarised several VSG structures including the high-order models and the low-order model. The low-order model follows the VSYNC strategy aforementioned, while the high order

models require a more complicated configuration with the introduction of several parameters. Therefore, the VSG controller adopted in this paper simplifies the synchronverter model and combines both the frequency and voltage characteristics of a synchronous generator based on voltage control. In addition, it is rare to find related work for the pre-synchronization of a VSG controller except [28]. However, the method proposed in [28] has its limitations. In this context, a pre-synchronization method based on the revised VSG controller is proposed for grid-connection consideration. The hybrid AC/DC microgrid system configuration is based on the microgrid structure at Griffith University, Australia. The system and the controllers are developed and tested through MATLAB/SIMULINK. Several cases are performed in order to validate the robust performance of the system. In summary, the contributions of this papers are as follows:

- An improved VSG controller with a simplified configuration is proposed for the better microgrid transient performance. The proposed VSG controller model, which considers both the frequency characteristic and the excitation voltage characteristic of a synchronous generator, is explained and analysed mathematically.
- Different controllers are designed for the DGs involved in the hybrid AC/DC microgrid system to ensure the normal operation of the system.
- The hybrid AC/DC microgrid performance is investigated under different scenarios in order to demonstrate the feasibility and the superiority of the proposed VSG control strategy compared to other existing control strategies.
- A pre-synchronization method is specifically designed for the proposed VSG controller in this paper for the grid-connection purpose.

The rest of the paper is organized as follows. Section 2 presents a brief introduction of the Griffith hybrid AC/DC microgrid system as well as the simulation model configuration based on it. The controller configurations for each generation unit are described in Section 3. In section 4, a small signal model is built based on the proposed controller in order to analyse the system's stability. The proposed controllers are verified through simulation combined with the real data. The simulation results of

different case studies are displayed and discussed in Section 5. Finally, Section 6 discusses the conclusion of the research presented in this paper.

2. Hybrid microgrid system

Fig. 2. Hybrid multi-microgrid system in Griffith University, Australia.

The hybrid AC/DC multi-microgrid system at Griffith University mainly contains three commercial buildings, i.e. N44, N79 and N74 which is shown in Fig. 2 [29]. Each building constructs a microgrid system itself. The N79 building is planned to be a multi-purpose building used for research, teaching, and official business. Except for the utilisation of solar PV panels, wind turbines, and batteries, there is also a requirement for the building to achieve an electric vehicle (EV) charging and discharging function, which means the building can be used as an EV charging station in the future. The N74 building is a semiconductor research and fabrication center which requires an uninterruptible power supply (UPS) function with a backup diesel generator. Extra PV and battery storage will contribute to the energy conservation. The battery storage is also responsible for the building power consumption during the power cut before the diesel generator fully started. The N44 building is a commercial building with several different kinds of DER units including PV panels, wind turbines, and a battery energy storage system. The PV panels and the BESS unit are connected to each other through a common DC bus which establishes a DC subgrid. By utilising a common AC bus, the

DC subgrid and wind turbines are combined which makes the N44 building a small-scale hybrid AC/DC microgrid itself.

The hybrid AC/DC microgrid system structure proposed in this paper is based on the N44 building system since the establishment of this system is reaching its final stages [30] while the other two buildings are still in their development stage. The N44 building contains a DC subgrid including 15.5 kW maximum power output PV panels and a 60 kWh lithium-ion battery energy storage system. The DC subgrid contains a low voltage DC bus, which is set at 650V in order to meet the converters' requirements. As an independent power supply, the DC subgrid is connected to the AC bus through an interlinking voltage source inverter (VSI) or a four-quadrant distribution static compensator (D-STATCOM). In addition, 12 kW maximum power output WTs are planned for installation on the rooftop of the N44 building. These are connected to the AC bus directly. In the actual case, there are currently only AC form loads (energy storage can be treated as a DC load during the charging mode). The loads are supplied by the AC bus, which can be connected to the utility grid. The AC bus RMS voltage is 400V according to the grid phase-to-phase voltage. A fully developed simulation model is shown in Fig. 3.

Fig. 3. Hybrid AC/DC microgrid simulation model based on the N44 system.

In addition, in order to study the multi-microgrid system operating characteristics, a simplified multi-hybrid-microgrid based on Fig. 2 is developed in Fig. 4. The system consists of three subgrids, which represent the N44, N74, and N79 respectively. In this model, three DC/AC inverters are utilized for each building, which are all under VSG

control strategies. However, the system reduced the involvement of the EV charging station, the coupling DC/DC converter and the diesel generator in order to facilitate analysis and test the feasibility of the proposed control strategy. Such simulation structure is mainly to investigate the multi-VSG operating performance. Based on this structure, the more complicated system configuration can be established in the future.

Fig. 4. Multi-hybrid-microgrid simulation structure.

3. Hybrid microgrid control strategy

For the hybrid microgrid, a master-slave control mode is adopted according to the energy capacity of the system. In this context, different control strategies for the generation units need to be utilized. A detailed description of the control strategies is presented in this section.

3.1. Master generation unit control strategy

In order to operate the microgrid under both grid-connected mode and islanding mode, droop control is a proper control strategy which enables the simplification of the system's complexity. A modified droop control based on VSG is eventually adopted as the master control strategy in order to optimise the microgrid's operating performance. The comparisons among the conventional droop control, the conventional VSG control, and the improved VSG control are presented in the following sections.

The VSG based controller includes the mathematical model of a three-phase round-rotor synchronous machine described by [26]

$$\frac{d\omega}{dt} = \frac{1}{J}(T_m - T_e + D_p\Delta\omega) \quad (1)$$

where T_m , T_e , and ω are the mechanical torque applied to the rotor, the electromagnetic torque and the rotor angular speed, respectively. J is the virtual moment of inertia of all the parts rotating with the rotor. D_p is the mechanical friction coefficient.

The output voltage of the synchronous generator will decrease with the increment of the output current. For this reason, an excitation regulator is necessary to regulate the excitation current in real time. The closed-loop equation for the excitation controller is as follows:

$$i_f = G(s)(\sqrt{2}V_{ref} - \sqrt{2}V_o) \quad (2)$$

V_{ref} is the reference voltage signal. V_o is the synchronous generator output voltage which is equivalent to the EMF mentioned above. $G(s)$ is the regulator for the excitation controller. To achieve the primary voltage regulation function, the reference voltage of the synchronous generator will change with the variation of the reactive power. The changing rule is shown as the following equation:

$$\sqrt{2}V_{ref} = \sqrt{2}V_n + \frac{1}{D_q}(Q_{set} - Q_e) \quad (3)$$

V_n is the root mean square (RMS) value of the rated voltage. By substituting (2) into (3), the excitation current can then be deduced as:

$$i_f = \frac{G(s)}{D_q}[D_q(\sqrt{2}V_n - \sqrt{2}V_o) + (Q_{set} - Q_e)] \quad (4)$$

Taking $G(s)$ as an integral regulator and making $G(s)/D_q = 1/K_i s$ ($1/K_i$ is the integrator gain), the equation (4) can be rewritten as

$$i_f = \frac{1}{K_i s}[D_q(\sqrt{2}V_n - \sqrt{2}V_o) + (Q_{set} - Q_e)] \quad (5)$$

For a synchronous generator, the only way to regulate the internal potential amplitude is to regulate the excitation current. However, for VSG, the reactive power loop only needs to mimic the primary voltage regulation function of the synchronous generator. Thus, it is not necessary to introduce the excitation current. Therefore, the excitation regulator output can be replaced by the VSG modulated voltage E with a new

integrator gain $1/K_e$. In addition, the modulated voltage e can be considered as the VSG output voltage as well. Thus, equation (5) can be rewritten as [31, 32]:

$$E = \frac{1}{K_e s} [D_q(U_{set} - E) + (Q_{set} - Q_e)] \quad (6)$$

According to the analysis above, the VSG controller could regulate the frequency during the transient case through the inertia section; however, both the frequency and the voltage lack a regulator to maintain the amplitude according to the reference. Therefore, a modified VSG controller with two PI controllers is utilised in this paper, each in the frequency regulation and the voltage regulation branch. With the PI controller, the sudden change in frequency and voltage amplitude can be minified since the PI controller is able to make the output exactly the same as the reference value. In addition, two first-order filters are used for the instantaneous power in order to stabilise the P-f and Q-U control loops [33]. An improved VSG controller based on the simplified configuration is shown in Fig.5. In this case, the real-time active power P_e and reactive power Q should be calculated through the instantaneous voltage u_0^{abc} and current i_0^{abc} measured after LC filter as shown in Fig. 3. The parameters shall be transformed into the d-q components u_0^{dq} and i_0^{dq} correspondingly.

Fig. 5. Improved simplified VSG controller

3.2. Slave generation unit control strategy

The slave generation unit is mainly for energy contribution, which simply needs to obey the reference voltage and frequency to generate electric power. Therefore, there is no need for the slave generation unit to consider frequency and voltage regulation in a microgrid system. A P-Q control (also known as constant power control) strategy is adopted for the slave generation part. The main purpose of the P-Q control is to keep the active power and reactive power output of a

DER unit constant according to the reference value. In this way, the active power and reactive power can be decoupled and controlled separately. Basically, the power regulation is achieved through adjusting the active and reactive current to the reference values. Similar to the master generation controller, the slave controller also needs to transform the instantaneous voltage u_1^{abc} and i_1^{abc} current to d-q components u_1^{dq} and i_1^{dq} . Reference current signals will be generated through a power controller according to the following equations [34]:

$$\begin{cases} i_{dref} = \frac{P_{ref}}{u_{1d}} \\ i_{qref} = -\frac{Q_{ref}}{u_{1d}} \end{cases} \quad (7)$$

The inverter output current is adopted as a feedback signal. A current controller is introduced to enhance the high dynamic response of the controller. It is also responsible for transferring the current components to voltage components in order to generate PWM signals. The configuration of the P-Q controller is shown in Fig. 6.

Fig. 6. P-Q controller configuration

3.3.DC/DC converter control strategy

The DC bus voltage is mainly regulated through the DC/DC converter, which connects the battery energy storage system to the DC bus. The main purpose to regulate the DC bus voltage is to set the microgrid output capacity. Since the active power output P_m obeys the VSG reference, the reactive power output Q_m is affected by the system's capacity S_m , which is related to the DC bus voltage. Therefore, the DC/DC converter should not only maintain the DC voltage steady but also determine the microgrid total power output. The DC/DC converter and its control strategy are designed in Fig. 7.

According to the figure, S_{ref} is the reference apparent power; V_{DC_ref} and V_{DC} are the reference DC voltage and DC bus voltage; I_{bat_ref} and I_{bat} are the reference battery

current and actual battery current. The differential algebraic equations for the battery controller can be given as follows:

$$\begin{cases} V_{DC_ref} = (S_{ref} - S_m)(K_p^{DC} + \frac{K_i^{DC}}{s}) \\ I_{bat_ref} = (V_{DC_ref} - V_{DC})(K_p^{DC} + \frac{K_i^{DC}}{s}) \\ D_{bat} = (I_{bat_ref} - I_{bat})(K_p^{DC} + \frac{K_i^{DC}}{s}) \end{cases} \quad (8)$$

where K_p^{DC} and K_i^{DC} are the proportional gain and integral gain for the PI controllers respectively. D_{bat} is the duty ratio for the PWM generator of the DC/DC converter.

Fig. 7. DC/DC Converter controller

3.4.Pre-synchronization control strategy

When there is a requirement for the microgrid to connect to the utility grid from the islanding mode, a significant impact may occur since the microgrid output voltage shares a different waveform from the utility grid. In this case, pre-synchronization is necessary for regulating the microgrid output to the same level as the utility grid. Researchers proposed a self-synchronisation method for VSG in [28], which makes the inverter automatically synchronise to the grid without the need to use any phase locked loops (PLLs). In this case, the microgrid should meet the requirement to set the reference active power and reactive power at 0 during the pre-synchronization process. This means the microgrid needs to operate under a zero-generation condition, which may not be accepted for some scenarios such as a remote area power supply system with an uninterruptible power supply function.

Fig. 8. Improved VSG controller with pre-synchronization section

Fig. 9. VSG pre-synchronization procedure

In this paper, a phase angle regulator is utilised for the synchronisation purpose. The phase angle regulator uses the difference between the grid phase angle θ_g and the microgrid phase angle θ_m to generate an angular frequency compensation component. It then adds the component to the frequency in order to regulate the microgrid phase angle. The output can be added to the inertia section directly to adjust the angular frequency in order to accelerate the regulation of the microgrid phase angle. Once the phase angle is adjusted and thus stable, the angular frequency can be settled as well due to the proportional relationship between the two parameters. Since the frequency and the voltage always follow the reference value, the frequency regulator and the voltage regulator are not so necessary for the pre-synchronization method. Therefore, the improved VSG controller with a pre-synchronization section can be developed as shown in Fig. 8.

The phase angle regulator also uses the difference between θ_g and θ_m to generate the angular frequency compensation through a PI controller. However, if the voltage amplitude varies too much during the pre-synchronization process, due to the phase angle change, the phase angle regulator adopts a graded compensation by using a series

of PI controllers. When the pre-synchronization section starts, the system compensates for the phase angle difference and also detects the phase angle difference. When the phase angle difference deviates from -0.05 rad to 0.05 rad for at least 0.02s, the phase angle difference is considered acceptable. If the phase angle difference is acceptable for the grid-connection, the pre-synchronization can be considered complete. If the phase angle difference is not acceptable, the system changes the PI controller's parameters to increase the compensation value. By compensating the difference step by step, the microgrid phase angle can be regulated to approach the grid phase angle. The pre-synchronization procedure for the VSG controller is shown in Fig. 9.

4. Small-signal stability analysis for the improved VSG

Since the frequency and the voltage are positively related to the active power and the reactive power, the stability of the active power and reactive power keep the frequency and the voltage of the system stable and vice versa. The general active power and reactive power of a synchronous generator are given as [28]:

$$P_e = 3V_g E \sin \theta / 2X_s \quad (8)$$

$$Q = 3(E \cos \theta - V_g)V_g/2X_s \quad (9)$$

where X_s is the synchronous reactance of the synchronous generator, θ is the difference between the angles of the VSG output voltage and the power grid voltage. In order to facilitate the analysis and design, θ is viewed very small since the microgrid is supposed to follow the utility grid during grid-disconnection and pre-synchronization conditions. Therefore, the equations can be derived as

$$P_e = 3V_g E \theta / 2X_s \quad (10)$$

$$Q = 3(E - V_g)V_g/2X_s \quad (11)$$

Take the U_{set} as V_g , then the active power loop and the reactive power loop can be built by combining the equations with the VSG structure shown in Fig. 3. Make $K_P = 3V_g E / 2X_s$ and $K_Q = 3V_g / 2X_s$, the VSG output active power closed-loop transfer function and the reactive power closed-loop transfer function can be calculated as:

$$\left[\frac{1}{\omega_n} (P_{set} - \frac{1}{T_{s+1}} P_e) + (\omega_n - \omega) \left(\frac{K_l^p}{s} + K_p^p \right) D_p \right] \frac{1}{J_s} = \omega \quad (12)$$

$$P_e = \frac{K_P}{s} \omega \quad (13)$$

is worse. As the mechanical friction coefficient increases D_p , the poles s_1 and s_2 become conjugate poles gradually, which may lead to a quick response to the system. As a conclusion, on the one hand, the bigger J is, the bigger the overshoot is during the dynamic process; on the other hand, the smaller D_p is, the longer it needs to take for the active power to respond. The pole-zero map for the reactive power small-signal loop is shown in Fig. 12. The only influencing factor for $G_q(s)$ is the excitation voltage integral gain K_e . There are three poles for $G_q(s)$ including s_1 , s_2 and a real pole (s_3). With the increasing of K_e , s_1 and s_2 become a pair of conjugate poles from real poles, and they get approach to the imaginary axis. This means K_e should not be too big or too small in order to give the consideration to both the regulation time and the response time. As long as the three parameters are chosen properly, the stability of the system can be guaranteed.

Fig. 11 Pole-zero map for active power loop

Fig. 12 Pole-zero map for reactive power loop

5. Case studies

In this section, case studies are carried out to demonstrate the operating performance of the improved VSG control strategy in a hybrid AC/DC microgrid based on the N44 building system at Griffith University. Five case studies are conducted to analyse the performance of the designed control system during: (A) mode transition from grid-connected mode to islanding mode of the hybrid microgrid system; (B) sudden load changes in the islanding mode; (C) a line-to-ground fault occurring under the islanding mode; (D) mode transition and load changing for multi-microgrid system; and (E) a pre-synchronization period and mode transition from islanding mode to grid-connected mode. The simulation parameters of the hybrid AC/DC microgrid are shown in Table 1.

Table 1 Simulation parameters of the hybrid microgrid system

Parameters	Values	Parameters	Values
R_f	0.01 Ω	K_p^q	10
L_f	3×10^{-3} H	K_i^q	1
C_f	1500×10^{-6} F	$K_{p(u)}, K_{p(i)}$	10
Rated power	95 kW	$K_{i(u)}, K_{i(i)}$	100
Nominal frequency	50 Hz	$K_{p(s)}^{DC}$	0.3
Nominal voltage (line-to-line)	400 V	$K_{i(s)}^{DC}$	20
D_p	30000	$K_{p(v)}^{DC}$	7
D_q	2703	$K_{i(v)}^{DC}$	800
J	0.01	$K_{p(i)}^{DC}$	10
K_e	43	$K_{i(i)}^{DC}$	100
K_p^p	10	T	0.01 s
K_i^p	1		

5.1.Case A: Mode switching from grid-connected mode to islanding mode

In this case study, the transient performance of the hybrid AC/DC microgrid is compared among the conventional droop control strategy, modified droop control with supplementary PI controllers [35], original VSG control and the improved VSG control method proposed in this paper during the mode transition from grid-connected mode to islanding mode. The system's frequency is set at 50 Hz, and the line-to-line voltage RMS value is set at 400 V according to the Australian standard. The power output of the hybrid microgrid is set at 85 kW/54 kVar, including 75 kW/54 kVar from the master generation and 10 kW/0 kVar from the slave generation. Before 4 s, the system operates in the grid-connected mode. At 4 s, the microgrid is disconnected from the utility grid. The frequency and voltage during mode transition among droop control, modified droop control, VSG control and the improved VSG control are shown in Fig. 13. Without the support of the main grid, the frequency starts to deviate from the reference value 50Hz. The system can still conduct normal operations without changing the control strategy within a sudden unplanned islanding case. The frequency drops are both optimised by 0.05 Hz under the modified droop control and the original VSG control than the conventional droop control. However, it can be seen that the frequency under the improved VSG control strategy is able to maintain at 50Hz, although there is a minor drop shoot during the transition period. Since the microgrid output is lower than the load, the output voltage will increase during the islanding mode in order to make the output power match the load. The VSG voltage performance is optimised by accelerating the voltage stabilisation compared to droop control strategy; however, the

transient change becomes a little bit larger. The improved VSG controller compromises the performance by taking both the voltage stabilisation speed and the transient transition into account. Compared to the conventional VSG control, the improved VSG control strategy lowers the voltage changing rate from 13% to 5%. The active power performances show a similar trend in the four control strategies, which all keep stable output at 95 kW in order to meet the load under islanding case. However, there is a tiny unnatural change in active power at the beginning of the grid-disconnection due to the operation condition change. The system is able to conduct a smooth transition from grid-connected mode to islanding mode.

Fig. 13. Hybrid microgrid performance comparison during the unplanned islanding case

5.2.Case B: Load changing during islanding mode

When the load changes during the islanding mode, all the DGs react promptly to stabilise the system and match the load automatically. This study includes two cases: the first case is one where the load increases by 20 kW; the second case is that the load decreases by 20 kW to a lower status. In the simulation, the load increases to 115 kW/54 kVar at 8s for the first case, while decreases to 75 kW/54 kVar at 8s for the second case. From 4s to 12s, the system operates in islanding mode. The performances of the hybrid microgrid during load changing are demonstrated in Fig. 14 and Fig. 15. According to Fig. 14 (a), during the load increasing case, the frequency response trend under the four control strategies are quite similar. However, after the sudden change, the frequency under VSG control can return to 49.93 Hz, which takes a bit longer for the improved droop control strategy to reach, while the frequency under droop control stays at 49.87 Hz. The frequency transience is optimised by reducing 0.05 Hz in the change under the VSG control and 0.04 Hz in the modified droop control. The improved VSG

keeps the frequency at exact 50 Hz, which shows the good frequency tracking performance of the improved VSG controller. In addition, it optimises the transient performance by lower 0.02 Hz of the frequency change. Moreover, the improved VSG control strategy keeps the good voltage characteristic of droop control, which gives a quicker response and eliminates the unnecessary fluctuation in the conventional droop control. The active power output behaves consistently under the four control strategies. As shown in Fig. 14 (a), the stabilised frequency under VSG control can reach 50.02 Hz, which is a lot better than that under droop control (50.1 Hz). However, the overall changing range of the frequency under the improved VSG control is only 0.07 Hz, which is much better than the 0.18 Hz under droop control and the 0.1 Hz under VSG control. When the load decreases to 75kW, the frequency under improved VSG control turns back to exact 50 Hz while there is still a 0.05 Hz frequency deviation under the improved droop control. The voltage under conventional VSG control shows the similar performance with the case when the load increases, while the ripples are also attenuated under the improved VSG control. During the load decreasing transience, there is an overshoot in the voltage performance. The improved VSG optimises this sudden change from 0.7% to 0.5%.

Fig. 14. Hybrid microgrid performance comparison during load increases

Fig. 15. Hybrid microgrid performance comparison during load decreases

Fig. 16. VSG output voltage during load changing

Under the load changing case, the improved VSG control reserved the advantage of the VSG, which draws the frequency back to 50 Hz. However, it has a better voltage reference tracking performance. The VSG output voltage follows the reference 400 V precisely under the improved VSG control rather than the conventional VSG control, which can be seen in Fig. 16. A minor change happens during the transient case which can be neglected. Since the load increases by 20 kW, the microgrid tries to match the load by increasing the output active power, which is determined by the main generation unit. The DC subgrid capacity is kept constant by maintaining the DC bus voltage stable. In this case, the reactive power drops, which results in the voltage drop of the microgrid system. The opposite occurs when the load decreases. Under normal circumstances, the load changing is the most common phenomenon, which may lead transient effect in an islanding microgrid system. To evaluate the system's performance, a 24-hour N44 building load data is adopted in the simulation based on the improved VSG control strategy. Fig. 17 shows the N44 microgrid performance in one day including the frequency and voltage variation according to the load.

Fig. 17. N44 microgrid performance in 24 hours

5.3. Case C: Mode transition and load changing for multi-microgrid

In this case study, the improved VSG performance for a multi-microgrid system which is shown in Fig. 4 is investigated. Since the VSG control method is a kind of

improved droop control strategy in essence, it inherits the advantages of the droop control. Therefore, the improved VSG control strategy possesses the inherent ability to achieve the power-sharing when several VSGs are operating in parallel. The power-sharing rule obeys the following equation[36]:

$$P_1/D_{p1}=P_2/D_{p2}=\dots=P_n/D_{pn} \quad (22)$$

$$Q_1/D_{q1}=Q_2/D_{q2}=\dots=Q_n/D_{qn} \quad (23)$$

P_n and Q_n represent the output active power and reactive power respectively for each VSG. D_{pn} and D_{qn} are the coefficients for each VSG.

Fig. 18. Multi-microgrid performance

As long as the parameter settings meet the requirements above, the power output will follow the reference value. It is similar to the conventional droop control, which means the improved VSG control strategy shares the similar power-sharing ability during the islanding mode when parallel VSGs are operating together. In this section, the power-sharing characteristic under the improved VSG control method is only compared with the conventional droop control strategy since all the four control strategies are based on the same power allocation principle. In this case study, the three VSG output active

power ratio is set as 1.4:1.15:1. The reactive power ratio is set as 1:1.25:1.4. The total loads of the three sub-systems are 253 kW/ 150 kVar. The frequency and the voltage variation are shown in Fig. 18. At 4s, the multi-microgrid system is disconnected from the utility network; at 8s, the total load increases 20 kW. Since the power supply capacity is much bigger than the single microgrid, the frequency and the voltage become more stable under both of the control strategies. However, due to the superiority of the improved VSG control method, the microgrid still performs better either in frequency variation or in voltage response compared to droop control.

The power-sharing characteristics are shown in Fig. 19 and Fig. 20. The microgrid active power and reactive power outputs follow the reference settings under the grid-connected mode. However, the output power will match the loads under the islanding mode. In this case, the power output for each inverter is following the setting power ratio during the islanding mode according to the figures. It can be seen that the improved VSG controller shares the same power allocation property as the droop control does with quicker power response. Due to the capacity limit, when the load increases 20 kW, the reactive power output decreases since the active power output is trying to match the load.

(a) Multi-microgrid under improved VSG control

(b) Multi-microgrid under droop control

Fig. 19. Active power-sharing property

(a) Multi-microgrid under improved VSG control

(b) Multi-microgrid under droop control

Fig. 20. Reactive power-sharing property

5.4.Case D: Single phase-to-ground fault occurring at PCC

This case study aims to verify the performance of the designed controller during an external fault. A single phase-to-ground fault is considered as this is the most common fault that occurs on a network. In the simulation, the fault happens at 8 s and lasts for 0.2 s. The transient frequency and the VSG output voltage are shown in Fig. 21 and Fig. 22. According to the figures, the VSG control and the improved droop control method can reduce the frequency drop shoot to 49.55 Hz from the 49.5 Hz under droop control. However, the improved VSG is able to optimise the drop shoot to 49.35 Hz and draw the frequency back to the reference value faster. When the fault is cleared, the frequency is regulated to return to 50 Hz through the control strategies. The improved VSG control reduces the overshoot to 50.3 Hz compared to the 50.45 Hz under the conventional VSG control and saves the unnecessary fluctuations of the frequency in order to shorten the regulation time within 0.6s, which is shortened by 40% than in conventional VSG control and droop control strategies. The improved droop control strategy shows a similar performance although with a little bit larger frequency deviation and slower response. This is due to the PI controller in the frequency loop, which makes the frequency response fast and precise. The improved VSG control method optimises the

VSG output voltage to an obvious extent. Although the voltage distortion is inevitable after the fault occurs, the improved VSG controller is still able to limit the voltage fluctuations around the reference voltage. However, the output voltage for conventional VSG has a severe distortion, which seriously affects the performance of the VSG. Due to the same reason in the voltage loop, the VSG output voltage can be stabilised back to the set value very quickly.

Fig. 21. Hybrid microgrid frequency during single phase-to-ground fault

Fig. 22. VSG output voltage during a single phase-to-ground fault

5.5. Case E: Synchronization to the utility grid

Before an islanding microgrid system connects to the utility grid, synchronisation is essential to ensure the stability of the system. The main aim of this case study is to validate the pre-synchronization method for the improved VSG control strategy proposed in this paper. In this study, the simulation operates under islanding mode for 2.5s. At 1.5s, the pre-synchronization module is put into operation. Until the phase angle difference between the utility grid and the microgrid reaches the tolerable zone (± 0.05 rad), the pre-synchronization control block stops operating. Until 2.5s, the system is connected to the utility grid. The phase angle difference, frequency, single-phase voltage and single-phase current of the microgrid system under the pre-synchronization process are shown in Fig. 23. According to the figures, the frequency deviates from 49.92 Hz to 50.45 Hz and the voltage deviates from 0.92 to 1.09 p.u. According to the Australian Renewable Energy Agency (ARENA) description [37], the performance of the system is considered to be operating steadily during the pre-synchronization process.

Fig. 24 shows the voltage waveforms of both the grid and the microgrid during pre-synchronization, which presents the process of the microgrid synchronisation to the utility grid. The step changes in the following parameters are caused by the graded regulation synchronisation method, which makes the voltage and frequency change smaller comparing with the one constant PI compensation. Fig. 23 also shows the hybrid microgrid performance during the grid-connection process complying with the IEEE 1547. From the figures mentioned above, it can be concluded that the hybrid microgrid system transitions smoothly from islanding mode to grid-connected mode. Without causing any harmful impacts during the connection process, the system aims to operate normally once connected to the main grid. The voltage, frequency, and phase angle are all regulated to a similar level to the utility grid through the pre-synchronization block. The method proposed in this paper is validated as effective, feasible and easy to implement.

(c) The single-phase voltage
(d) The single-phase current
Fig. 23. Microgrid performance during the pre-synchronization process

Fig. 24. Single-phase voltage waveform during pre-synchronization

6. Conclusion

In this paper, an improved VSG control strategy is proposed which enables the stable operation of the Griffith hybrid AC/DC microgrid under both grid-connected and islanding modes. The main objective of the proposed control strategy is to optimise the transient performance of the microgrid system in different operating conditions. The control method developed in this paper simplified the control block configuration based on the conventional synchronverter and explained the simplification process from a mathematical aspect. Some modifications are made on the simplified model to ensure a smooth frequency and voltage change during the transient cases. The optimisation

effects are validated through several case studies under different operating conditions. In addition, an effective pre-synchronization method is also proposed for the improved VSG control scheme in order to achieve a smooth grid-connection. The pre-synchronization strategy adopted a graded compensation method to maintain the stability of the microgrid system during the synchronisation process. The effectiveness of the synchronisation plan is verified. The future vision of this research is to integrate the microgrid system with other subgrids to develop a multi-microgrid system and to keep the system operating steadily under both stable and transient cases.

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Appendix A

The N44 hybrid microgrid testing facilities are shown in Fig. A1 and Fig. A2. The equipment is described in Table A1.

Fig. A1 N44 hybrid microgrid testing facility

Fig. A2 PV panels installation

Table A1 N44 hybrid microgrid testing facility

Device	Description
A	10 kW SMA Inverter
B	Solar Architecture Testing Enclosure
C	2 kW SMA Inverters
D	Microgrid Switchboard
E	1.5 kW SMA Inverter
F	Data Acquisition and Monitoring Enclosures
G	DC Bus
H	Communication and Monitoring Enclosure
I	AC Bus

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