CONTROL AND OPERATION OF A DC GRID-BASED WIND POWER GENERATION SYSTEM IN A MICROGRID

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***Abstract*— The poultry farming is the raising of domesticated birds such as chickens and ducks for the purpose of farming meat or eggs for food. To ensure that the poultries remain productive, the poultry farms in Singapore are required to be maintained at a comfortable temperature. Cooling fans, with power ratings of tens of kilowatts, are usually installed to regulate the temperature in the farms .Besides cooling the farms, the wind energy produced by the cooling fans can be harnessed using wind turbines(WTs) to reduce the farms demand on the grid. The major difference between the situation in poultry farms and common wind farms is in the wind speed variability.**

In recent years, the research attention on dc grids has been resurging due to technological advancements in power electronics and energy storage devices ,and increase in the variety of dc loads and the penetration of dc distributed energy resources(DERs) such as solar photovoltaic and fuel cells. Many research works on dc micro grids have been conducted to facilitate the integration of various DERs and energy storage systems. In a dc micro grid based wind farm architecture in which each wind energy conversion unit consisting of a matrix converter, a high frequency transformer and a single-phase ac/dc converter are proposed. However, the proposed architecture increases the system complexity as three stages of conversion are required.

In this project as an alternative solution we are proposing a dc grid based distribution network. Where the ac output of the wind generators (WGs) in a poultry form are rectified to a common voltage at the dc grid. Most significant advantage of the proposed system is that only the voltage at the dc grid has to be controlled for parallel operation of several WGs without the need to synchronize the voltage, frequency and phase thus allowing the WGs to be turned ON (or) OFF any time without causing disruptions.

***Index Terms*— Wind power generation, dc grid, energy management, model predictive control.**

I. INTRODUCTION

Microgrid enhances the integration of renewable and distributed energy sources, integration of combined power and heat, reduces losses by locating generation near demand. A utility grid connection is used in order to replenish energy levels in the case of power shortage from the renewable energy sources. The combination of wind generator and PV modules with local energy storage devices may reduce exposure to natural disasters. Microgrids require defined Industrial costumer, substation, voltage, power factor with tolerances match load and generation. It also defines loads; determine island duration, peak load, and typical outage. Microgrid promotes demand side management and load leveling, ensuring energy supply for critical loads, reliability control. The microgrid is having reduced fuel consumption, having good efficiency. Microgrids require defined microgrid boundary, Industrial customer, campus, substation, match load and generation, voltage, frequency and power factor within tolerances.

The applications of Microgrids can vary in storage, advanced controls, size in Mega Watts, generation resource types, microgrid value proposition. The Microgrids gives Energy security, grid independence capability and ensure energy supply for critical loads utilizing on site generation. Multiple input dc-dc converters are used for integrating into the main bus. The use of multiple input converters reduces use of additional parallel converters in each energy source. The wind/solar hybrid power system with a multiple input dc-dc converter in which the variations in the local ac load power and dispatch power to the distribution grid are considered. Many research works on dc microgrids have been conducted to facilitate the integration of various DERs and energy storage systems.

In a dc microgrid based wind farm architecture in which each wind energy conversion unit consisting of a matrix converter, a high frequency transformer and a single-phase ac/dc converter is proposed. However, the proposed architecture increases the system complexity as three stages of conversion are required. In a dc microgrid based wind farm architecture in which the WTs are clustered into groups of four with each group connected to a converter is proposed. However, with the proposed architecture, the failure of one converter will result in all four WTs of the same group to be out of service. The research works conducted are focused on the development of different distributed control strategies to coordinate the operation of various DERs and energy storage systems in dc microgrids. These research works aim to overcome the challenge of achieving a decentralized control operation using only local variables. However, the DERs in dc microgrids are strongly coupled to each other and there must be a minimum level of coordination between the DERs and the controllers. In a hybrid ac/dc grid architecture that consists of both ac and dc networks connected together by a bidirectional converter is proposed. Hierarchical control algorithms are incorporated to ensure smooth power transfer between the ac microgrid and the dc microgrid under various operating conditions.

However, failure of the bidirectional converter will result in the isolation of the dc microgrid from the ac microgrid. An alternative solution using a dc grid based distribution network where the ac outputs of the wind generators (WGs) in a poultry farm are rectified to a common voltage at the dc grid is proposed in this paper. The most significant advantage of the proposed system is that only the voltage at the dc grid has to be controlled for parallel operation of several WGs without the need to synchronize the voltage, frequency and phase, thus allowing the WGs to be turned ON or OFF anytime without causing any disruptions. To increase the controller's robustness against variations in the operating conditions when the microgrid operates in the grid-connected or islanded mode of operation as well as its capability to handle constraints, a model-based model predictive control (MPC) design is proposed in this paper for controlling the inverters. As the microgrid is required to operate stably in different operating conditions, the deployment of MPC for the control of the inverters offers better transient response with respect to the changes in the operating conditions and ensures a more robust microgrid operation.

There are some research works on the implementation of MPC for the control of inverters. In a finite control set MPC scheme which allows for the control of different converters without the need of additional modulation techniques or internal cascade control loops is presented but the research work does not consider parallel operation of power converters. In an investigation on the usefulness of the MPC in the control of parallel-connected inverters is conducted. The research work is, however, focused mainly on the control of inverters for uninterruptible power supplies in standalone operation. The MPC algorithm will operate the inverters close to their operating limits to achieve a more superior performance as compared to other control methods which are usually conservative in handling constraints. In this paper, the inverters are controlled to track periodic current and voltage references and the control signals have a limited operating range. Under such operating condition, the MPC algorithm is operating close to its operating limits where the constraints will be triggered repetitively. In conventional practices, the control signals are clipped to stay within the constraints, thus the system will operate at the sub-optimal point.

This results in inferior performance and increases the steady-state loss. MPC, on the contrary, tends to make the closed-loop system operate near its limits and hence produces far better performance. MPC has also been receiving increased research attention for its applications in energy management of microgrids because it is a multi-input, multi-output control method and allows for the implementation of control actions that predict future events such as variations in power generation by intermittent DERs, energy prices and load demands. In these research works, the management of energy is formulated into different multi-objective optimization problems and different MPC strategies are proposed to solve these optimization problems. The scope of this paper is however focused on the application of MPC for the control of inverters.

II. SYSTEM MODELING

When the micro grid is operating connected to the distribution grid, the WTs in the micro grid are responsible for providing local power support to the loads, thus reducing the burden of power delivered from the grid. The SB can be controlled to achieve different demand side management functions such as peak shaving and valley filling depending on the time-of-use of electricity and SOC of the SB. During islanded operation where the CBs disconnect the micro grid from the distribution grid, the WTs and the SB are only available sources to supply the load demand.

The micro grid to operate in both grid-connected and islanded modes of operation, a model based controller using MPC is proposed for the control of the inverters. MPC is a model-based controller and adopts a receding horizon approach in which the optimization algorithm will compute a sequence of control actions to minimize the selected objectives for the whole control horizon, but only execute the first control action for the inverter. The overall configuration of the proposed dc grid based wind power generation system for the poultry farm is shown in Fig. 1. The system can operate either connected to or islanded from the distribution grid and consists of four 10 kW permanent magnet synchronous generators (PMSGs) which are driven by the variable speed WTs. The PMSG is considered in this paper because it does not require a dc excitation system that will increase the design complexity of the control hardware.

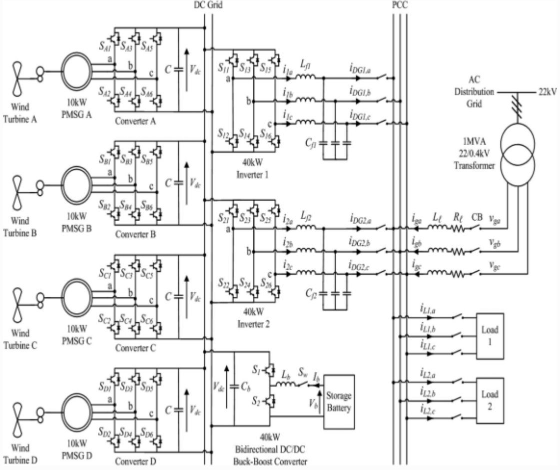

Fig.1. Overall configuration of the proposed dc grid based wind power generation system in a microgrid.

The three-phase output of each PMSG is connected to a three-phase converter (i.e., converters A, B, C and D), which operates as a rectifier to regulate the dc output voltage of each PMSG to the desired level at the dc grid. The aggregated power at the dc grid is inverted by two inverters (i.e., inverters 1 and 2) with each rated at 40 kW. Instead of using individual inverter at the output of each WG, the use of two inverters between the dc grid and the ac grid is proposed. This architecture minimizes the need to synchronize the frequency, voltage and phase, reduces the need for multiple inverters at the generation side, and provides the flexibility for the plug and play connection of WGs to the dc grid. The availability of the dc grid will also enable the supply of power to dc loads more efficiently by reducing another ac/dc conversion.

A. DC/AC INVERTER MODELING:

The two 40 kW three-phase dc/ac inverters which connect the dc grid to the point of common coupling (PCC) are identical, and the single-phase representation of the three-phase dc/ac inverter. To derive a state-space model for the inverter, Kirchhoff's voltage and current laws are applied to loop i and point x respectively, the grid is set as a large power system, which means that the grid voltage is a stable three-phase sinusoidal voltage. Hence, when operating in the CCM, a three-phase sinusoidal signal can be used directly as the exogenous input. During islanded operation, the inverters will be operated in the voltage control mode (VCM). The voltage of the PCC will be maintained by the inverters when the micro grid is islanded from the grid.

B. AC/DC CONVERTER MODELING:

The effectiveness of the proposed design concept is evaluated under different operating conditions when the micro grid is operating in the grid-connected or islanded mode of operation. The impedances of the distribution line are obtained. In practical implementations, the values of the converter and inverter loss resistance are not precisely known. Therefore, these values have been coarsely estimated. When the micro grid is operating in the grid-connected mode of operation, the proposed wind power generation system will supply power to meet part of the load demand. Under normal operating condition, the total power generated by the PMSGs at the dc grid is converted by inverters 1 and 2 which will share the total power supplied to the loads. When one of the inverters fails to operate and needs to be disconnected from the dc grid, the other inverter is required to handle all the power generated by the PMSGs. In this test case, an analysis on the Micro grid operation when one of the inverters is disconnected from operation is conducted.

C. NUMERICAL SIMULATION ANALYSIS:

When the micro grid operates islanded from the distribution grid, the total generation from the PMSGs will be insufficient to supply for all the load demand. Under this condition, the SB is required to dispatch the necessary power to ensure that the micro grid continues to operate stably. The third case study shows the micro grid operation when it islands from the grid. The micro grid is initially operating in the grid-connected mode. The grid is supplying real power of 40 kW and reactive power of 4 kVAr to the loads for $0 \leq t < 0.2$ s while each inverter is delivering real power of 10 kW and reactive power of 4 kVAr to the loads.

D. REPORT GENERATION:

The design of a dc grid based wind power generation system in a micro grid that enables parallel operation of several WGs in a poultry farm has been presented. As compared to conventional wind power generation systems, the proposed micro grid architecture eliminates the need for voltage and frequency synchronization, thus allowing the WGs to be switched on or off with minimal disturbances to the micro grid operation. The design concept has been verified through various test scenarios to demonstrate the operational capability of the proposed micro grid and the simulation results has shown that the proposed design concept is able to offer increased flexibility and reliability to the operation of the micro grid. However, the proposed control design still requires further experimental validation because measurement errors due to inaccuracies of the voltage and current sensors, and modeling errors due to variations in actual system parameters such as distribution line and transformer impedances will affect the performance of the controller in practical implementation.

III. SIMULATION RESULTS

The simulation model of the proposed dc grid based wind power generation system shown in Fig. 1 is implemented in MATLAB/Simulink. The effectiveness of the proposed design concept is evaluated under different operating conditions when the microgrid is operating in the grid-connected or islanded mode of operation. In practical implementations, the values of the converter and inverter loss resistance are not precisely known. Therefore, these values have been coarsely estimated.

A. Failure of One Inverter during Grid-Connected Operation:

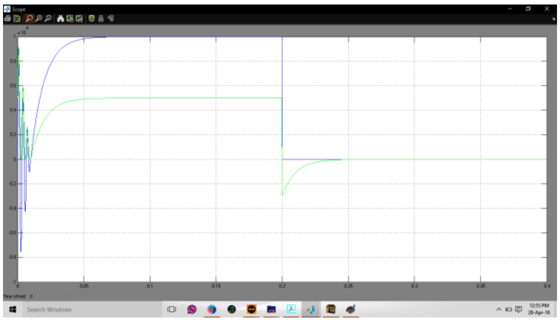

Fig. 2. Real (top) and reactive (bottom) power delivered by inverter 1.

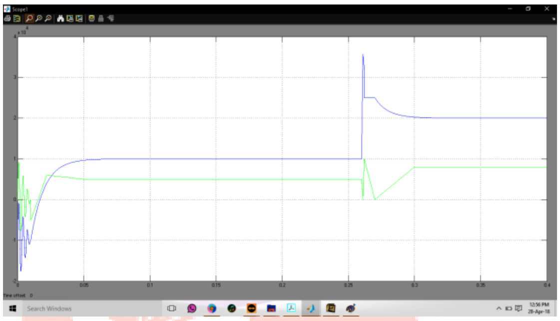

Fig. 3. Real (top) and reactive (bottom) power delivered by inverter 2.

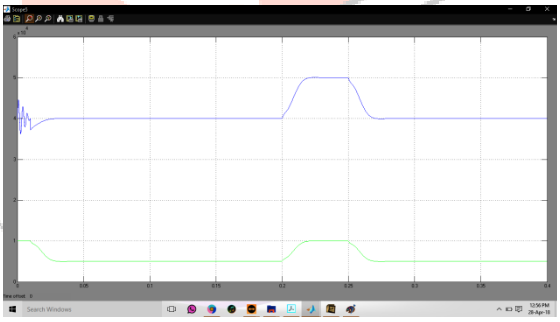

Fig. 4. Real (top) and reactive (bottom) power delivered by the grid.

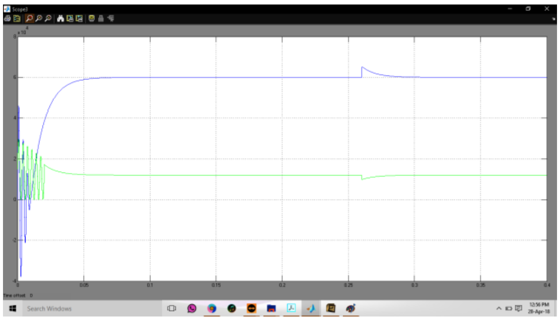

Fig. 5. Real (top) and reactive (bottom) power consumed by the loads.

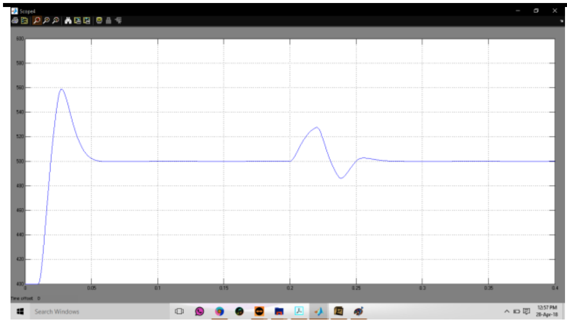
Fig. 6. DC grid voltage.

In this test case, an analysis on the microgrid operation when one of the inverters is disconnected from operation is conducted. With each PMSG generating about 5.5 kW of real power, the total power generated by the four PMSGs is about 22 kW which is converted by inverters 1 and 2 into 20 kW and 8 kVAr of real and reactive power respectively. Figs. 2 and 3 show the waveforms of the real and reactive power delivered by inverters 1 and 2 for $0 \leq t < 0.4$ s respectively. For $0 \leq t < 0.2$ s, both inverters 1 and 2 are in operation and each inverter delivers about 10 kW of real power and 4 kVAr of reactive power to the loads. The remaining real and reactive power that is demanded by the loads is supplied by the grid which is shown in Fig.4. It can be seen from Fig. 4 that the grid delivers 40 kW of real power and 4 kVAr of reactive power to the loads for $0 \leq t < 0.2$ s. The total real and reactive power supplied to the loads is about 60 kW and 12 kVAr as shown in the power waveforms of Fig. 5. The unsteady measurements observed in the power waveforms for $0 \leq t < 0.08$ s are because the controller requires a period of about four cycles to track the power references during the initialization period. At $t = 0.2$ s, inverter 1 fails to operate and is disconnected from the microgrid, resulting in a loss of 10 kW of real power and 4 kVAr of reactive power supplied to the loads. As shown in Fig. 2, the real and reactive power supplied by inverter 1 is decreased to zero in about half a cycle after inverter 1 is disconnected. This undelivered power causes a sudden power surge in the dc grid which corresponds to a voltage rise at $t = 0.2$ s as shown in Fig. 6. To ensure that the load demand is met, the grid automatically increases its real and reactive power generation to 50 kW and 8 kVAr respectively at $t = 0.2$ s, as shown in Fig. 4. At $t = 0.26$ s, the EMS of the microgrid increases the reference real and reactive power supplied by inverter 2 to 20 kW and 8 kVAr respectively. A delay of three cycles is introduced to later for the response time of the EMS to the loss of inverter 1. As shown in Fig. 3, inverter 2 manages to increase its real and reactive power supplied to the loads to 20 kW and 8 kVAr for $0.26 \leq t < 0.4$ s. At the same time, the grid decreases its real and reactive power back to 40 kW and 4 kVAr as shown in Fig. 4 respectively. The power balance in the microgrid is restored after three cycles from $t = 0.26$ s. It is observed from Fig. 6 that the voltage at the dc grid corresponds to a voltage dip at $t = 0.26$ s due to the increase in power drawn by inverter 2 and then returns to its nominal value of 500 V for $0.26 \leq t < 0.4$ s. As observed in Fig. 5, at $t = 0.26$ s, the changes in power delivered by inverter 2 and the grid also cause a transient in the load power.

B. Connection of AC/DC Converter during Grid-Connected Operation:

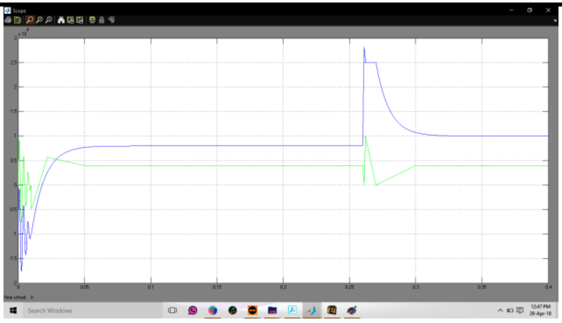
Fig. 7. Real (top) and reactive (bottom) power delivered by inverter 1.

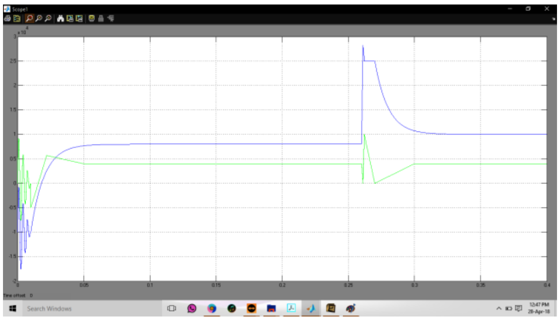
Fig. 8. Real (top) and reactive (bottom) power delivered by inverter 2.

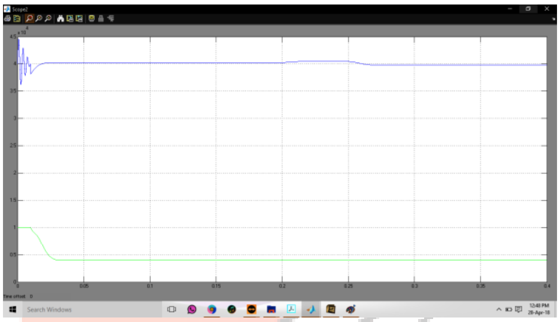
Fig. 9. Real (top) and reactive (bottom) power delivered by the grid.

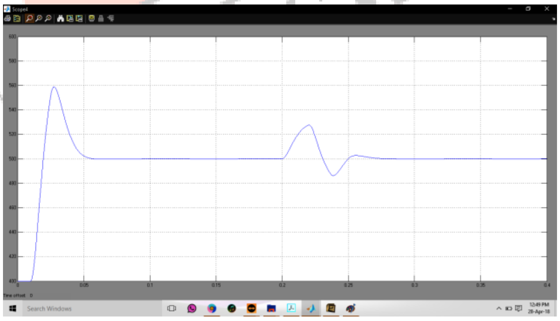
Fig. 10. DC grid voltage.

The most significant advantage of the proposed dc grid based wind power generation system is that it facilitates the connection of any PMSGs to the microgrid without the need to synchronize their voltage and frequency. This capability is demonstrated in this case study. The microgrid operates connected to the grid and PMSG A is disconnected from the dc grid for $0 \leq t < 0.2$ s as shown in Fig.1. The real power generated from each of the remaining three PMSGs is maintained at 5.5 kW and their aggregated real power of 16.5 kW at the dc grid is converted by inverters 1 and 2 into 14 kW of real power and 8 kVAr of reactive power. As shown in Figs. 7 and 8, each inverter delivers real and reactive power of 7 kW and 4 kVAr to the loads respectively. The rest of the real and reactive power demand of the loads is supplied by the grid as shown in Fig. 9. It can be seen from Fig. 9 that the grid delivers 46 kW of real power and 4 kVAr of reactive power to the loads. At t = 0.2 s, PMSG A which generates real power of 5.5 kW is connected to the dc grid. This causes a sudden power surge at the dc grid and results in a voltage rise at t = 0.2 s as shown in the voltage waveform of Fig. 10. At t = 0.26 s, the EMS increases the real delivered by each inverter to 10 kW while the reactive power supplied by each inverter remains unchanged at 4 kVAr as shown in Figs. 7 and 8. This causes a momentarily dip in the dc grid voltage at t = 0.26 s as observed in Fig. 10 which is then restored back to its nominal voltage of 500 V for 0.26 ≤ t < 0.4 s. The grid also simultaneously decreases its supply to 40 kW of real power for 0.26 ≤ t < 0.4 s while its reactive power remains constant at 4 kVAr as shown in Fig. 9.

C. Islanded Operation:

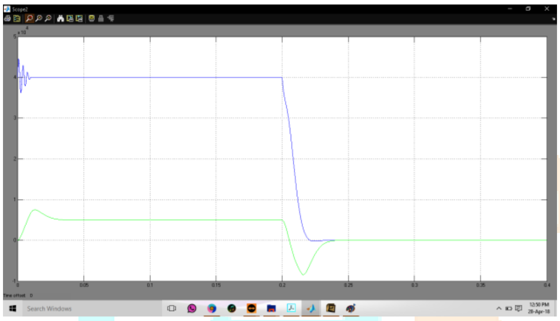

Fig. 11. Real (top) and reactive (bottom) power delivered by the grid.

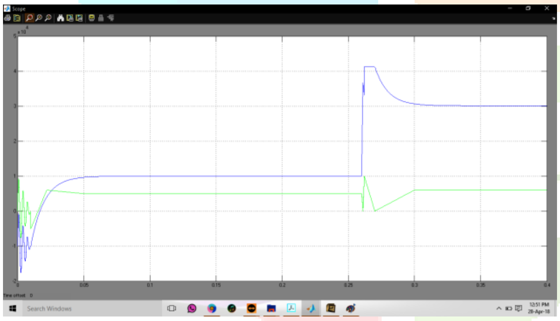

Fig. 12. Real (top) and reactive (bottom) power delivered by inverter 1.

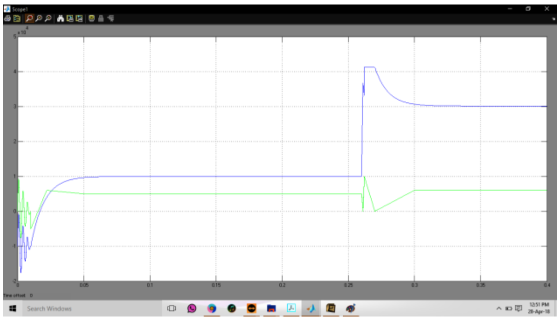

Fig. 13. Real (top) and reactive (bottom) power delivered by inverter 2.

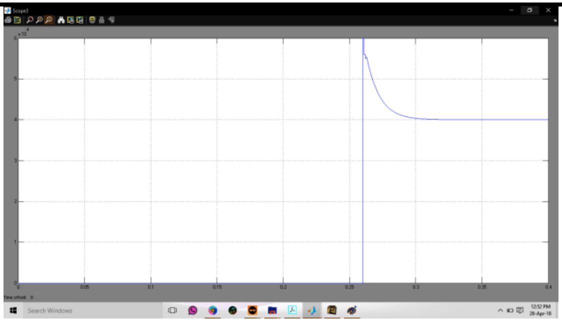

Fig. 14. Real power delivered by SB.

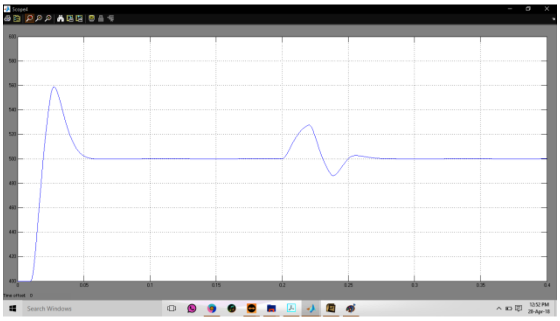

Fig. 15. DC grid voltage.

When the microgrid operates islanded from the distribution grid, the total generation from the PMSGs will be insufficient to supply for all the load demand. Under this condition, the SB is required to dispatch the necessary power to ensure that the microgrid continues to operate stably. The third case study shows the microgrid operation when it islands from the grid. The microgrid is initially operating in the grid-connected mode. The grid is supplying real power of 40 kW and reactive power of 4 kVAr to the loads for 0 ≤ t < 0.2 s as shown in Fig. 11 while each inverter is delivering real power of 10 kW and reactive power of 4 kVAr to the loads as shown in Figs. 11 and 12. At t = 0.2 s, the microgrid is disconnected from the distribution grid by the CBs due to a fault occurring in the upstream network of the distribution grid. It can be seen from Fig. 13 that the CBs fully separate the microgrid from the grid in about half a cycle, resulting in zero real and reactive power supplied by the grid for 0.2 ≤ t < 0.4 s. With the loss of power supply from the grid, the power imbalance between the generation and load demand is detected by the EMS. To maintain the stability of the microgrid, the SB is tasked by the EMS to supply real power of 40 kW at t = 0.26 s as shown in Fig. 14. At the same time, the real and reactive power delivered by each inverter is also increased by the EMS to 30 kW and 6 kVAr as shown in Figs. 11 and 12 respectively. Fig. 15 shows the dc grid voltage where slight voltage fluctuations are observed at t = 0.26 s. The initial voltage rise at t = 0.26 s is due to the power supplied by the SB while the subsequent voltage dip is due to the increase in power drawn by the inverters.

IV. CONCLUSION

In this paper, the design of a dc grid based wind power generation system in a microgrid that enables parallel operation of several WGs in a poultry farm has been presented. As compared to conventional wind power generation systems, the proposed microgrid architecture eliminates the need for voltage and frequency synchronization, thus allowing the WGs to be switched on or off with minimal disturbances to the microgrid operation. The design concept has been verified through various test scenarios to demonstrate the operational capability of the proposed microgrid and the simulation results has shown that the proposed design concept is able to offer increased flexibility and reliability to the operation of the microgrid.

However, the proposed control design still requires further experimental validation because measurement errors due to inaccuracies of the voltage and current sensors, and modeling errors due to variations in actual system parameters such as distribution line and transformer impedances will affect the performance of the controller in practical implementation. In addition, MPC relies on the accuracy of model establishment; hence further research on improving the controller robustness to modeling inaccuracy is required. The simulation results obtained and the analysis performed in this paper serve as a basis for the design of a dc grid based wind power generation system in a microgrid.

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