Transition from Grid Connected Mode to Islanded Mode in VSI fed Microgrids

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Abstract—This paper investigates the behaviour of a microgrid system during transition from grid connected mode to islanded mode of operation. A sample system consisting of two inverter interfaced distributed generators (DGs) and one local load is considered. A systematic approach for modelling the sources has been presented. The control schemes are developed for both grid connected and islanded mode of operation. A PLL based synchronization scheme is used during grid connected mode. During islanded mode a droop control based strategy is used to ensure proper load sharing among DGs. A passive island detection scheme is used to detect an island and facilitate the transition from grid connected mode to islanded mode. Two kinds of transition schemes are discussed and a comparative study is presented for various step changes in the load.

Keywords—Distributed Generation, d-q axis current Control, Droop Control, Island Detection.

I. INTRODUCTION

With the advent of distributed generation, the concept of microgrid is becoming popular in the recent times. A microgrid is a small power system network with distributed generators such as wind, solar, combined heat power (CHP) plants which can operate in conjunction with the grid (grid connected) to supply a fraction of the total load [1]. To increase the system reliability, the distributed generation units can be operated in islanded mode when the grid is lost keeping the load voltage and frequency within limits [2]. The continuous operation of these units have advantages such as additional revenue generation, increased system reliability, etc. Operation of the DG units during islanded mode of operation requires special control schemes [3] [4].

During grid connected mode the frequency and voltage of the system are dictated by the grid. The local sources supply constant active and reactive power (P and Q) as set by an external reference. But during islanded mode of operation, when the grid is not present, the local sources must undertake the job of catering the loads [5]. The controls under such situation are also known as grid forming controls. Usually a droop control strategy is used for a system having multiple DG units [6]. Sometimes the controls may become more complex than grid connected mode of operation. The converters being a fast acting source can quickly respond to power system disturbances [6] [7]. However the system dynamics can be much slower with inertial sources. Coordination of these sources brings up new challenges. Another challenge that comes with the operation of microgrid is the stabilized operation during grid connected and islanded mode and proper strategy for a stable transition from grid connected to islanded mode [8]. The controller parameters must be judiciously chosen while designing the system.

This paper provides a systematic approach of developing the controls for grid connected and islanded modes. During grid connected mode the inverters are modelled as sources supplying constant real and reactive power (P-Q) using d-q axis current control. A step by step procedure for designing the controllers is also discussed. The load sharing between different inverter based sources for islanded mode is achieved using droop control [6]. A passive islanding algorithm based on voltage and frequency measurement is used for detecting the island and facilitating the transition [9].

Two strategies are proposed for the transition from grid connected mode to islanded mode. In one scheme only one mode controllers, either grid connected mode or islanded mode, will be active and calculate the set points required for the inverter at any given point of time. Whenever a switch over command is issued by the island detection unit the other controller start calculating the input for the inverter and the previously active controller becomes offline. In another scheme, both the the grid connected mode and islanded mode controllers will be online and continuously calculate the set points based on local measurements but only one of them remains active depending on the status of the island detection command. A comparative study of both the transition schemes is presented. It was observed that the second control strategy performs better during the transition from grid connected mode to islanded mode.

II. MICROGRID MODEL

The microgrid model used for the analysis in this paper consists of two inverter based sources as shown in Fig 1a. The distribution lines connecting the inverters and point of common coupling (PCC) bus are modelled as short lines (series R-L model). The load considered in this case is a series R-L load with a rating of 10kW (0.8 pf lag). The X/R ratio considered for the grid is 3. Fig.1b shows the inverter model along with the first order filter. There are two different sets of
controllers, d-q axis current controller for grid connected mode and droop controller for islanded mode. The island detection algorithm facilitates transition from grid connected mode to islanded mode. The system parameters are given in Table I. The control schemes for grid connected and islanded mode are explained in the subsequent sections.

A. Control Scheme during Grid Connected Mode

The microgrid in grid connected mode should operate in constant P-Q mode. Thus the inverter is operated in constant current control mode using d-q axis based current control. Consider the inverter model as shown in Fig.1b along with the filter. The inverter equations in the abc-domain are as follows

\[
\begin{align*}
L_f \frac{d i_{abc}}{dt} + R_f i_{abc} &= V_{abc} - V_{1abc} \\
L_f \frac{d i_d}{dt} + R_f i_d + \omega L_f i_q &= V_i - V_{id} \\
L_f \frac{d i_q}{dt} + R_f i_q - \omega L_f i_d &= V_i - V_{iq}
\end{align*}
\]

(1)

where \( i = \) inverter 1 or 2. Transforming (1) to d-q reference frame, the following can be obtained

\[
\begin{align*}
L_f \frac{d i_d}{dt} + R_f i_d + \omega L_f i_q &= V_{id} - V_{id} \\
L_f \frac{d i_q}{dt} + R_f i_q - \omega L_f i_d &= V_{iq} - V_{iq}
\end{align*}
\]

(2)

These equations are coupled because the d and q axis currents appear in each equation. The controller action can be decoupled by defining \( V'_d \) and \( V'_q \) as:

\[
\begin{align*}
V'_d &= V_{id} - V_{id} - \omega L_f i_q \\
V'_q &= V_{iq} - V_{iq} + \omega L_f i_d
\end{align*}
\]

(3)

The equation under the aforementioned substitution becomes:

\[
\begin{align*}
V'_d &= L_f \frac{d i_d}{dt} + R_f i_d \\
V'_q &= L_f \frac{d i_q}{dt} + R_f i_q
\end{align*}
\]

(4)

A synchronous reference frame phase locked loop (PLL) as shown in Fig.2 [10] is used to obtain the voltage phase at the connection point of the inverter. A simple PI controller is used as current controller to generate \( V'_d \) and \( V'_q \) as shown in Fig.3. The controller output can then be used to calculate the inverter d-q voltages using (3). A dq0-abc transformation is then carried out to determine the inverter voltage in abc domain. Since the observation time scale is much larger than the switching time period, the inverter can be modelled as an average model [11]. It is equivalently replaced by delay equal to the switching time period for the design of PI controller as shown below

\[
G_{inv}(s) = \frac{V_{out}(s)}{V_{in}(s)} = K_{inv} e^{-0.5sT_d}
\]

(5)

where the gain of the transfer function depends on the DC bus

### TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid SCC</td>
<td>20 MVA (X/R=3)</td>
</tr>
<tr>
<td>Transformer Rating</td>
<td>11kV/400V((\Delta - Y))</td>
</tr>
<tr>
<td>Distribution Line Resistance</td>
<td>0.9Ω</td>
</tr>
<tr>
<td>Distribution Line Reactance</td>
<td>0.31Ω</td>
</tr>
<tr>
<td>Inverter Rating</td>
<td>12.5 kVA(DG1) 6.25 kVA(DG2)</td>
</tr>
<tr>
<td>Inverter Switching Frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Filter Inductance</td>
<td>0.1088 mH</td>
</tr>
<tr>
<td>Filter Resistance</td>
<td>1.02 mΩ</td>
</tr>
<tr>
<td>Load</td>
<td>10 kW and 7.5 kVar</td>
</tr>
</tbody>
</table>

Fig. 2. Phase Locked Loop

Fig. 3. Current Controller

Fig. 4. DC Link Voltage Controller
The aim of the DC link voltage controller is to maintain the DC bus voltage. The rms value of current is related to the d-axis component as:

\[ I_{\text{rms}} = \sqrt{2} I_{d} \]

ac side gives:

\[ I_{d} = \sqrt{2} I_{\text{rms}} \]

The power balance equation in dc and ac side inverter currents. The power balance equation in dc and ac side needs to be determined which relates the ac and dc side inverter currents. The power balance equation in the inverter can be expressed as:

\[ P_{\text{in}} = P_{\text{out}} \]

\[ Q_{\text{in}} = Q_{\text{out}} \]

The DC bus voltage is related to the capacitor current as:

\[ V_{\text{dc}} = \frac{C_{\text{d}}}{L_{\text{d}}} \]

Where 

\[ C_{\text{d}} \]

is the DC bus capacitance and

\[ L_{\text{d}} \]

is the DC bus inductance. The time delay is 

\[ T_{\text{d}} = 100 \mu s \]

When there is an imbalance between the power set point and actual power delivered by the inverter (because of system losses) the surplus power is supplied by the DC bus capacitor which results in reduction of the DC bus voltage. However, to maintain desired power transfer DC bus voltage is regulated using an outer PI loop. The DC bus voltage controller provides a d-axis current reference for the inner current controller which should be added to the original d-axis current reference. The detailed block diagram is shown in Fig.4. The design procedure for the current and DC link voltage controllers are outlined below.

1) Design of Current Controller: The current controller should be designed in such a way that it has a high bandwidth so that speed of response is fast. But the gain provided by the closed loop system at switching frequency should be low [12] [13]. Good practice is to keep the closed loop system bandwidth 10 times smaller than the switching frequency. For switching frequency of 10kHz, the closed loop system bandwidth of 1kHz is considered. The closed loop transfer function of the current controller is given by:

\[ G_{c}(s)G_{\text{inv}}(s) = \frac{1}{1 + G_{c}(s)G_{\text{inv}}(s)} \]

\[ \frac{R_{f} + sL_{f}}{R_{f} + sL_{f}} = \frac{1}{\tau s + 1} \]

where \( G_{c}(s) \) is the PI controller transfer function and \( \tau \) is the time constant corresponding to the bandwidth chosen. Rearranging the terms in (6) the values of \( K_{p} \) and \( K_{i} \) can be obtained as follows,

\[ K_{p} = \frac{L_{f}}{\tau} \]

\[ K_{i} = \frac{R_{f}}{\tau} \]

2) Design of DC link Voltage Controller: Before the voltage controller can be designed the plant transfer function on the DC side needs to be determined which relates the ac and dc side inverter currents. The power balance equation in dc and ac side gives,

\[ V_{\text{dc}}I_{\text{dc}} = 3V_{\text{ph}}I_{\text{ph}} \]

The rms value of current is related to the d-axis component as:

\[ I_{d} = \sqrt{2} I_{\text{rms}} \]

Using this relation in (8), \( I_{\text{dc}} \) can be expressed as,

\[ I_{\text{dc}} = \sqrt{\frac{3}{2}} \frac{V_{L} - L_{d}}{V_{\text{dc}}} I_{d} = K_{D}I_{d} \]

The DC bus voltage is related to the capacitor current as:

\[ C_{d}\frac{dV_{\text{dc}}}{dt} = I_{\text{dc}} \]

The aim of the DC link voltage controller is to maintain the DC bus voltage constant at \( V_{\text{dc}} \). Hence the system should resemble an all pass filter. However the parameter under consideration being DC, the total system can be made equivalent to a low pass filter with cutoff frequency closer to zero. So one can represent the voltage control loop as a low pass filter with a cutoff frequency between 1 to 20 Hz. Since the inner current loop is much faster than the voltage loop, the current controller and the inverter can be replaced by a unity gain block as shown in Fig.4. Here 20Hz bandwidth is selected with a phase margin of 68.4 degrees.

B. Control Scheme during Islanded mode

When the grid is removed an active and reactive power mismatch occurs at the load terminal. Because of the difference between load and generation, the load voltage and/or frequency settles at a different value [2]. To bring the voltage and frequency back to the limits the loading level of the generators need to be increased to supply the total load.

With multiple DGs supplying a load, proper load sharing of the generators need to be achieved without overloading. Similar to parallel operation of alternators in a conventional power system framework, an artificial droop characteristic need to be incorporated in the inverter as shown in Fig.5 [14]. A droop control method is advantageous because it does not require any communication between various sources and a decentralized control can be achieved. In this paper, a P-\( \omega \) and Q-V droop is implemented in the inverter. Although this scheme can perform very well, the PQ sharing may be influenced by the X/R ratio of the system which is quite low in distribution systems. In droop control the frequency and voltage output of the inverter is dependent on P and Q output as shown below

\[ \omega_{\text{act}} = \omega_{0} - K_{pd}(P_{\text{cal}} - P_{\text{ref}}) \]

\[ V_{\text{act}} = V_{0} - K_{qd}(Q_{\text{cal}} - Q_{\text{ref}}) \]

where \( K_{pd} \) and \( K_{qd} \) are the droop controller slopes. \( \omega_{\text{act}} \) and \( V_{\text{act}} \) are the measured values of frequency and voltage. \( \omega_{0} \) and \( V_{0} \) are the rated frequency and voltages. The \( P_{\text{ref}} \) and \( Q_{\text{ref}} \) are the references corresponding to initial operating conditions with rated voltage and frequency.

As shown in Fig.6, the voltage and currents at PCC of each inverter are used to determine the P and Q. These values are filtered and then passed to the droop controller which uses (11) to determine the magnitude and frequency of the voltage that needs to be produced by the inverter. A PI controller based voltage regulator is also implemented to ensure that the inverter tracks the reference voltage generated by the voltage droop controller properly.

1) Selection of Droop Constants: The droop controller slopes can be decided based on the ratings of the inverters and acceptable voltage and frequency limits [6]. Over the rated power range of any inverter the frequency variation should be within 1Hz. Similarly the voltage limit should be restricted within 0.95-1.05 pu [2]. These facts can be utilized to calculate
PCC voltage and frequency deviate by ± switch-over command to the inverter controllers whenever the connected and islanded mode. The island detection unit issues a [9]. Each DG is designed with separate controls for grid connected mode or islanded mode using local voltage and frequency measurements. The microgrid system described in Section II, Fig.1a has been modelled in Simulink. The system performance is assessed in the following section.

C. Controller for Grid Connected to Island mode Transition

The controller consists of an island detection unit to detect loss of grid using local voltage and frequency measurements [9]. Each DG is designed with separate controls for grid connected and islanded mode. The island detection unit issues a switch-over command to the inverter controllers whenever the PCC voltage and frequency deviate by ±10% V and ± 0.5 Hz for a duration of 100 ms. On receiving this command the inverter takes the reference values from the island mode controller and a transfer from grid connected to island mode will be achieved. Depending upon the state of the island mode controller (online or offline) at the instant of the transition, two schemes have been proposed here.

In Scheme-I, only one of the controllers, either grid connected mode or islanded mode controller, will be online and calculate the set points required for the inverter at any given point of time. Whenever a switch-over command is issued by the island detection unit the previously active controller goes offline and the other controller takes over and starts calculating the input for the inverter. In Scheme-II, both the grid connected and islanded mode controllers will be online and continuously calculate the set points based on local measurements. However, only one of them will be active depending on the status of the island detection command. Performance of both these schemes is assessed in the following section.

III. RESULTS AND DISCUSSIONS

The microgrid system described in Section II, Fig.1a has been modelled in Simulink. The system performance is assessed with several sets of load/generation patterns. The grid connected mode, transition from grid connected mode to islanded mode using proposed schemes have been analysed. The results and corresponding voltage and frequency at the PCC bus are shown in Fig.7a and 7b. Prior to the creation of disturbance DG1 and DG2 supply 2.5 kW at unity power factor. The remaining power of 5 kW is supplied by the grid as seen from figure. At t=1.5 s, the active and reactive powers of DG2 increase to 5 kW and 3 kVar respectively. DG1 power remains unchanged and the grid active and reactive power reduce to 2.5 kW and 4.5 kVar respectively. The voltage and frequency settle within limits (±10% V and ± 0.5 Hz) with a small transient. At t=2 s, the entire active power is supplied locally and the grid supplies the system losses (0.2 kW) and the reactive power requirement of the load (4.5 kVar) as per the set points. Finally, when DG2 set points are made zero at t=2.5 s, the grid active and reactive power increases back to 5 kW and 7.5 kVar respectively. DG1 power remains unchanged. In all these step responses of power set points a settling time of 10 ms is achieved as per the design.

A. Grid Connected Mode

The following sequence of operations are simulated in the microgrid:

- At t=0 s, the real and reactive power set points of each DG is set to 2.5 kW and 0 kVar (upf).
- At t=1.5 s, the real and reactive power set point of DG2 is changed from 2.5 kW and 0 kVar (upf) to 5 kW and 3 kVar (0.85 pf).
- At t=2 s, the real power set point of DG1 is changed from 2.5 kW (upf) to 5 kW (upf).
- At t=2.5 s, DG2 both real and reactive power set points are made 0.

Fig.7a shows the real and reactive powers of DG1, DG2 and the grid for the events considered above. Fig.7b shows the corresponding voltage and frequency at the PCC bus. Prior to the creation of disturbance DG1 and DG2 supply 2.5 kW at unity power factor. The remaining power of 5 kW is supplied by the grid as seen from figure. At t=1.5 s, the active and reactive powers of DG2 increase to 5 kW and 3 kVar respectively. DG1 power remains unchanged and the grid active and reactive power reduce to 2.5 kW and 4.5 kVar respectively. The voltage and frequency settle within limits (±10% V and ± 0.5 Hz) with a small transient. At t=2 s, the entire active power is supplied locally and the grid supplies the system losses (0.2 kW) and the reactive power requirement of the load (4.5 kVar) as per the set points. Finally, when DG2 set points are made zero at t=2.5 s, the grid active and reactive power increases back to 5 kW and 7.5 kVar respectively. DG1 power remains unchanged. In all these step responses of power set points a settling time of 10 ms is achieved as per the design.

B. Transition from Grid Connected to Islanded Mode

The grid is disconnected at t=3 s. The islanding detection algorithm detects an island and the controller switches from grid connected to island mode at t=3.11 s.

Fig.8a shows the voltage transient during transition for Scheme-I and Scheme-II. Prior to the loss of grid the voltage and frequency were 229 V and 50 Hz respectively. On grid disconnection, it can be observed from the figure that the load voltage and frequency deviate considerably from the nominal values. The island detection unit senses the situation and issued a switch over command at t=3.11 s as designed. The inverters activate the island mode controller according to Scheme-I or Scheme-II. It can be observed that, in Scheme-I the voltage reduces to a very low value and quickly rises to the steady state value at the instant of control switch over. However, in Scheme-II the voltage rises to the steady state value directly without any voltage dip. Frequency settles quickly in Scheme-II compared to Scheme-I. In both the schemes the frequency and voltage settle to 49.85 Hz and 222 V respectively, which are well within the prescribed limits [2].

Fig.9 shows real and reactive powers of DG1, DG2 and load during transition for both the schemes. In Scheme-I the active power of DG1 drops to zero and quickly rises to its steady state value. Since DG2 is already at P=0kW, no dip

\[ K_{pd} = \frac{\Delta \omega}{P_{max} - P_{min}} \]
\[ K_{qd} = \frac{\Delta V}{Q_{max} - Q_{min}} \]
can be seen. This dip causes a momentary load drop as seen in the figure. However, Scheme-II doesn’t show such drop in $DG_1$ as well as in the load and reaches steady state quickly without any overshoot.

With Scheme-I, one can observe a short dip in reactive power of $DG_1$, $DG_2$ and load. However, in Scheme-II no such dip is observed. But in Scheme-II, $DG_1$ reactive power goes negative and then raises to the steady state value and $DG_2$ reactive power settles to steady state following a long overshoot. The load however does not experience any such long overshoots in reactive power in Scheme-II. It means that there is a circulating reactive current between the two inverters during the transition.

C. Islanded Mode

The droop controllers are designed for each inverter as described in Section II-B. The $P_{ref}$ for the controllers is chosen as 0.2 p.u. The following droop constants are obtained using (12).

\[ K_{pd1} = 3.14 \quad \text{and} \quad K_{pd2} = 6.28 \]
\[ K_{qd1} = 0.1 \quad \text{and} \quad K_{qd2} = 0.2 \]

Fig.10a shows the active and reactive power of $DG_1$ and $DG_2$ during island mode. Fig.10b shows the voltage and frequency at the PCC bus during the island mode. It can be observed that after transition to islanded mode real and reactive powers of $DG_1$ and $DG_2$ are settled to 6.6 kW, 4 kVar and 3.3 kW, 3.3 kVar respectively. The voltage and frequency settle to 49.85 Hz and 222.2 V respectively as per the droop characteristics. It has been observed that the reactive powers are not shared exactly in accordance with the droop curve ratio due to high R/X ratio of the system. At t=5s the load is reduced from 10 kW (0.8 pf) to 7.5 kW (0.8 pf). On load reduction, it can be observed that the responses of DG’s P and Q settled within 80 ms to the reference values. However the voltage and frequency (224.2 and 49.91 Hz) increase according to the droop curve.

IV. CONCLUSIONS

Transition from grid connected mode to islanded mode operation in a microgrid with inverter based distributed generators is investigated in this paper. A systematic approach for designing the grid connected and island mode controllers is described. The performance of the designed controllers is verified during grid connected and islanded modes using step responses. Satisfactory performance of the controllers is obtained for various step changes in the load. Two transition schemes are investigated for the transition from grid connected to island mode and a comparative study is presented. The voltage and frequency are always maintained within the op-
erating limits irrespective of the load changes. In Scheme-II, the islanded mode controllers are always kept online and made active up on receiving the island detection command, which mitigated momentary interruption to the load during transition. However, a circulating reactive power between the sources is observed. Future work includes resynchronization of the microgrid to the grid connected mode and seamless transition without any circulating currents.

REFERENCES