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A Novel Neurofuzzy Topology for Grid Integrated Wind Power Generation System

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***Abstract*: This Thesis presents the design of a dc grid-based wind power generation system in small firms. The proposed system of hybrid Neuro-Fuzzy control allows flexible operation of multiple parallel-connected wind generators by eliminating the need for voltage and frequency synchronization. A model predictive control algorithm that offers better transient response with respect to the changes in the operating conditions is proposed forthe control of the inverters. The design concept is verified through various test scenarios to demonstrate the operational capability of the proposed micro grid when it operates connected to and islanded from the distribution grid, and the results obtained are discussed.**

I. INTRODUCTION

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 [1]–[3]. 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 Singapore government is actively promoting this new concept of harvesting wind energy from electric ventilation fans in poultry farms which has been implemented in many countries around the world [4]. The major difference between the situation in poultry farms and common wind farms is in the wind speed variability. The variability of wind speed in wind farms directly depends on the environmental and weather conditions while the wind speed in poultry farms is generally stable as it is generated by constant-speed ventilation fans. Thus, the generation intermittency issues that affect the reliability of electricity supply and power balance are not prevalent in poultry farm wind energy systems.

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's 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 [5], [6], 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 is proposed. However, the proposed architecture increases the system complexity as three stages of conversion are required. In [7], 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 in [8]–[10] are focused on the development of different distributed control strategies to coordinate the operation of various DERs and energy storage systems in dc micro grids. 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[11], [12], 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 micro grid and the dc micro grid under various operating conditions. However, failure of the bidirectional converter will result in the isolation of the dc micro grid from the ac micro grid. 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 signifificant 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. Many research works on designing the controllers for the control of inverters in a micro grid during grid-connected and islanded operations is conducted in [13]–[15]. A commonly adopted control scheme which is detailed in [13], [14] contains an inner voltage and current loop and an external power loop to regulate the output voltage and the power flow of the inverters. In [15], a control scheme which uses separate controllers for the inverters during grid-connected and islanded operations is proposed. Although there are a lot of research works being conducted on the development of primary control strategies for DG units, there are many areas that require further improvement and research attention. These areas include improving the robustness of the controllers to topological and parametric uncertainties, and improving the transient response of the controllers. 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 [16], a fifinite 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 [17], 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 [18], [19]. 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 [20]–[22]. 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. In what follows, a comprehensive solution for the operation of a dc grid based wind power generation system in a micro grid is proposed for a poultry farm and the effectiveness of the proposed system is verified by simulation studies under different operating conditions.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

The overall configuration of the proposed dc grid based wind power generation system for the poultry farm. 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. 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 effificiently by reducing another ac/dc conversion.

The coordination of the converters and inverters is achieved through a centralized energy management system (EMS). The EMS controls and monitors the power dispatch by each WG and the load power consumption in the microgrid through a centralized server. To prevent excessive circulating currents between the inverters, the inverter output voltages of inverters 1 and 2 are regulated to the same voltage. Through the EMS, the output voltages of inverters 1 and 2 are continuously monitored to ensure that the inverters maintain the same output voltages. The centralized EMS is also responsible for other aspects of power management such as load forecasting, unit commitment, economic dispatch and optimum power flflow. Important information such as fifield measurements from smart meters, transformer tap positions and circuit breaker status are all sent to the centralized server for processing through wireline/wireless communication. During normal operation, the two inverters will share the maximum output from the PMSGs (i.e., each inverter shares 20 kW). The maximum power generated by each WT is estimated from the optimal wind power Pwt,opt as follows

$$P_{\mathrm{wt,opt}} = k_{\mathrm{opt}}(\omega_{r,\mathrm{opt}})^3 \quad (1)$$

$$k_{\mathrm{opt}} = \frac{1}{2} C_{p,\mathrm{opt}} \rho A \left(\frac{R}{\lambda_{\mathrm{opt}}}\right)^3 \quad (2)$$

$$\omega_{r,\mathrm{opt}} = \frac{\lambda_{\mathrm{opt}} v}{R} \quad (3)$$

where $k$opt is the optimized constant, $\omega r,$opt is the WT speed for optimum power generation, Cp,opt is the optimum power coeffificient of the turbine, ρ is the air density, A is the area swept by the rotor blades, λopt is the optimum tip speed ratio, v is the wind speed and R is the radius of the blade. When one inverter fails to operate or is under maintenance, the other inverter can handle the maximum power output of 40 kW from the PMSGs. Thus the proposed topology offers increased reliability and ensures continuous operation of the wind power generation system when either inverter 1 or inverter 2 is disconnected from operation. An 80 Ah storage battery (SB), which is sized according to [24], is connected to the dc grid through a 40 kW bidirectional dc/dc buck-boost converter to facilitate the charging and discharging operations when the microgrid operates connected toor islanded from the grid. The energy constraints of the SB in the proposed dc grid are determined based on the system-on-a-chip (SOC) limits given by wind speed and R is the radius of the blade. When one inverter fails to operate or is under maintenance, the other inverter can handle the maximum power output of 40 kW from the PMSGs. Thus the proposed topology offers increased reliability and ensures continuous operation of the wind power generation system when either inverter 1 or inverter 2 is disconnected from operation. An 80 Ah storage battery (SB), which is sized according to [24], is connected to the dc grid through a 40 kW bidirectional dc/dc buck-boost converter to facilitate the charging and discharging operations when the microgrid operates connected to or islanded from the grid. The energy constraints of the SB in the proposed dc grid are determined based on the system-on-a-chip (SOC) limits given by

$$\mathrm{SOC}_{\min} < \mathrm{SOC} \leq \mathrm{SOC}_{\max} \quad (4)$$

Although the SOC of the SB cannot be directly measured, it can be determined through the estimation methods as detailed in [25], [26]. With the use of a dc grid, the impact of flfluctuations between power generation and demand can be reduced as the SB can swiftly come online to regulate the voltage at the dc grid. During off-peak periods when the electricity demand is low, the SB is charged up by the excess power generated by the WTs. Conversely, during peak periods when the electricity demand is high, the SB will supplement the generation of the WTs to the loads.

B. System Operation

When the microgrid is operating connected to the distribution grid, the WTs in the microgrid 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 valleyfilling depending on the time-of-use of electricity and SOC of the SB.

During islanded operation where the CBs disconnect the microgrid from the distribution grid, the WTs and the SB are only available sources to supply the load demand. The SB can supply for the defificit in real power to maintain the power balance of the microgrid as follows:

$$P_{\mathrm{wt}} + P_{\mathrm{sb}} = P_{\mathrm{loss}} + P_l \quad (5)$$

where Pwt is the real power generated by the WTs, Psb is the real power supplied by SB which is subjected to the constraint of the SB maximum power Psb,max that can be delivered during discharging and is given by

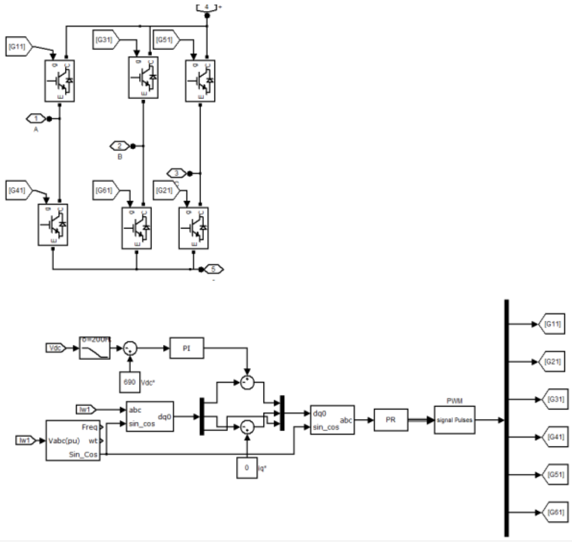
$$P_{\mathrm{sb}} \leq P_{\mathrm{sb,max}} \quad (6)$$

Ploss is the system loss, and Pl is the real power that is supplied to the loads.

III. CONTROL DESIGN

A. Control Design for the AC/DC Converter

Fig. 4 shows the configuration of the proposed controller for each ac/dc voltage source converter which is employed to maintain the dc output voltage Vdc of each converter and compensate for any variation in Vdc due to any power imbalance in the dc grid. The power imbalance will induce a voltage error ($V * \mathrm{dc} - V\mathrm{dc}$) at the dc grid, which is then fed into a proportional integral controller to generate a current reference $i{*}d$ for id totrack. To eliminate the presence of high frequency switching ripples at the dc grid, Vdc is fifirst passed through a first-order LPF. The current iq is controlled to be zero so that the PMSG only delivers real power. The current errors Δid and Δiq are then converted into the *abc* frame and fed into a proportional resonant (PR) controller to generate the required control signalsusing pulse-width modulation.



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B. Control Design for the DC/AC Inverter

In order for 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 fifirst control action for the inverter. At the next time step, the optimization process is repeated based on new measurements over a shifted prediction horizon. By doing so, MPC can make the output track he reference at the next step, as well as plan and correct its control signals along the control process. This will guarantee a better transient response compared to conventional Neuro-Fuzzy controllers. To derive the control algorithm for the inverters, the state-space equations are transformed into augmented state-space equations by deifying the incremental variables.

IV .MATLAB/SIMULINK MODELING AND RESULTS

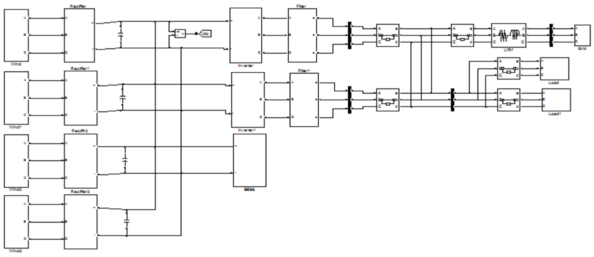

Fig 1 Simulink model for DC grid based wing power energy based system

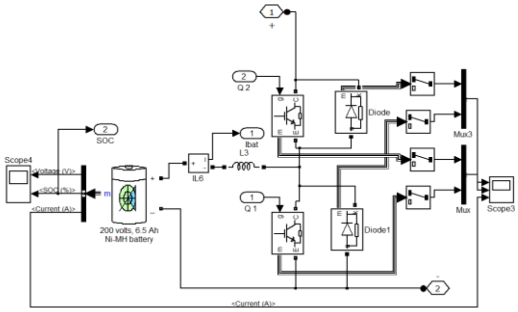

Fig 2 Simulink model for PI controlling diagram

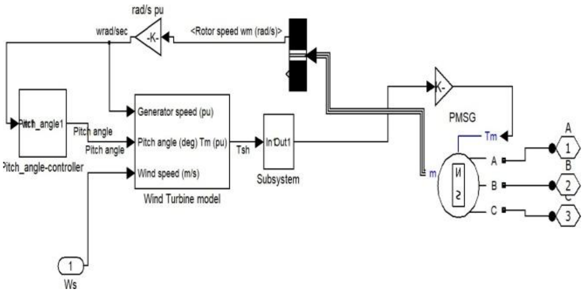

Fig 3 Simulink model for Wind Energy conversion

Fig 4 Simulink model for DC Battery energy stored system

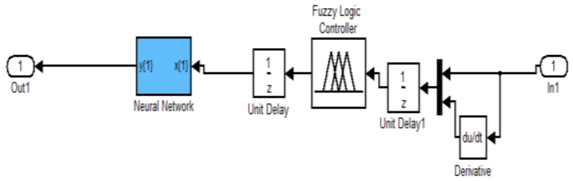

Fig 5 Neuro-Fuzzy Scheme Simulink Model

CASE 1: FAILURE OF ONE INVERTER DURING GRID CONNECTED MODE

When the microgrid 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 microgrid operation when one of the inverters is disconnected from operation is conducted.

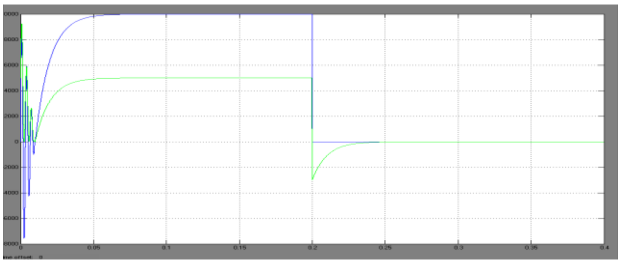

Fig 6 Power Delivered by Inverter 1

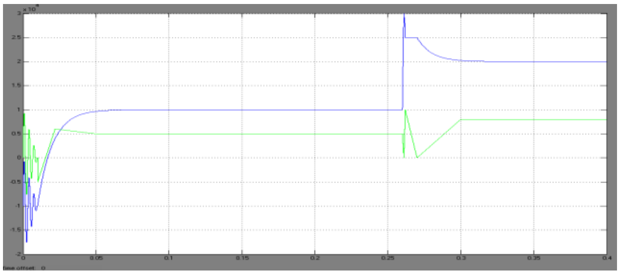

Fig 7 Power Delivered by Inverter 2

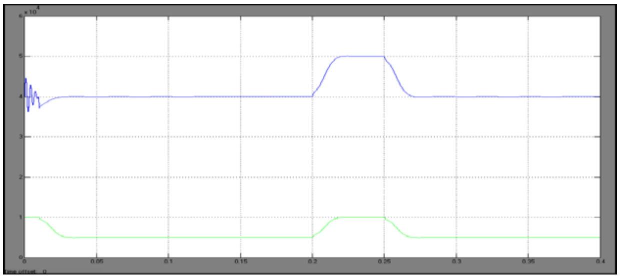

Fig 8 Power Delivered by Grid

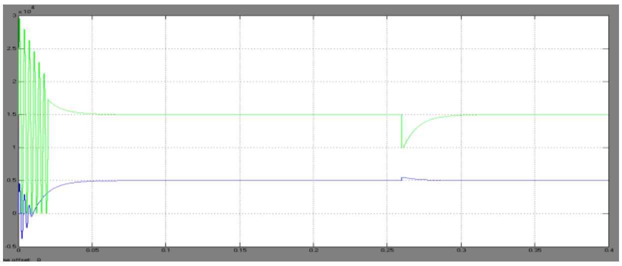

Fig 9 Power Delivered by Load

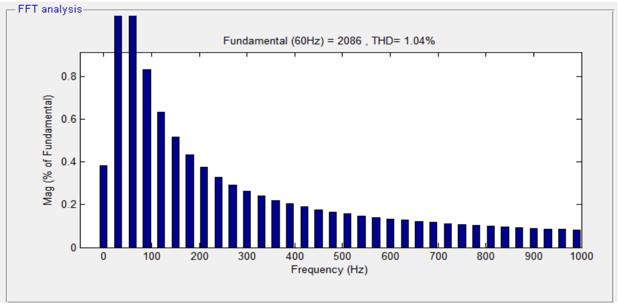

Fig 10 FFT Analysis of Load

CASE 2: CONNECTION OF INVERTER DURING GRID CONNECTED MODE

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.

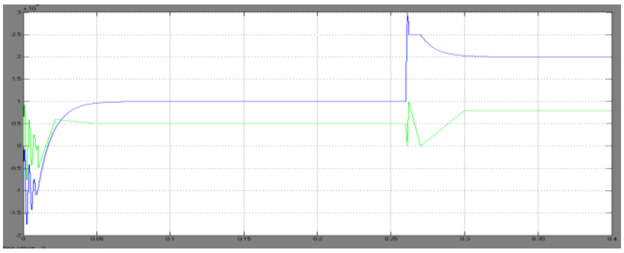

Fig 11 Power Delivered by Inverter 1

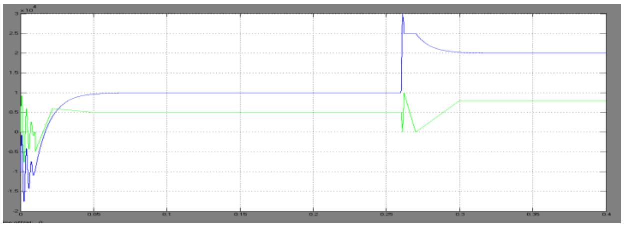

Fig 12 Power Delivered by Inverter 2

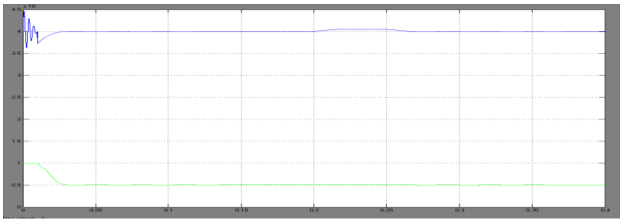

Fig 13 Power Delivered by Grid

CASE 3: ISLANDED OPERATION MODE

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.

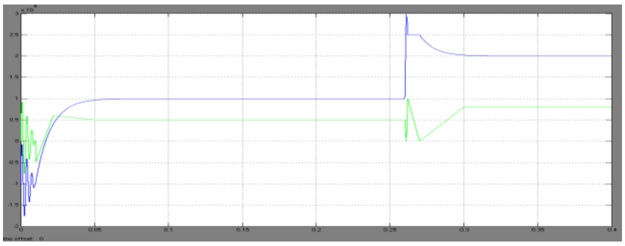

Fig 14 Power Delivered by Inverter 1

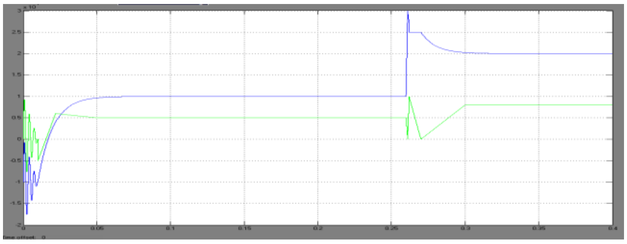

Fig 15 Power Delivered by Inverter 2

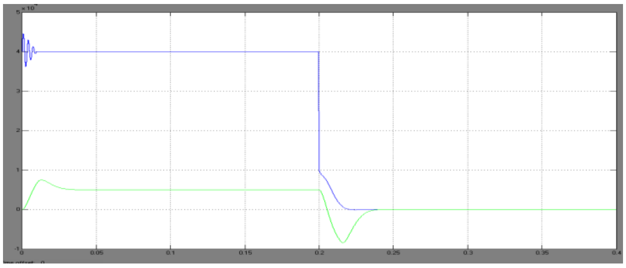

Fig 16 Power Delivered by Grid

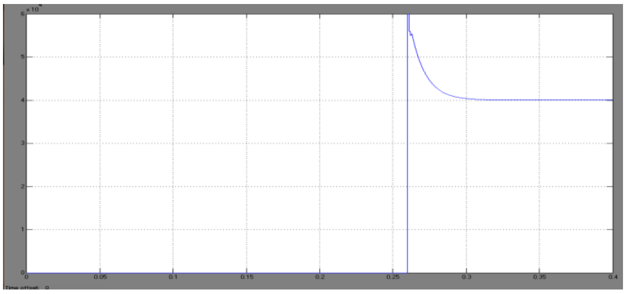

Fig 17 Power Delivered by Load

V.CONCLUSION

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 Neuro-Fuzzy controlled micro grid architecture eliminates the need for voltage and frequency synchronization, thus allowing the WGs to be switchedon 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 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 serve as a basis for the design of a dc grid based wind power generation system in a micro grid.

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