Transition between grid-connected mode and islanded mode in VSI-fed microgrids

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Abstract. This paper investigates the behaviour of a microgrid system during transition between grid-connected mode and islanded mode of operation. During the grid-connected mode the microgrid sources will be controlled to provide constant real and reactive power injection. During the islanded mode the sources will be controlled to provide constant voltage and frequency operation. Special control schemes are needed to ensure proper transition from constant P – Q mode to constant f – V mode and vice versa. Transition from one mode to other will introduce severe transients in the system. Two kinds of transition schemes based on the status of the off-line controller are discussed and a comparative study is presented for various step changes in the load. An additional-pole-placement-based output feedback controller augmentation during transition between the modes is proposed to reduce the transients. A static output feedback compensator design is proposed for the grid connected to island mode transition and a dynamic output feedback compensator design is proposed for resynchronisation. The performance of the output feedback controllers is tested under various operating conditions and found to be satisfactory for the tested conditions.

Keywords. Distributed generation; d – q axis current control; droop control; output feedback controller.

1. Introduction

With the advent of distributed generation (DG), 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 and combined heat power (CHP) plants that can operate in conjunction with the grid (grid connected) to supply a fraction of the total load [1]. To increase the system reliability, the DG 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 has 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].

In the 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. However, in the islanded mode of operation, when the grid is not present, the local sources must undertake the job of catering to 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 islanded mode controls may become more complex than

grid-connected mode controls. The control, protection and stability issues, being much different from those of the conventional power system, open up new prospects of research in this field.

Two types of sources are mainly used in a small-scale microgrid, converter-interfaced sources and rotating-machine-based sources, (inertial source). The mix of various kinds of sources brings several challenges in control during different modes of operation. The converters, being fast-acting sources, 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 stabilised operation during grid-connected and islanded modes and proper strategy for a stable transition from grid-connected to islanded mode and vice versa [8, 9]. This paper investigates the behaviour of inverter-based DG sources during transition between grid-connected and islanded mode.

This paper provides a systematic approach of developing the controls for grid-connected and islanded modes. During the 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

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islanding algorithm based on voltage and frequency measurement is used for detecting the island and facilitating the transition [10]. Two strategies are proposed for the transition between grid-connected mode and islanded mode. In one scheme only one mode controllers, either grid-connected mode or islanded mode, will be on-line 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 starts calculating the input for the inverter and the previously on-line controller becomes off-line. In another scheme, both the grid-connected mode and islanded mode controllers will be on-line and continuously calculate the set points based on local measurements but only one of them actively controls the inverter 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 between grid-connected and islanded mode but the transients are still significant with the second control strategy. To reduce the transients, a novel output feedback controller is augmented to the off-line controller during the transition period. A static feedback compensator is shown to be sufficient for transition to island mode and a first-order dynamic compensator is shown to be sufficient for resynchronisation to the grid. These controllers are realised based on the outputs of the island and grid-connected mode controllers. A systematic approach for developing the design of these output feedback controllers is presented and the performance is validated for different operating conditions.

2. Microgrid model

The microgrid model used for the analysis in this paper consists of two inverter-based sources as shown in figure 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 10 kW (0.8 power factor (pf) lag). The X/R ratio considered for the grid is 3. Figure 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 system parameters are given in table 1. The control schemes for grid-connected and islanded modes are explained in the subsequent sections.

2.1 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 figure 1b along with the filter. The inverter equations in the abc -domain are as follows:

$$L_f \frac{di_{abc}}{dt} + R_f i_{abc} = V_{iabc} - V_{1abc} \quad (1)$$

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

$$\begin{aligned} L_f \frac{di_d}{dt} + R_f i_d + \omega L_f i_q &= V_{id} - V_{1d}, \\ L_f \frac{di_q}{dt} + R_f i_q - \omega L_f i_d &= V_{iq} - V_{1q}. \end{aligned} \quad (2)$$

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 follows:

$$\begin{aligned} V'_d &= V_{id} - V_{1d} - \omega L_f i_q, \\ V'_q &= V_{iq} - V_{1q} + \omega L_f i_d. \end{aligned} \quad (3)$$

The equation under the aforementioned substitution becomes

$$\begin{aligned} V'_d &= L_f \frac{di_d}{dt} + R_f i_d, \\ V'_q &= L_f \frac{di_q}{dt} + R_f i_q. \end{aligned} \quad (4)$$

A synchronous reference frame phase-locked loop (PLL) as shown in figure 2 [11] is used to obtain the voltage phase at the connection point of the inverter. A simple PI controller

Figure 1. System model. (a) Network model. (b) Inverter model.

Table 1. System and control parameters.

Parameter	Value
Grid SCC	20 MVA ($X/R = 3$)
Transformer rating	11 kV/400 V ($\Delta - Y$)
Distribution line resistance	0.9 Ω
Distribution line reactance	0.314 Ω
Inverter rating	12.5 kVA (DG_1) 6.25 kVA (DG_2)
Inverter switching frequency	10 kHz
Filter inductance	0.1088 mH
Filter resistance	1.02 m Ω
Load	10 kW and 7.5 kVar
Current controller	$K_p = 0.683$ and $K_i = 6.405$
DC bus voltage controller	$K_p = 0.0191$ and $K_i = 0.9527$
Voltage controller	$K_p = 0.01$ and $K_i = 5.2$

Figure 2. Phase-locked loop.

is used as the current controller to generate V'_d and V'_q as shown in figure 3. The controller output can then be used to calculate the inverter d - q voltages using (3). Since the observation time scale is much larger than the switching time period, the inverter can be modelled as an average model [12].

To maintain desired power transfer the 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 figure 4. The design procedure for the current and DC link voltage controllers are outlined below.

2.1a Design of current controller: The current controller should be designed in such away that it has a high bandwidth so that speed of response is large. But the gain provided by the closed loop system at switching frequency should be low [13, 14]. For switching frequency of 10 kHz, a closed loop system bandwidth of 1 kHz is considered [15]. The closed loop transfer function of the current controller is given by

$$\frac{G_{ci}(s)G_m(s)\frac{1}{R_f + sL_f}}{1 + G_{ci}(s)G_m(s)\frac{1}{R_f + sL_f}} = \frac{1}{\tau_1 s(\tau_2 s + 1) + 1} \quad (5)$$

where $G_{ci}(s)$ is the PI controller transfer function of the current controller and $G_m(s)$ is measurement filter transfer

Figure 3. Current controller. **Figure 4.** DC link voltage controller.

function ($\omega_c = 1/\tau_2$); τ_1 is the time constant corresponding to the bandwidth chosen. Simplifying the terms in (5) we have

$$\frac{R_f + sL_f}{G_{ci}(s)G_{inv}(s)} = \tau_1 s. \quad (6)$$

Rearranging the terms in (6), the values of K_p and K_i can be obtained as follows:

$$\begin{aligned} K_p &= \frac{L_f}{\tau_1}, \\ K_i &= \frac{R_f}{\tau_1}. \end{aligned} \quad (7)$$

The current controller parameters based on (7) are calculated as $K_p = 0.683$ and $K_i = 6.405$.

2.1b 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

$$V_{dc}I_{dc} = 3V_{ph}I_{ph}. \quad (8)$$

The rms value of current is related to the d -axis component as follows: $I_d = \sqrt{2}I_{rms}$. Using this relation in (8), I_{dc} can be expressed as follows:

$$I_{dc} = \sqrt{\frac{3}{2}} \frac{V_{L-L}}{V_{dc}} I_d = K_{DC} I_d. \quad (9)$$

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

$$C \frac{dV_{dc}}{dt} = I_{dc}. \quad (10)$$

The aim of the DC link voltage controller is to maintain the DC bus voltage constant at V_{dc}^* . The total system can be made equivalent to a low-pass filter with cut-off frequency close to zero (between 1 and 20 Hz) [15]. 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 seen by the voltage controller) as shown in figure 4. The voltage controller is designed with a bandwidth of 20 Hz and a phase margin of 68.4°. The PI controller gains of the voltage controller are calculated to be $K_p = 0.0191$ and $K_i = 0.9527$. Figure 5 shows the Bode diagram of the loop transfer function.

2.2 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]. With multiple DGs supplying a load, proper load sharing of the generators needs to be achieved without overloading. An artificial droop characteristic is incorporated in the inverter as shown in figure 6 [16]. This droop control method is advantageous because it does not require any communication between various sources and a decentralised control can be achieved. In this work, a P - ω and Q - V droop is implemented in the inverter. In droop control the frequency and voltage output of the inverter is dependent on P and Q output, respectively, as shown here:

Figure 5. Bode diagram of DC link voltage controller.

Figure 6. Droop control strategy.

$$\begin{aligned}\omega_{act} &= \omega_0 - K_{pd}(P_c - P_r) \\ V_{act} &= V_0 - K_{qd}(Q_c - Q_r)\end{aligned}\quad (11)$$

where K_{pd} and K_{qd} are the droop controller slopes; ω_{act} and V_{act} are the measured values of frequency and voltage; ω_0 and V_0 are the rated frequency and voltages. The P_r and Q_r are the references corresponding to initial operating conditions with rated voltage and frequency. P_c and Q_c are the calculated values of active and reactive power, respectively. 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. The design of voltage controller is carried out based on [6] ($K_p = 0.01$, $K_i = 5.2$).

2.2a 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 1 Hz. Similarly the voltage limit should be restricted within 0.95–1.05 pu [6]. These facts can be utilised to calculate the droop slopes as follows:

$$\begin{aligned}K_{pd} &= \frac{\Delta\omega}{P_{max} - P_{min}}, \\ K_{qd} &= \frac{\Delta V}{Q_{max} - Q_{min}}.\end{aligned}\quad (12)$$

The following droop constants are obtained using (12):

$$\begin{aligned}K_{pd1} &= 3.14 \text{ and } K_{pd2} = 6.28, \\ K_{qd1} &= 0.1 \text{ and } K_{qd2} = 0.2.\end{aligned}$$

2.3 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 [10]. The island detection unit issues a switch-over command to the inverter controllers whenever the PCC voltage and frequency deviate respectively, by $\pm 10\%$ 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 (on-line or off-line) 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 on-line and calculate the set points required for the inverter at any given point of time. In Scheme-II, both the grid-connected and islanded mode controllers will be on-line and continuously calculate the set points based on local measurements. However, only one of them will be actively controlling depending on the status of the island detection command. A feedback controller is augmented in Scheme-II to improve the transient performance further. The design

of output feedback controller for islanding is described in section 3.1.

2.4 Controller for island to grid-connected mode transition

To minimise the transients during resynchronisation the PCC breaker is closed when the microgrid system voltage, frequency and phase are within the acceptable limits as specified by IEEE 1547 standards [2]. The grid side voltage and the microgrid PCC voltage are monitored using PLLs. After issuing the grid reconnection command, the PCC breaker is closed automatically when the phase, frequency and voltage are within $\pm 10^\circ$, ± 0.3 Hz and $\pm 10\%$, respectively. The inverter DGs consequently return to current-controlled mode of operation. Scheme-I and Scheme-II described in section 2.3 are also analysed during resynchronisation. To improve the transient performance with Scheme-II an additional dynamic output feedback compensator is proposed. The design of the dynamic output feedback controller for resynchronisation is described in section 3.4.

3. Output feedback controller design using pole placement

Consider a generic situation where two or more controllers operate on a single plant for different modes of operation of the plant as shown in figure 7. Initially the plant operates with Controller-1, which is the on-line controller. Upon receipt of the transfer command the plant switches to Controller-2, which is the off-line controller. The on-line controller is driven by the error command $e_1(t)$ and the off-line controller is driven by the error command $e_2(t)$ when it becomes on-line. A feedback compensator is designed to reduce the error between the output of the two controllers at the instant of transition. The feedback compensator takes the error between the outputs of off-line and on-line controllers and generates input for the off-line controller. In this way the error between the outputs of off-line and on-line controllers can be reduced [17].

Consider the off-line controller to be described by the following set of state-space equations:

Figure 7. Output feedback controller architecture.

$$\begin{aligned} \dot{x}_2(t) &= Ax_2(t) + Be_2(t) \\ u_2(t) &= Cx_2(t) \end{aligned} \quad (13)$$

where $x_2(t)$ is the off-line controller state vector and $u_2(t)$ is the controller output; $e_2(t)$ is the error input to the off-line controller.

The objective of the feedback controller F is to minimise the error between the controller outputs $u_1(t)$ and $u_2(t)$ at the instant of transition [17]. The feedback compensator output $\alpha(t)$ will be given as input to off-line controller for minimising error between $u_1(t)$ and $u_2(t)$. The output of the feedback compensator is given by the following equation:

$$\alpha(t) = F(u_2(t) - u_1(t)). \quad (14)$$

Hence the state equation (13) becomes

$$\dot{x}_2(t) = Ax_2(t) + BF(Cx_2(t) - u_1(t)). \quad (15)$$

Rearranging the terms, we have

$$\dot{x}_2(t) = (A + BFC)x_2(t) - BFu_1(t). \quad (16)$$

The transient response of the system subjected to any change in the on-line controller output $u_1(t)$ is determined by the eigenvalues of the matrix $(A + BFC)$, which is hereafter referred to as A_c . In the microgrid, when the grid is disconnected, the control mode will change from P - Q to f - V mode. Similarly during grid synchronisation the control mode changes from f - V to P - Q . Hence a feedback controller needs to be designed for the off-line controller, i.e., the island mode controller during islanding and for grid connected mode controller during resynchronisation to achieve seamless transition. The following subsections discuss the derivation of state space model of the islanded and grid-connected mode controllers along with the design of the proposed output feedback compensators.

3.1 State space model of island mode controller

For converting the droop controller in figure 8 into state-space model the following state variables are defined:

- x_1 , x_2 and x_3 are the states of the measurement filters,

Figure 8. Droop controller.

- x_4 is the state of the integrator in the PI voltage controller and
- x_5 is the phase of the inverter voltage, $\theta(t)$.

The differential equation governing the states are

$$\begin{aligned}\dot{x}_1 &= -\omega_c x_1 + \omega_c \Delta P \\ \dot{x}_2 &= -\omega_c x_2 + \omega_c \Delta Q \\ \dot{x}_3 &= -\omega_c x_2 + \omega_c \Delta V \\ \dot{x}_4 &= K_{qd} x_2 + x_3 \\ \dot{x}_5 &= K_{pd} x_1 + \omega_0\end{aligned}\quad (17)$$

where ω_c is the cut-off frequency of the measurement filter. ΔP , ΔQ and ΔV are the errors in P , Q and voltage, respectively. The output equations are

$$\begin{aligned}V &= \frac{K_p V_{dc}}{\sqrt{3}} (K_{qd} x_2 + x_3) + \frac{K_i V_{dc}}{\sqrt{3}} x_4 \\ \theta &= x_5\end{aligned}\quad (18)$$

where K_p and K_i are PI controller gains. V is the peak value of line to neutral voltage. The controller state space model can be expressed as follows:

$$\begin{aligned}\dot{X}_2 &= \begin{bmatrix} -\omega_c & 0 & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 & 0 \\ 0 & 0 & -\omega_c & 0 & 0 \\ 0 & K_{qd} & 1 & 0 & 0 \\ K_{pd} & 0 & 0 & 0 & 0 \end{bmatrix} X_2 + \begin{bmatrix} \omega_c & 0 & 0 & 0 & 0 \\ 0 & \omega_c & 0 & 0 & 0 \\ 0 & 0 & \omega_c & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} e_2 \\ U_2 &= \begin{bmatrix} 0 & \frac{K_{qd} K_p V_{dc}}{\sqrt{3}} & \frac{K_p V_{dc}}{\sqrt{3}} & \frac{K_i V_{dc}}{\sqrt{3}} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} X_2\end{aligned}\quad (19)$$

$$\begin{aligned}e_2 &= [\Delta P \ \Delta Q \ \Delta V \ \omega_0]', & U_2 &= [V \ \theta]' & \text{and} \\ X_2 &= [x_1 \ x_2 \ x_3 \ x_4 \ x_5]'\end{aligned}$$

3.2 Design of output feedback compensator for island mode controller

As explained in section 3 a feedback compensator matrix F needs to be designed to achieve seamless transition. This can be achieved using pole placement techniques [18]. Theorem 1 given here describes the conditions for achieving arbitrary pole placement using static output feedback. A detailed proof of the theorem is given in [18].

Theorem 1 *If a system is controllable and observable, and if $n \leq r + m - 1$, an almost arbitrary set of distinct closed-loop poles is assignable by gain output feedback, where n , r and m are the numbers of state variables, inputs and outputs, respectively [18].*

For the island mode controller $n = 5$, $r = 4$ and $m = 2$, which satisfies $n(5) \leq r + m - 1(5)$. It is also observed

that the island mode controller state space model (19) of the test system is controllable and observable (in canonical form). Hence a static output feedback is sufficient as per Theorem 1. To determine the feedback compensator matrix F , the desired pole locations of A_c need to be determined first. The eigenvalues of A_c are chosen such that output of island mode controller $u_2(t)$ tracks $u_1(t)$ within 100 ms from the instant of grid disconnection. This is because the island detection takes a minimum of 100 ms to give a switch-over command. During this period $u_2(t)$ should track $u_1(t)$ with minimum error to avoid switching transients. Consider a generic 2nd-order system described by the following equation:

$$\frac{y(s)}{x(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \quad (20)$$

The settling time (2% criterion) of the system is given by

$$t_s = \frac{4}{\zeta\omega_n}. \quad (21)$$

Considering a settling time of at most 100 ms and $\zeta = 0.7$ the poles of the second-order system can be easily determined. Since the closed-loop system has five poles, the remaining three poles are chosen to be five times the negative real part of the complex poles. Based on the location of the poles the desired characteristic polynomial of the closed loop system is determined as follows:

$$\begin{aligned}\Delta(s) &= s^5 + 680s^4 + 1.7 \times 10^4 s^3 + 1.95 \times 10^7 s^2 \\ &\quad + 1.02 \times 10^9 s + 2.56 \times 10^{10}.\end{aligned}\quad (22)$$

The feedback matrix design is carried out to ensure that the loop transfer functions of both $Q-V$ and $P-\omega$ droop controllers have a settling time of 100 ms. The matrix F calculated in this way is very easy to implement as the outputs of both on-line and off-line controller are readily accessible. The feedback matrix for DG_1 island mode controller, F_1 is shown below,

$$F_1 = \begin{bmatrix} 0 & 1147.6 & -152.79 & 0 \\ 69.8 & 0 & 0 & 0 \end{bmatrix}^T.$$

Similarly one can arrive at the feedback matrix F_2 for DG_2 :

$$F_2 = \begin{bmatrix} 0 & 344.94 & -152.79 & 0 \\ 139.6 & 0 & 0 & 0 \end{bmatrix}^T.$$

3.3 State space model of grid-connected mode controller

In order to convert the equations to a state space model, the following states are defined:

- x_1 and x_2 are the states of the measurement filter in d and q -axis controllers, respectively.
- x_3 and x_4 are the states of integrators in PI controllers of the d and q axis, respectively.

Using these state variable definitions the differential equations of the measurement filter and the PI controllers can be obtained as follows:

$$\begin{aligned} \dot{x}_1 &= -\omega_c x_1 + \omega_c \Delta i_d, \\ \dot{x}_2 &= -\omega_c x_2 + \omega_c \Delta i_q, \end{aligned} \quad (23)$$

$$\begin{aligned} \dot{x}_3 &= x_1, \\ \dot{x}_4 &= x_2. \end{aligned} \quad (24)$$

The output of the controllers are expressed as follows:

$$\begin{aligned} v'_d &= K_p x_1 + K_i x_3 \\ v'_q &= K_p x_2 + K_i x_4 \end{aligned} \quad (25)$$

where $\Delta i_d = i_d^* - i_d$ and $\Delta i_q = i_q^* - i_q$. K_p and K_i are parameters of the PI controller. The controller state space model can be expressed as follows:

$$\begin{aligned} \dot{X}_1 &= \begin{bmatrix} -\omega_c & 0 & 0 & 0 \\ 0 & -\omega_c & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} X_1 + \begin{bmatrix} \omega_c & 0 \\ 0 & \omega_c \\ 0 & 0 \\ 0 & 0 \end{bmatrix} e_1 \\ U_1 &= \begin{bmatrix} K_p & 0 & K_i & 0 \\ 0 & K_p & 0 & K_i \end{bmatrix} X_1 \end{aligned} \quad (26)$$

$$e_1 = [\Delta i_d \ \Delta i_q]', \quad U_1 = [v'_d \ v'_q]', \quad \text{and } X_1 = [x_1 \ x_2 \ x_3 \ x_4]'$$

3.4 Design of output feedback compensator for grid-connected mode controller

To achieve seamless transition during resynchronisation, an additional feedback compensator needs to be augmented to the grid-connected mode controller. For the grid-connected mode controller state space model given in (26), $n = 4$, $r = 2$ and $m = 2$. It can be found from theorem 1 that the condition $n(4) \leq r + m - 1(3)$ for arbitrary pole placement is not satisfied. Hence, arbitrary pole placement using static output feedback is not possible even though the state space model is found to be controllable and observable. However, a dynamic compensator can be designed for arbitrary pole placement as per the following theorem [18].

Theorem 2 *If a system is both controllable and observable, then a dynamic compensator of order $p = n - m - r + 1$ can assign almost arbitrary poles for the overall closed-loop system provided that the poles to be assigned are all distinct.*

Figure 9. Grid-connected mode controller along with a dynamic output feedback compensator.

According to Theorem 2 the minimum order of dynamic compensator is found to be 1. The first-order dynamic output feedback compensator is as follows [18]:

$$\alpha = \begin{bmatrix} \frac{F_1}{s} & 0 \\ 0 & \frac{F_2}{s} \end{bmatrix} (u_2 - u_1). \quad (27)$$

A block diagram of the grid-connected mode controller with the augmented dynamic feedback compensator is shown in figure 9. The loop transfer functions of the system given in figure 9 for d and q axes are given as follows:

$$\begin{aligned} L_d(s) &= \frac{F_1}{s} \frac{\omega_c}{s + \omega_c} \left(K_p + \frac{K_i}{s} \right), \\ L_q(s) &= \frac{F_2}{s} \frac{\omega_c}{s + \omega_c} \left(K_p + \frac{K_i}{s} \right). \end{aligned} \quad (28)$$

Since the equations for d - and q -axis controllers are completely decoupled a Bode-plot-based design can be carried out, which will ensure an arbitrary pole placement corresponding to a given settling time requirement. The design parameters in (28) are the constants F_1 and F_2 , which are selected so as to obtain a reasonable speed of response without compromising with the phase margin of the system. In this scenario a settling time of 100 ms (phase margin: 86.9°) is chosen and accordingly the values of F_1 and F_2 can be easily determined ($F_1 = F_2 = 494.6$). The Bode plot of the loop transfer function is shown in figure 10.

4. Results and discussion

The microgrid system described in section 2, figure 1a has been modelled in Simulink. The system performance is assessed with several sets of load/generation patterns. The microgrid operations during grid-connected mode and during transition from grid-connected to islanded mode and vice versa have been analysed using the proposed schemes. The following sequence of events are simulated in this case.

- Initial operating conditions: At $t = 0$ s, the real and reactive power set points of each DG are set to 2.5 kW and 0 kVar (unity power factor—upf).

Figure 10. Bode diagram of the loop transfer function.

- Event 1: At $t = 1.5$ s, the real and reactive power set points of DG_2 are changed from 2.5 kW and 0 kVar (upf) to 5 kW and 3 kVar (0.85 pf).
- Event 2: At $t = 2$ s, the real power set point of DG_1 is changed from 2.5 to 5 kW (upf).
- Event 3: At $t = 2.5$ s, both real and reactive power set points of DG_2 are made 0.
- Event 4: At $t = 3$ s, the grid is disconnected and the system transitions into islanded mode of operation.
- Event 5: At $t = 5$ s, the system load is reduced from 10 to 7.5 kW keeping the pf unchanged.
- Event 6: At $t = 7$ s, the grid reconnection command is issued and the system returns to grid-connected mode of operation.

4.1 Grid-connected mode: Events 1–3

Events 1–3 are created to test the performance of the grid-connected mode controllers. Figure 11a shows the real and

reactive powers of DG_1 , DG_2 and the grid for the events considered earlier. Figure 11b shows the corresponding voltage and frequency at the PCC bus. Prior to the creation of disturbance, DG_1 and DG_2 supply 2.5 kW at upf. The remaining power of 5 kW is supplied by the grid as seen from the figure. It can be observed from figure 11a that corresponding to Event-1, the active and reactive powers of DG_2 increase to 5 kW and 3 kVar, respectively. DG_1 power remains unchanged and the grid active and reactive powers reduce to 2.5 kW and 4.5 kVar, respectively. In figure 11b it can be observed that the voltage and frequency settle within limits ($\pm 10\%$ V and ± 0.5 Hz) with a small transient. At $t = 2$ s (Event-2), 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 DG_2 set points are made zero at $t = 2.5$ s (Event-3), the grid active and reactive powers increase back to 5 kW and 7.5 kVar, respectively. DG_1 power remains unchanged. In all these step responses of power set points a settling time of 10 ms is achieved as per the design.

4.2 Grid-connected to islanded mode transition: Event 4

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.

Figure 12a shows the voltage transient during transition for Scheme-I (dotted line), Scheme-II (dashed line) and Scheme-II with output feedback (solid line). 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

Figure 11. Simulation results for grid-connected mode (Events 1–3). (a) Active and reactive power. (b) Voltage and frequency.

Figure 12. Load voltage and frequency during grid-connected to island mode transition (Event 4). (a) Voltage. (b) Frequency.

Figure 13. P and Q during grid-connected to island mode transition (Event 4). (a) Active power. (b) Reactive power.

senses the situation and issues a switch-over command at $t = 3.11$ s. 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 after a small voltage dip. Frequency settles quickly in Scheme-II compared with Scheme-I. In both the schemes the frequency and voltage settle to 49.94 Hz and 222.2 V, respectively, which are well within the prescribed limits [2]. It can be observed that with the output feedback controller, there is no dip in the voltage at the instant of transition and quick recovery of voltage and frequency is also achieved.

Figure 13a shows real powers of DG_1 , DG_2 and total DG powers supplied to load during transition. In Scheme-I the active power of DG_1 drops to zero and quickly rises to its steady-state value. Since DG_2 is already at $P = 0$ kW, no dip can be seen. This dip causes a momentary load drop as seen in the figure. With Scheme-II, DG_1 shows very small drop in active power and reaches steady state quickly without any over-shoot. With the output feedback controller, DG_1 and DG_2 do not show any harmful transients in real power and the load is served quickly.

Figure 13b shows reactive powers of DG_1 , DG_2 and total DG powers supplied to load during transition. With Scheme-I, at the instant of transition, there is a significant dip in reactive powers of both DG_1 and DG_2 followed by

Figure 14. Simulation results for islanded mode (Event 5). (a) Active and reactive power. (b) Frequency and voltage.

gradual recovery. With Scheme-II, DG_1 reactive power continuously rises and reaches a steady-state value. Similarly, DG_2 reactive power reduces significantly and takes a long time to reach steady-state value. The load power supplied by the DGs however does not experience any such long overshoots in reactive power with Scheme-II. It means that there is a circulating reactive current between the two inverters during the transition. With output feedback it can be observed that DG_1 and DG_2 reactive powers do not show any harmful transient and quickly settle to steady-state value.

4.3 Islanded mode operation: Event 5

The droop controllers designed in section 2.2 are tested in this event. Figure 14a shows the active and reactive power of DG_1 and DG_2 during island mode. Figure 14b 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 settle to 6.6 kW, 3.9 kVar and 3.0 kW, 3.3 kVar, respectively. The voltage and frequency settle to 49.94 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 $t = 5$ s 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 DGs P and Q settle within 80 ms and the voltage and frequency (224.2 and 49.96 Hz) settle according to the droop curve.

Several other test cases have been simulated by varying load, generation, grid voltage and frequency. Under all these conditions, Scheme-II with feedback controller has shown superior performance. Hence, it can be concluded

that the transients during grid-connected to island mode transition can be significantly reduced using a simple feedback controller.

4.4 Island to grid-connected mode transition: Event 6

This event is created to analyse the behaviour of microgrid system during resynchronisation with the grid. Figure 15a shows the active power of the DGs and the grid during the transition from islanded mode to the grid-connected mode. Figure 15b shows the reactive power of the DGs and the grid during the transition from islanded mode to the grid-connected mode. Upon grid reconnection, the inverter DGs again transition to current-controlled mode and follow the reference P and Q prior to islanding (DG_1 : 5 kVA (upf), DG_2 : 0 kVA). It can be observed that DG_1 and DG_2 draw huge reactive powers from the grid during resynchronisation with Scheme-I. However DG_1 reactive power becomes negative and DG_2 becomes positive, which indicate a circulating reactive power between the generators during resynchronisation. However, with the proposed dynamic compensator, the circulating reactive current is eliminated. Also it can be seen that the grid power increases to balance the load and generation.

Figure 16 shows the corresponding PCC voltage and the frequency during the transition. The voltage and the frequency are now determined by the grid and the frequency has settled exactly to 50 Hz after undergoing a transient (figure 16). With Scheme-I, considerable frequency and voltage transients can be observed during resynchronisation. From this simulation, it can be concluded that the dynamic output feedback compensator facilitates smooth transition during resynchronisation.

Figure 15. P and Q during island to grid-connected mode transition (Event 6). (a) Active power of DGs and grid. (b) Reactive power of DGs and grid.

Figure 16. Voltage and frequency during island to grid-connected mode transition (Event 6).

5. Conclusions

This paper investigates the operation of microgrid during transition from grid-connected to island mode and vice versa with inverter-based DG sources. A systematic approach for designing the grid connected and island mode controllers is described. Contributions of the paper are the following:

- Two strategies are proposed for transition from grid-connected to island mode and vice versa based on the status of island mode controls.
- Significant transients in load, P and Q are observed in Scheme-I with momentary interruption to load during transition from grid-connected to islanded mode of operation.

- The transients in active power with Scheme-II are significantly reduced compared with Scheme-I. However, with Scheme-II, large circulating reactive currents between the sources are observed during islanding.
- A novel output feedback controller augmentation to scheme-II is proposed for reducing the transients and circulating currents. A static feedback is shown to be sufficient for transition to island mode and a first order dynamic compensator is shown to be sufficient for resynchronisation to the grid.
- The output feedback controllers are easy to implement using local measurements. The performance of the system with output feedback controllers is found to be satisfactory under all operating conditions tested.

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