Improved Control Strategy for Fuel Cell and Photovoltaic Inverters in a Microgrid

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Abstract: - This paper presents an improved control strategy for parallel inverters so as to better manage power sharing among the distributed generation units in a microgrid. The proposed control strategy combines both power and voltage control schemes implemented on the voltage source inverters which are used as power electronics interface systems for conversion of power generated by fuel cell and photovoltaic generation units. Dynamic models of the fuel cell and photovoltaic systems available in the PSCAD/EMTDC simulation software are used as distributed generation units present in the microgrid. To evaluate the effectiveness of the developed control strategy, the microgrid is operated in grid connected, islanding and transition modes of operation.

Key-Words: - Distributed generation, microgrid, fuel cell, photovoltaic, inverter

1 Introduction

A cluster of distributed generation (DG) units are usually connected to a distribution network to maintain the reliability of critical loads, especially when the grid supply is not available. However, an increase in the number of DG connections can give rise to several technical concerns in the operation of the power system. To overcome this problem, a microgrid is formed when multiple DG units in electrical proximity to each other are grouped together in a distribution system. Thus, the microgrid concept assumes a cluster of loads and DG units operating as a single controllable system that provides both power and heat to its local area [1]. From the grid’s point of view, a microgrid can be regarded as a controlled entity within a power system that can be operated as a single aggregated load and as a small source of power supporting the network. From a customer point of view, microgrids are considered to provide their thermal and electricity needs, enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage sags and potentially reduce costs of energy supply.

The DG units in a microgrid may take many forms of technologies, namely, diesel engines, micro turbines, fuel cells, photovoltaics and wind turbines. The capacity of the DG units usually varies from few kW to 1-2 MWs. The form of the microgrid takes with the different types of DG units and loads will have a large impact on the operating and control regime of the system. Therefore, coordinated operation and control of DG units together with storage devices, such as flywheels, energy capacitors, batteries, and controllable loads are central to the concept of microgrids.

A microgrid must have the capability to operate either in grid connected mode or in islanding mode depending on factors like planned disconnection, grid outages or economical convenience [2,3]. Considering the operating modes, a series of technical challenges with regards to the operation and control of microgrids need to be addressed such as sharing of loads between DG units and smooth switching from grid-connected to island operation. An important consideration in managing microgrids is to control the parallel operation of inverters so that they can work efficiently to achieve high performance. In [4], a master/slave control scheme for operating the DG units both in grid-connected and islanding modes was developed. Here, two local controls schemes for master/slave operation were used. However, a drawback of this control method is that there is a need for having one unit to act as a master unit and if this unit fails the overall system will be down.

A phase-locked loop control technique is commonly used in grid-connected converters to provide accurate estimation of phase angle for grid synchronization [5]. Another control scheme known as the voltage and frequency droop control method is proposed to obtain good sharing of the parallel inverters for different modes of operation [6]. The droop control method makes the parallel inverters share both active and reactive powers, which allows power management on power lines for far-away
parallel inverters. This approach does not directly incorporate the load dynamics in the control loop, large or fast load changes and hence may result in either poor dynamic response or even voltage/frequency instability. Thus, it is very important for the microgrid to utilize the local measurements of the parallel inverters to achieve better active and reactive power sharing.

In this paper, an improved control strategy is presented, which is able to better manage power sharing accuracy of the parallel connected inverters used in a microgrid. The developed control strategy combines the advantages of both power and voltage control schemes. Power control ensures stability of the whole conversion system, while voltage control allows a more accurate generation of the reference voltage necessary to apply in the pulse width modulation technique. The combined use of power and voltage control schemes allow the implementation of a simple and effective three-phase control scheme, particularly to deal with critical conditions that can occur in the microgrids.

To test the performance of the proposed control strategy, simulations were carried out by considering two DG units, namely fuel cell and photovoltaic connected to the grid system.

2 Microgrid System Configuration

The microgrid system consisting of two DG units, a radial distribution system, six transformers with voltage levels of 132/11 kV and 11/0.415 kV and three loads with a 100 kW capacity for each load is shown in Figure 1. The DG units and loads are operated at 0.415 kV and connected to the distribution grid through the transformers, lines and a switch. The DG units comprise of solid oxide fuel cell (SOFC) and photovoltaic arrays which are connected to the grid through converters. The two DG units are controlled such that they can provide local power and voltage support for loads 1 to 3. This configuration reduces the burden on generation and ensures the delivery of power directly from the main grid. It also enhances the immunity of critical loads to system disturbances in the grid.

The distributed generation powered by fuel cell and photovoltaic has gained popularity due to their higher operating efficiency, improved reliability and lower emissions. Fuel cell is attractive because it is modular, efficient and environmentally friendly. The dynamic models of SOFC and photovoltaic are described accordingly.

2.1 Solid oxide fuel cell model

The SOFC model is derived by considering the total stack voltage of the fuel cell stack [7]. Considering ohmic losses of the stack, the expression of total stack voltage can be written as,

$$V_f = N_a \left( E_0 + \frac{RT}{2F} \left( \ln \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \right) - r I_f$$  (1)

where

- $V_f$: Total stack voltage
- $E_0$: Standard reversible cell potential
- $r$: Internal resistance of stack
- $I$: Stack current
- $N$: Number of cells in stack
- $R$: Universal gas constant
- $T$: Stack temperature
- $F$: Faraday’s constant
- $P_{H_2}$: Partial pressure of hydrogen
- $P_{O_2}$: Partial pressure of oxygen
- $P_{H_2O}$: Partial pressure of water

The total power generated by the fuel cell is given by,

$$P_f = N_a V I$$  (2)

The parameters of this model can be found in [8].

2.2 Photovoltaic model

Solar cells are grouped in larger units to form PV modules, which are then interconnected in a
parallel-series configuration to form PV arrays. The output voltage of the solar cell is a function of the photocurrent that depends on the solar irradiation level during its operation. The output current of the solar cell is represented by equation (3). For the PV array consisting of $N_s$ series module and $N_p$ parallel branches, the PV voltage and current are given by equations (4) and (5). The power output of the PV array is the product of output current and output voltage of PV, which is represented by equation (6).

$$I_v = I_{ph} - I_o = I_{ph} - I_{sat} \left[ e^{\frac{q}{K} \left( V + IR_s \right)} - 1 \right]$$ \hspace{1cm} (3)

$$V_{pv} = N_s \left( V_{ref} - \beta \left( T - T_{ref} \right) - R_s \left( T - T_{ref} \right) \right)$$ \hspace{1cm} (4)

$$I_{pv} = N_p \left( I_{ref} + A \left( \frac{G}{1000} \right) \left( T - T_{ref} \right) + \left( \frac{G}{1000} - 1 \right) I_o \right)$$ \hspace{1cm} (5)

where

- $I_{ph}$: Light generated current in a solar cell
- $I_o$: Reverse saturation current of diode
- $T_c$: Cell temperature in Kelvin
- $A$: Ideality factor
- $K$: Boltzman constant
- $q$: Electron charge
- $\alpha$: Current temperature coefficient
- $G$: Irradiance
- $\beta$: Voltage temperature coefficient
- $N_s$: Number of modules connected in series
- $N_p$: Number of modules connected in parallel

$$P_{pv} = I_{pv} \times V_{pv}$$ \hspace{1cm} (6)

### 3 Proposed Inverter Control Strategy

Two DG units were considered in this study in which the interconnection between the two DG units with the main grid at the point of common coupling is shown in Figure 1. Each DG unit comprises of a dc source and a voltage source inverter (VSI). The configuration of the VSI used in each DG unit is shown in Figure 2. The inverter transfers energy produced by the DG and at the same time controls the power flow by using impedances with resistance $R_1$, inductance $L_1$ and parallel capacitive filter. These impedances provide a path for some high-order harmonics generated at the switching frequency. For the inverter operating in voltage control mode, its controller generates three reference signals, $E_{grida}$, $E_{gridb}$, $E_{gridc}$, each of which is referred to the output voltage that is to be applied on each phase, so that the currents $I_a$, $I_b$, $I_c$, track its desired values corresponding to the power flows required between the dc and ac sides. The output voltages of the VSI are required to track the reference voltages by applying the pulse width modulation (PWM) technique.

The proposed inverter control strategy is explained in terms of three different modes of operation, namely, i) grid connected mode (Switch close), ii) islanding mode (Switch open) and iii) transition mode (Switch open and close within 2 seconds). When the inverter operates in grid connected mode, it uses power control while in islanding mode, it uses voltage control.

#### 3.1 Inverter power control

To control the active and reactive output powers, the developed control system is implemented in the $dq0$ reference frame. The inverter output current components, $I_d$ and $I_q$ are controlled by means of some current reference values, $I_{dref}$ and $I_{qref}$, obtained from the outputs of the power control block shown in Figure 3. Power measurement is made at the inverter output and the powers are compared with the power reference values, $P_{ref}$ and $Q_{ref}$. The difference between the output and the reference powers, $dP$ and $dQ$, provides inputs to a PI controller which allows generation of the reference signals, $I_{dref}$ and $I_{qref}$. Thus, as comparison is made to provide the error signals which are subsequently passed through the PI controller to obtain the inverter modulating signals of the PWM. Then, by using the $dq0$-to-$abc$ transformation block, the pulse signals for the inverter are obtained. The PWM implementation of the VSI is also shown in Figure 3.
3.2 Inverter voltage control

In order to accomplish an islanding mode operation for the microgrid system, a suitable control is required for the DG units. Since the system is disconnected from the utility grid in the islanding mode of operation, the voltage is no longer regulated by the grid. Therefore, a control scheme is needed to actively regulate the local voltage. In this control scheme the inverters are operated as voltage control inverters. In the islanding mode, inverter can no longer track the grid voltage and it needs to have an external frequency reference.

During the operation of the microgrid system from the islanding mode to the grid-connected mode, the inverter output voltage has to be synchronized to the grid and this can be achieved by using a phase-locked loop (PLL). The PLL assists to track and transform the VSI voltage into angle theta. Special consideration needs to be taken into account for the generation of the angle. Once synchronization is achieved, the grid and VSI voltages are made equal to ensure synchronism.

4 Simulation Results

The performance of the proposed inverter control strategy is evaluated by simulation using the PSCAD/EMTDC simulation software. Simulations were carried out to investigate the effectiveness of the combined power and voltage control scheme in managing power sharing among the DG units in a microgrid. Simulation results are presented for the performance of the DGs in grid connected (Switch close), islanding mode (Switch open) and transition mode (Switch open and close within 2 seconds) of operations.

4.1 Results of DG in grid connected mode of operation

In the simulation for grid connected mode of operation, initially the transfer switch is turned on (Switch close) at 0.2s. The DG inverters are now controlled by using the power control scheme so as to manage power sharing among the DG units. The variation of active power of DGs and loads are shown in Figures 4 and 5, respectively. From Figure 4, the active power from the grid is 0.25 MW while the power from both DG units is 0.05 MW. Hence, the total power generated is 0.35 MW. Figure 5 shows that load 1, 2 and 3 consume similar power of about 0.100 MW, thus giving a total load of 0.3 MW.
4.2 Results of DG in islanding mode of operation

In the simulation for islanding mode of operation, the transfer switch is turned off (Switch open) at 0.2s. The voltage control scheme of the DG inverters is now activated to allow the DG units to continue supply power to the loads and at the same time to meet the voltage amplitude and frequency reference of the main grid. The variation of active power of DGs and loads in the islanding operation are shown in Figures 8 and 9, respectively. Under this condition, the DG units generate higher power so as to meet the load requirements. Figure 8 and Figure 9 show the total power generated by the DG units and the total power of load which is approximately 0.3 MW and 0.255 MW, respectively.

4.3 Results of DG in transition mode of operation

In the simulation for transition mode of operation, the transfer switch is first turned on (Switch close) and operates in the power control scheme. At 4s later, the transfer switch is turned off (Switch open) so as to disconnect the grid from the system. The DG units increase its power to compensate for the loss of grid supply during 4s to 6s time period as shown in Figure 10. The simulation shows that the proposed method for controlling the DG units is effective during the 2s islanding period. In addition, the voltage control scheme guarantees continuity of power supply to the loads even during islanding from the main utility grid. When this happens, the inverter responds accordingly, with the load voltage returning quickly to its pre-disturbance value as shown in Fig.11.
5 Conclusion

Improved control strategy for SOFC and PV inverters used in a microgrid is established in this work. The control strategy is based on power control and voltage control schemes to control the SOFC and PV voltage source inverters. The effectiveness of the control strategy is evaluated by operating the microgrid in grid connected, islanding and transition modes of operation. Test results showed that the proposed control strategy is able to correctly manage power sharing among the DG units in a microgrid, regulate quickly the DG power outputs to meet the requirements of the loads, tolerate the rapid changes in various mode of operations and maintain voltage quality at the grid and loads.

References:
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