A Multi-Purpose Interlinking Converter Control for Multiple Hybrid AC/DC Microgrid Operations

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Abstract— This paper presents a multi-purpose interlinking converter control design along with a simplified centralized multi-microgrid operation controller (MMOC) to achieve smooth and coordinated operations among multiple hybrid AC/DC microgrids with electric vehicle-energy storage systems (EV-ESSs). The primary purpose of the multi-microgrid operation is to share required active/reactive power among multiple microgrids. In order to achieve this objective interlinking converters of each microgrid is designed with embedded droop controllers. The conventional droop controllers are replaced with proportional-derivative (PD) compensated droop controllers. The PD compensated droop controller ensures proper damping and avoids the limitations of power sharing accuracy associated with the conventional droop controllers during islanded to multi-microgrid mode transition. A simplified centralized MMOC has been designed to control the initiation and the termination period of the multi-microgrid operation. The MMOC also generates necessary reference signals for the interlinking converters to achieve successful multi-microgrid operation among multiple hybrid AC/DC microgrids. Two islanded hybrid AC/DC microgrids are designed in MATLAB/ SIMULINK environment based on N44 and N05 buildings in Griffith University, Australia. The PD compensated droop method has been embedded into the interlinking voltage source inverter (VSI) controllers of each microgrids. Simulation has been carried out for islanded mode, multi-microgrid operational mode and the transition between these two modes under variable loading and three-phase fault condition. All the simulation results show that the designed controller provides superior and robust performance for variable scenarios.

Index Terms— Multi-microgrid, hybrid AC/DC microgrid, PV module, electric vehicles (EV), energy storage systems (ESS), droop control, VSI, interlinking converter.

I. INTRODUCTION

Renewable resources are getting global acceptance for electricity generation due to their proven technical, economic and environmental feasibilities. Advantages such as abundance of energy, low greenhouse gas emission, stable energy prices and low operational costs make them very appealing alternatives to conventional fossil fuel based energy generation. Microgrids provide the opportunity of integrating renewable resources in distributed manners. Microgrids are discrete electrical systems that ensure affordable, local and reliable electricity. This miniature version of the legacy system is considered to be the building blocks of the futuristic smart grid vision. Microgrids can operate both islanded and grid-tied

mode. Thus, they can be considered as contingencies for the existing grid in case of emergencies such as natural disasters and faults at the point of common coupling (PCC). However, limitations associated with renewable resources like intermittency, low inertia and storage requirements make the control of islanded microgrid more challenging. Additional complexity takes in when multiple-islanded microgrids interact each other to ensure overall power balancing [1], [2]. Therefore, a microgrid should have the following features [3]:

- Throughout grid-tied operation:

- Provision of renewable, non-dispatchable and non-inertial distributed resources
- Support for distributed resources market involvement
- Optimized economical operation

- Throughout islanded operation:

- Durable, improved and economical islanded operation
- Islanding detection, support and operation
- Smooth islanded operating condition with high distributed resources penetration
- Management of critical/non-critical loads with proper voltage and frequency regulation

- For both operations:

- Distributed, resilient and robust architecture
- Secure cyber-physical network

Proper control strategies are required in order to achieve these expected features of microgrid. However, the design of microgrid control and protection systems requires addressing functional challenges to ensure contemporary level of reliability and to extract potential benefits of distributed energy resources (DERs). As a whole, microgrid control challenges can be identified as bidirectional power flows, stability issues, system modelling, low inertia of distributed generation (DG) units, uncertainty and intermittency of various renewable sources for all operational modes (i.e grid-tied mode, islanded mode and transition between two modes) [3]. However, throughout the islanded operation, attached DG units of the microgrid are solely responsible for those requirements. To achieve that objective, proper power sharing among multiple DG units within a microgrid or within multiple microgrids are required. Power sharing using droop control method is popular in literatures due to its simple configuration and ease in implementation. The main concept of the droop control is to emulate the behaviour of synchronous machine. However, the conventional droop

Fig. 1: Multiple hybrid AC/DC microgrids in Griffith University, Australia

control method has its limitation which includes the trade-off between accurate active/reactive power sharing among multiple DG units and overall voltage and frequency regulation. In order to tackle this limitation several modified droop control strategies are proposed such as adjustable load sharing control, VPD/FQB droop control for highly resistive microgrid, virtual frame transformation method, virtual output impedance method, adaptive voltage droop method, signal injection method and non-linear load sharing method [4]. An adaptive PD compensated droop control is proposed in [5] to tackle this trade-off limitation. However, the controller is applied only considering single AC microgrid with AC loads. Excellent literature reviews on several power sharing control strategies for islanded AC microgrid, DC microgrid and hybrid AC/DC microgrid can be found in [6]–[8]. Several power control monitoring strategies with EV-ESSs are given in [9]. However, the feasibility of applying these control methods for multi-microgrid power sharing purpose particularly for multiple hybrid AC/DC microgrids has not been explored considerably. A conventional droop control has been utilized to achieve multi-microgrid operation in [10]. In [11] several control strategies are explored for multi-microgrid energy management but their feasibilities are analysed properly. A distributed control scheme is proposed in [12] for regulating power flow among three microgrids which requires sparse communication among neighbouring microgrids. A communication assisted optimized central controller and an artificial neural network (ANN) based central autonomous management controller (CAMC) for the multi-microgrid operations have been proposed in [13] and [14] respectively.

In order to achieve simultaneous accuracy in both active/reactive power sharing and voltage/frequency regulation for

multiple hybrid AC/DC microgrid operations, a PD compensated droop control method has been designed and utilized for two islanded hybrid AC/DC microgrids in this paper. The PD compensated droop control method is simpler to implement and it requires minimum communication links. A centralized MMOC has been proposed for successful decision making of the multi-microgrid operation. The islanded hybrid AC/DC microgrids are designed based on the real life microgrid model in Griffith University, Australia. The overall system has been designed in MATLAB/SIMULINK environment considering composite loads and dual operational mode of the microgrid (i.e. islanded and multi-microgrid operation). Original contributions of this paper are as follows:

- design of a properly damped PD compensated local controller (LC) for the interlinking converter of an islanded hybrid AC/DC microgrid to ensure simultaneous regulation of AC and DC bus voltages and the stabilization of microgrid frequency;
- development of a simplified multi-microgrid operation control algorithm to achieve effective operation among multiple hybrid AC/DC microgrids;
- coordination of LCs and the MMOC during multi-microgrid operation to achieve concurrent regulation of AC and DC bus voltages and frequency
- impact analysis and utilization of high capacity energy storage system (ESS) like EV-ESS attached to both microgrids.

The rest of the paper is organized as follows. The multi-microgrid system is introduced in section II. The control strategies including interlinking converter control, DC/DC converter control and multi-microgrid operation control are

discussed in. Section III. Case studies to validate the controller performance are presented in Section IV and the concluding remarks on the research outcome are presented in Section V.

II. MULTI-MICROGRID SYSTEM

The test multi-microgrid system is formed considering the under construction multi-microgrid model in Griffith University, Australia. The multi-microgrid system comprises of three buildings (N44, N05 and N74) as illustrated in Fig. 1. Each building operates as separate autonomous electric entity with individual AC and DC buses. Alike type buses accommodates likewise sources and loads. N44 building contains PV panel with ESS which are connected to corresponding DC bus through DC/DC converters. Smart EV/plug-in hybrid electric vehicle (PHEV) charging station are placed in N05 to expedite V2G process. N74 accommodates critical loads which are aided by backup diesel generator and battery ESS during power outage [15].

Since the main focus of the paper is directed towards the multi-microgrid operation utilizing EV-ESS, the simulation model is designed containing only islanded N44 and N05 microgrid system. N44 building is modelled using a 40 kW PV with 48 kWh high capacity ESS. PV units are composed of PV panels and maximum power point tracking (MPPT) system enabled boost converters. ESS are integrated through individual DC/DC converter which is operated with a charge/discharge process. N05 is designed with an EV-ESS which contains DC/DC converter integrated energy storages connected to the DC bus. DC buses of N44 and N05 are intertwined with corresponding AC buses via interlinking VSIs and LC filters. Control parameters of the system is given in Appendix A.

III. CONTROL STRATEGY

The hierarchical control strategies, to ensure efficient multi-microgrid operation, are consists of three types of controller i.e. interlinking converter controller, DC/DC converter controller and the MMOC. The following sections will briefly discuss about the overall control strategies.

A. Interlinking VSI control

Islanded microgrid control requires specific control action to achieve voltage and frequency regulation. Droop embedded VSIs can achieve these objectives. The basic idea of drooping is to emulate the features of synchronous generators which can smoothly control both active and reactive powers. Due to high values of LC filter inductors the X/R ratio of a microgrid is really high. Therefore, well known P/ω and Q/V droop control can be applied to an inductive microgrid for frequency and voltage regulations respectively. Conventional droop control scheme can be expressed as [3]:

$$\begin{aligned}\omega &= \omega^* - D_p(P - P^*) \\ E &= E^* - D_q(Q - Q^*)\end{aligned}\quad (1)$$

where $\omega = 2\pi f$, and f is the frequency of the system, E^* , ω^* ,

P^* and Q^* are reference values for voltage, angular velocity, active power and reactive power, respectively.

Fig. 2: Local controller of the interlinking converters

The primary purpose of multi-microgrid operation is to share active and reactive power among multiple microgrids to meet the load requirements. But this conventional drooping possesses inherent trade-off between active and reactive power sharing accuracy and frequency and voltage regulations.

Considering this issue, a modified droop control is designed assuming the output impedance being proportional to the power sharing ratio as in [5], which ensures adequate damping for both frequency and voltage regulation during transient mode. The modified droop control equations for multi-microgrid operation can be expressed as:

$$\begin{aligned}\omega &= \omega^* - D_p(P - P^*) - D_{dp} \frac{d}{dt}(P - P^*) \\ E &= E^* - D_q(Q - Q^*) - D_{dq} \frac{d}{dt}(Q - Q^*)\end{aligned}\quad (2)$$

The VSI controller structure is illustrated in Fig. 2. The controller includes a measurement unit, a voltage controller unit, a current controller unit and a power controller unit. The measurement unit measures line current i_{abc} and line voltage v_{abc} and convert them into corresponding d and q components. It also measures the frequency (f) of the system through a discrete-time synchronous reference frame phase-locked loop (SRF-PLL), which is later converter into angular velocity ω . The main purpose of voltage controller unit is to generate reference values of i_d and i_q which are i_d^* and i_q^* respectively. Later the current controller will generate necessary reference signal for the associated pulse-width-modulator (PWM) which controls the VSI. The detailed structure of the voltage, current and power controller units with their large signal model can be obtained from [15] and the small signal model can be obtained from [16]. The power controller is comprised of an instantaneous power calculator and the PD compensated droop control method as presented in (2). The outputs of the power controller are v_d^* and ω .

B. DC/DC converter control

Charge/discharge algorithm proposed in [17] has been utilized in this paper to control DC/DC converters of ESSs. In grid connected mode it is expected that grid will provide

necessary load requirement at the same time it will contribute as the active and reactive power regulator [18]. But for islanded microgrid active and reactive power need to be balanced through proper charge/discharge control algorithm or by DC droop method (P-V droop). In a microgrid generation and load demand can be calculated as below:

$$P_{Generation} = \sum P_{AC(DGs)} + \sum P_{DC(DGs)} \quad (3)$$

where $P_{DC(DGs)}$ = power generated by DC DGs, and overall load demand can be calculated as:

$$P_{Consumption} = \sum P_{AC(Loads)} + \sum P_{DC(Loads)} + P_{Loss} \quad (4)$$

In normal condition it is expected that:

$$P_{Generation} \geq P_{Consumption}$$

During that time ESS will be charged via buck/boost converter or maintain halt mode based on battery state-of-charge (SOC) requirement. But if there is any generation-consumption mismatch occurs at the PCC then there might be condition when the following situation will occur:

$$P_{Generation} < P_{Consumption}$$

For this case ESS will measure the power difference δP and compare δP with maximum allowable power range of ESS battery packs. If the δP is in the allowable range then the controller will check battery state-of-charge (SOC) and based on SOC status control signals will be generated either to discharge battery power or to maintain halt condition. If P is higher than the maximum allowable battery power then it will generate a load shedding command to maintain overall power balance in the system. In a microgrid, ESS are used primarily for bus voltage regulation and secondarily as an active power balancer. As a result conventionally DC bus voltage is taken as a reference which is further compared to battery current through PI controller [19]. The designed DC/DC converter controller only contributes to active power balancing thus it features plug and play service.

C. Multi-microgrid operation control (MMOC)

A simplified centralized MMOC has been proposed in this paper for efficient multi-microgrid operation. The main purpose of this controller is to generate command for initiating multi-microgrid operation. As illustrated in Fig. 3, initially the controller collects the total power generation and total load of individual microgrids through smart meters (PM5350A) [15]. Afterwards, it calculates the deviation between total generation and total load and checks whether additional power is required or not for a particular microgrid. If any microgrid lacks required power then the controller generates references for both active and reactive power which are P^* and Q^* respectively. In the next step it checks whether the generated references are within the critical limit for the aiding microgrid. If the references are within the critical limit then the MMOC initiates multi-microgrid operation, otherwise it commands the LC of the interlinking converter to switch back to the grid or

Fig. 3: Simplified multi-microgrid operation control algorithm

to curtail additional load. The initiation of the multi-microgrid operation includes two steps. At first the switch closing command is sent to the intelligent bypass switch (IBS) between two microgrids. The IBS simultaneously checks for the synchronism in both microgrids which are achieved via SRF-PLLs. IBS will be closed when both microgrids are in synchronism. Then the references for both active and reactive power are sent to the droop control part of the LCs of the interlinking converters between multiple microgrids.

IV. CASE STUDIES

Simulation has been carried out to demonstrate the efficacy and the performance of the designed controllers for smooth multi-microgrid operations. “Smooth multi-microgrid operations” refer that the controller should be able to perform efficiently in all three operational modes i.e. islanded, multi-microgrid and transition between these two modes. Thus the overall system is exposed to islanded mode, multi microgrid mode and transition between two modes to evaluate the performance of the controller. The system is also exposed to three-phase fault condition to evaluate the robustness of the controller. The overall system and the control structures have been designed in MATLAB/SIMULINK® environment using SimPowerSystems™ toolbox. The simulations are run on Intel(R) Core(TM)i5-4570 CPU 3.20 GHz with 8.00 GB RAM. The time period for the simulation has been kept as 5 s. In order to accelerate the simulation speed, the whole system has been discretised with sample time of $T_s = 1 \times 10^{-6}$ s. All the results obtained from the simulation are given in Fig. 4.

A. Islanded operation

From 0 s to 1.5 s both designed microgrids (N44 and N05) are isolated from each other. During this time PV panels and

Fig. 4: Simulation results for islanded scenario: (0 s - 1.5 s) and (4 s - 5 s); multi-microgrid scenario: 1.5 s - 4 s

ESS of N44 will serve its AC and DC loads and ESS of N05 will serve its AC and DC loads. The individual droop control of each microgrid maintains the frequency and voltage within acceptable range. Droop coefficients for individual islanded microgrid model have been chosen carefully keeping the standard values in mind. The Australian Energy Market Operator (AEMO) specifies the voltage magnitude limit for islanded microgrid operation to be within - 6% to +10% [20] and the standard frequency range to be in between 49.5Hz to 50.5Hz [21]. It can be observed from Fig. 4 (a-c) the DC bus voltage, AC bus RMS voltage and the frequency are within the standard range.

B. Multi-microgrid operation

At 1.5 s the N05 microgrid is overloaded. The MMOC senses the overloading condition and sends command to the IBS in between N44 and N05 to close so that the islanded N04 microgrid can be connected with the high power capacity microgrid N44. As a result, the multi-microgrid operation between N44 and N05 is initiated. Both N44 and N05 share their active and reactive power according to the pre-set droop coefficients. The active and reactive power of the N44 and N05 inverters are given in Fig. 4 (d-e). Fig. 4 (f) shows the active power contribution from each ESS. At 4 s multi-microgrid operation is terminated by the MMOC as the overloading condition is removed. Both microgrids start operating in islanded mode. Individual droop mechanisms maintain voltage and frequency within acceptable range. Overall system active and reactive power profile are given in Fig. 4 (g-h).

C. Severe three-phase (3-P) fault

In order to test the robustness of the designed controller the multi-microgrid system is exposed to a three-phase fault at the point of interconnection with a duration of 5 cycles i.e: 0.1 s. It can be observed from the Fig. 5 (a-b) that the conventional droop control is unable to maintain the overall system frequency and voltage within acceptable range whereas PD compensated droop can efficiently maintain voltage and frequency stability throughout the period of multi-microgrid operation.

Fig. 5: Three phase (3-P) fault scenario

V. CONCLUSION

In this paper a multi-purpose interlinking converter has been designed along with a centralized MMOC for smooth and coordinated operation among multiple hybrid AC/DC microgrid systems. The MMOC generates required reference

signals for the embedded droop controllers of each LC and decides whether a particular microgrid should participate in multi-microgrid operation. Based on those commands the LC operate the power sharing mechanism among multiple microgrids. The multi-microgrid scenario is designed based on the real-life microgrid in Griffith University, Australia. Overall system has been tested for islanded, multi-microgrid and the transition between two modes operational conditions. The system is also exposed to severe three-phase fault condition in order to compare the controller's performance with the conventional design. From simulation results it is evident that the designed controller show excellent performance with accurate active/reactive power sharing and voltage/frequency regulation capabilities. Future direction of this research is directed towards the consideration of unbalanced weak grid conditions [22] and the distributed coordination of DG units.

APPENDIX A

SIMULATION MODEL PARAMETERS

Energy sources: PV: 40 kW, ESS - 1: 48 kWh, ESS - 2: 48 kWh, EV-ESS: 48 kWh

Nominal AC bus RMS voltage: 230 ~ 240 V

Nominal DC bus voltage: 600 ~ 800 V

LC filter (N44): $2 \times 10^{-3} \Omega$, $250 \times 10^{-6} \text{H}$, 0.0169F

LC filter (N05): $2 \times 10^{-3} \Omega$, $250 \times 10^{-6} \text{H}$, 0.0169F

Control parameters:

ω^* : 314.16 rad/s, E^* : 340 V

N44 side:

Power controller: D_p : $3.14 \times 10^{-5} \text{ rad/s/W}$, D_{dp} : 0.0003 rad/W,

D_Q : $3.14 \times 10^{-5} \text{ V/VAR}$, D_{dq} : 0.0003 V-s/VAR

Voltage controller: k_p : 4.1497; k_i : 3.90×10^3

Current controller: k_p : 0.7390; k_i : 3.90×10^3

DC/DC converter: k_p : 7; k_i : 800; 0.005Ω , $5 \times 10^{-3} \text{H}$

N05 side:

Power controller: D_p : $3.14 \times 10^{-5} \text{ rad/s/W}$, D_{dp} : 0.0003 rad/W,

D_Q : $3.14 \times 10^{-5} \text{ V/VAR}$, D_{dq} : 0.0003 V-s/VAR

Voltage controller: k_p : 4.1497; k_i : 3.90×10^3

Current controller: k_p : 0.7390; k_i : 3.90×10^3

DC/DC converter: k_p : 7; k_i : 800; 0.005Ω , $5 \times 10^{-3} \text{H}$

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