Controller Design and Implementation of Indirect Current Control based Utility-Interactive Inverter System

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Abstract—The indirect current control algorithm has been proposed for seamless transfer of utility-interactive inverters. The inverter is able to provide critical loads with a stable and seamless voltage during control mode change as well as clearing time. This paper proposes an indirect current controller based on classical control theory so that the controller gains can easily be determined. Also, a PLL technique is proposed to maintain the constant frequency during the unintentional islanding. A passive islanding detection based on current variation which is suitable for the indirect current control is proposed. The proposed control method is validated through simulation and experiment.

I. INTRODUCTION

Recently, new and renewable energy sources such as fuel cells, photovoltaic and wind turbines have been recognized as major alternative means to fossil fuels. Utility-interactive inverters have been playing an important role in the DG (Distributed Generation). The utility-interactive inverter should operate in both grid-connected and stand-alone modes to provide uninterrupted and continuous power to critical loads, for example, such as power supplies for MBOP (mechanical balance of plant) in fuel cell systems. During the grid-connected mode the inverter is operated to inject power from the DG unit to the grid. When a fault occurs in the grid, a recloser switch is open and the DG unit enters into islanding. Then, the inverter should detect the islanding and cease to energize the grid by disconnecting the DG unit from the grid within two seconds which is a required clearing time [1]. During this unintentional islanding, the voltage across the critical load may experience severe transient state since the inverter switch is still closed and the voltage is determined by the amount of injected power and unknown load condition. Further, there exists a large transient across the critical load even after actual turn-off of the inverter switch since the conventional controller should be changed from current controlled mode to voltage controlled mode. Thus, one of the key functions of the utility-interactive inverter is seamless transfer during control mode change transition from grid-connected to stand-alone modes as well as clearing time which includes unintentional islanding.

A sequence for smooth mode transfer between two modes has been addressed and implemented in [2,3]. A control technique proposed in [4] reduces turn-off time of a static switch (SCR) by controlling voltage across the grid-side inductor, which results in quick grid current decrease. In order to alleviate the transient voltage and inrush current associated with operating time of a circuit breaker a control algorithm using the feedback status of circuit breakers has been proposed [5]. However, the control methods proposed in [2-5] have a drawback of large transient associated with control mode transition. A control method has been proposed to eliminate the transient associated with the control mode change by utilizing both current and voltage controllers in both grid-tied and off-grid modes [6]. However, none of the above mentioned control algorithms for seamless transfer [2-6] did consider the transient state during the whole transition period including both clearing time and control mode change.

The concept of indirect current control method for seamless transfer of a single-phase utility interactive inverter has been proposed in [7], where the transient associated with control mode change has significantly been reduced by controlling the peak value of the output current with an inner voltage loop in both grid-connected and stand-alone modes. For three-phase utility interactive inverters dq-transformation is introduced to control instantaneous values of the output current, and a control technique is proposed for seamless transfer during the control-mode-change transition as well as clearing time [8]. However, a drawback of controllers in [7,8] is that determination of controller gains should be on the trial and error basis since sine and cosine tables, which are a non-linear factor, are included in the control block. Also, during the unintentional islanding the controller is
capable of providing the critical load with constant voltage, but the frequency of voltage across the critical load can be changed depending on the load condition and real, reactive power mismatches, which may result in misoperation of the load. Further, the conventional islanding detection method based on voltage and frequency variation cannot be applied to this indirect current control since the voltage across the critical load should be regulated at the rated values.

In this paper, the controller is modified to eliminate the sine and cosine tables in the control block, and therefore the classical control theory such as root locus and bode diagram can be applied and the controller gain can easily be determined based on this analysis. Also, a PLL technique is proposed to maintain the constant frequency during the islanding occurrence. A passive islanding detection based on current variation which is suitable for indirect current control is proposed.

II. PROPOSED CONTROL ALGORITHM

Fig. 1 shows the circuit diagram of a three-phase utility-interactive inverter for distributed power generation. The three-phase inverter with LCL filters is connected to the grid through an inverter switch, a step-up transformer and a recloser. A critical load is located between the LCL filter and the switch.

The idea of the proposed control is to regulate grid-side inductor current \( I_{Lg} \) by controlling the magnitude and phase angle of capacitor voltage \( V_{Cf} \) so that desired magnitude of grid current which is in phase with the utility voltage is injected to the grid as shown in Fig. 2. From Fig. 2, the nominal value of desired magnitude of dq-capacitor voltage can be expressed as,

\[
V_{Cf, nom}^{d} = V_{Lg} = I_{Lg} \times \omega L_{g} \tag{1}
\]

\[
V_{Cf, nom}^{q} = V_{g} \tag{2}
\]

Fig. 3 shows the proposed control block diagram for grid-connected and stand-alone operations of the three-phase utility-interactive inverter. The dq-capacitor voltage reference can be obtained by adding the nominal value of desired magnitude of dq-capacitor voltage to the output of the dq-grid-side inductor current controller. Assuming that the decoupling is done by controller, the control block diagram shown in Fig. 3 can be simplified as shown in Fig. 4. The closed-loop transfer function of the inner voltage loop is obtained by,

\[
v_{Cf}^{d}(s) = \frac{K_{p}^{d} + K_{i}^{d}s + K_{d}^{d}s^{2}}{s^{2} + A^{s} + B^{s} + C^{s} + D^{s} + E} \tag{3}
\]

where, \( A = L_{Cf}L_{g} \), \( B = R_{Cf}L_{g} + L_{Cf}R_{g} + K_{dv}L_{g} \), \( C = K_{dv}R_{g} + L_{i} + R_{i}L_{g} + K_{pv}L_{g} + L_{g} \), \( D = K_{pv}R_{g} + R_{i} + K_{iv}L_{g} + R_{g} \), \( E = K_{iv}R_{g} \)
Then, from characteristic eq (3), given desired damping factor $\zeta$ and natural frequency $\omega_i$ of the inner voltage loop, voltage controller gains can be obtained by, respectively,

$$K_{pv} = \omega_i^2 (1 + 2\zeta m) LC_f - 1 - \left( \frac{L_i}{L_g} \right)$$  \hspace{1cm} (4)

$$K_{vi} = \zeta \omega_i^3 m / L_g$$  \hspace{1cm} (5)

$$K_{vi} = \zeta \omega_i (2 + m) L_i C_f - R_f C_f$$  \hspace{1cm} (6)

where, in general, $m$ is chosen to be greater than 10.

Assuming that the control bandwidth of inner voltage loop is larger than that of the outer current loop, the transfer function of the inner voltage loop can be approximated to 1. Then the closed-loop transfer function of the whole system becomes,

$$i_{ig} \frac{ds}{ds} = \frac{K_{pi} + K_{vi}}{s^2 L_g + (R_g + K_{pi}) s + K_{vi}}$$  \hspace{1cm} (7)

Also, from characteristic eq (7), given desired damping factor $\zeta$ and natural frequency $\omega_i$ of the output current loop, current controller gains can be obtained by, respectively,

$$K_{pi} = 2\zeta \omega_i L_g - R_g$$  \hspace{1cm} (8)

$$K_{vi} = \omega_i^2 L_g$$  \hspace{1cm} (9)

For an example calculation of controller design the following system parameters are assumed, • $L_i = 1.78 mH$, • $C_f = 3uF$, • $L_g = 3 mH$, • $R_i = 10 m\Omega$, • $R_f = 20 m\Omega$. If the desired damping and controller bandwidth of the inner voltage loop are 0.7 and 1130 rad/sec, respectively, the bode diagram of the voltage loop gain can be obtained by using equations (4)–(6), as shown in Fig. 5(a). It can be seen that the phase margin and cut-off frequency of the voltage loop are around 75° and 1300 rad/sec which are close to the desired values. Also, if the desired damping and controller bandwidth of the outer current loop are 0.6 and 500 rad/sec, respectively, the bode diagram of the current loop gain can be obtained by using equations (8) and (9), as shown in Fig. 5(b). It can be seen that the phase margin and cut-off frequency of the voltage loop are around 67.6° and 534 rad/sec.

III. PROPOSED PLL ALGORITHM

Fig. 6(a) shows the block diagram of the conventional PLL algorithm. The conventional method obtains phase angle $\theta$ synchronized to the grid voltage by controlling d-axis voltage to zero. The output frequency $\omega$ of the PLL is determined by adding $\Delta \omega$ which is output of the PI controller to desired angular frequency $\omega_d$. The variation in angular frequency $\Delta \omega$ becomes zero in the steady state, and then the output frequency is equal to desired angular frequency $\omega_d$. Also, in the transient state $\Delta \omega$ does not become zero, which causes the output frequency of the PLL is adjusted so that it is synchronized to the grid frequency. However, when an islanding occurs the frequency of the sensed grid voltage changes according to difference between inverter output power and demanded critical load power, resulting in deviation of the frequency of the critical load, as shown in Fig. 7(a), which may cause bad effects on the critical load. Fig. 6(b) shows the block diagram of the proposed PLL algorithm. The reference phase angle $\theta$ is obtained by summation of feedforward angle $\theta_f$ which is integral of rated frequency of the grid voltage and compensating angle $\Delta \theta$ which is the output of the PI controller for d-axis grid voltage. Since the slope of the reference phase angle $\theta$ is constant, the output frequency of the PLL maintains at $\omega_d$ without regard to the compensating angle $\Delta \theta$. Therefore,
during the unintentional islanding the controller is capable of providing the critical load with constant voltage as well as constant frequency across the critical load without regard to the load condition, as shown in Fig. 7(b).

![Fig. 6 dq PLL algorithm (a) conventional (b) proposed](image)

**IV. PROPOSED PASSIVE ANTI-ISLANDING ALGORITHM**

In the conventional current control method islanding is usually detected by a change in voltage and frequency of the critical load which is determined by difference between real and reactive power consumed by the critical load and real and reactive power supplied by the inverter. However, the proposed indirect current control and PLL technique do not cause a change in the voltage and frequency of the critical load when the islanding occurs. Therefore, the conventional islanding detection method based on voltage and frequency variations cannot be applied to the proposed indirect current control. Instead, in the proposed indirect current control the islanding can be detected by a change in the grid-side inductor current. This is because the q-axis and d-axis grid-side inductor currents are changed, respectively, by mismatches between real and reactive power consumed by the critical load and real and reactive power supplied by the inverter, as shown Fig. 8.

Fig. 9 shows a flowchart of the proposed anti-islanding algorithm for the indirect current control. First, current $I_{Lg}$ is sampled and then dq-axis values are calculated. If differences between reference value and actual value of d-axis or q-axis are larger than user defined limiting values $K_d$ or $K_q$, respectively, the index ‘cnt’ keeps increasing until $K_n$, and then the islanding can be confirmed. The limiting values should carefully be chosen since smaller limiting values may result in frequent tripping of inverter switch and larger limiting values may result in increased non-detection zone. The limiting values $K_n$ for the index can be decided to meet IEEE std. 929-2000 or IEEE std. 1547-2003.

![Fig. 8 Simulation of the proposed control algorithm when the islanding occurs with specifications based on Table I](image)

Fig. 7 Simulation of the PLL algorithm when the islanding occurs with specifications based on Table I (a) conventional (b) proposed
V. EXPERIMENTAL RESULT

A three-phase utility-interactive inverter system has been built to verify the proposed control method with the parameters shown in Table I. Fig. 10 shows the experimental setup for the proposed utility-interactive inverter system. A programmable AC source is used to emulate the utility grid. A magnetic contactor which is used as the inverter switch is located between critical load and the programmable AC source. The DSP TMS320F28335 chip is used to implement the proposed control. An on/off signal for magnetic contactor is generated by the DSP controller. Fig. 11 shows the photograph of the laboratory prototype. Fig. 12 shows experimental waveforms for the transfer from stand-alone mode to grid-connected mode. After the phase match the inverter switch is closed, then the grid-side inductor current reduces to zero since the commanded real and reactive power are zeroes. Then the demanded critical load power is supplied from the grid. With the signal for grid current injection the grid current $i_{dG}$ is gradually increased according to its commanded real power.

Fig. 13 shows experimental waveforms for the transfer from grid-connected mode to stand-alone mode. In the grid-connected mode grid current is almost sinusoidal with THD of 2%. It should be noted that there is no change in voltage and frequency of the critical load during an islanding occurrence. Any noticeable transient is not observed across the load throughout the whole transition period including the clearing time and control mode change which is performed right after actual turn-off of the inverter switch.
VI. CONCLUSION

In this paper an indirect current controller based on classical control theory is proposed for easy determination of controller gain and simple implementation of the controller. Also, a PLL technique is proposed to maintain the constant frequency across the critical load during the islanding occurrence. The proposed method is capable of providing critical load with a stable and seamless voltage during the whole transition period including both clearing time and control mode change transition. A passive islanding detection method based on current variation which is suitable for the indirect current control is also proposed. The proposed control method has been validated through simulation and experiment.

REFERENCES