Cross Coupling Method to Detect Islanding Instant in Inverter Based Distributed Generation

Karthick Sekkappan and K. S. Swarup

***Abstract*— Conventional relays cannot detect islanding instant if the generation and local load are perfectly matched in the islanded distributed generation (DG) system. Moreover if the islanded system frequency is equal to the resonance frequency of the load, it results in stabilizing effect. This keeps the voltage and frequency of the islanded system in stable operating region resulting in failure to detect islanding. This stabilizing effect is directly related to the quality factor (QF) of the load. A new islanding detection method is proposed which does not have any adverse power quality problems, NDZ or need of additional infrastructure. Cross coupling in control action between the components I_d (direct axis component) and I_q (quadrature axis component) is introduced by a novel method which makes the system unstable in islanded mode thereby shifting the frequency out of nominal range. This frequency drift can be used as a mean to detect islanding. The coupling between I_d and I_q is in such a way that it does not adversely affect the control system dynamics in grid connected mode. Mathematical result is shown to support the claim. The proposed method does not induce power quality problems and has no Non-Detection Zone (NDZ). Small signal stability analysis and Simulink simulation are performed to find the effectiveness of this scheme for a worst case scenario.**

I. INTRODUCTION

One of the promising ways to increase renewable energy into the current energy mix is through distributed generation. The IEEE defines DG as an electricity generating source that is significantly smaller in capacity than conventional power plant and that can be connected to any point in power system [1]. DGs can be realized either as a standalone system connected to power grid or as microgrid. Microgrid is a cluster of small scale DGs and local loads connected together which can operate with and without connection to main grid. Apart from being a mean for including renewable energy to the grid, DG's close proximity to load helps in reducing power transmission loss and in reducing transmission line traffic. DGs are not free from technical challenges. One of the challenge in widespread DG use is islanding detection. For both microgrids and standalone DGs islanding detection is essential. Island, in power system terminology, is defined as a subsystem that gets disconnected from the main grid and continue to supply power to its local load within operable limit. Detecting the instant at which the system gets islanded is called islanding detection. In this paper need for islanding detection is justified, existing methods to detect islanding instant is discussed, a new islanding detection scheme is proposed and its performance is analyzed.

II. NEED FOR ISLANDING DETECTION

In microgrids, islanding detection is required for successful islanded mode operation. Faster the islanding detection smoother is the mode transfer. In case of individual DG connected to main grid, islanding detection is required for successful prevention of islanding operation [2]. There are multiple reasons for preventing island formation when DG is connected to a utility grid. Safety, liability and quality of power delivered to customers are the utility's list of reasons to prevent islanding which can be explained below [3],

1) The utility has no control over voltage and frequency in the islanded system. Hence, damage of equipment to utility customers is possible.
2) Utilities and the DG owner, is liable for electrical damage to customer equipment connected to their lines that results from voltage or frequency variations outside of the acceptable range.
3) Island may pose a hazard to unaware utility workers
4) Reclosing the line into an islanded system will cause re-tripping when islanded system and grid are not synchronized.
5) Islanding may interfere with the manual or automatic restoration of normal service by the utility.

The last three points also holds for microgrids. Hence islanding detection is an important function for both microgrids and individual DGs.

III. THEORY BEHIND ISLANDING DETECTION

Traditionally islanding detection, also known as loss of main protection is done through monitoring voltage and frequency at the point of common coupling (PCC). Consider a simplified system as shown in Fig. 1. The load is modeled as a constant impedance parallel RLC circuit. The real (P_l) and reactive (Q_l) power of load is met by real (P_{dg}) and reactive (Q_{dg}) power generation of DG and real (P_g) and reactive (Q_g)

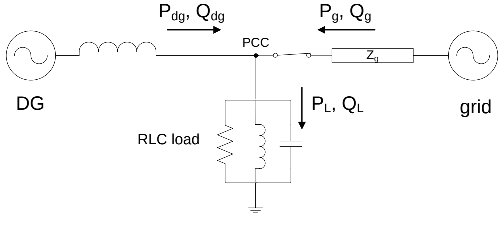


Fig. 1. DG connected to main grid with local load

Karthick Sekkappan and K. S. Swarup are with the Department of Electrical Engineering, Indian Institute of Technology, Madras, Chennai, India. e-mail: ee12s007@ee.iitm.ac.in.

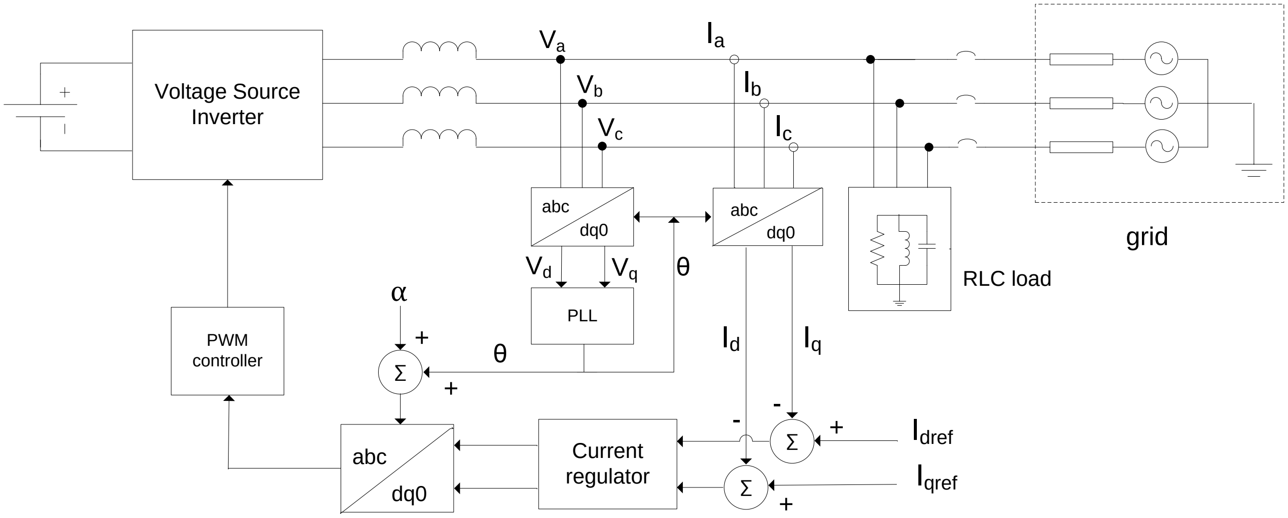


Fig. 2. Block diagram of proposed system

power flow from grid. When the circuit breaker is opened, the power flow to the load changes to P_{dg}, Q_{dg}. This results in change in frequency and voltage at PCC. The change in frequency at PCC depends on the reactive power mismatch of the load while the change in voltage at PCC depends upon real power mismatch of the load [4]. If the change is significant enough then Overvoltage and Undervoltage relay (OVR/UVR) or Overfrequency and Underfrequency relay (OFR/UFR) will actuate thereby safely shutting down the generation. This scheme of islanding detection is one among the passive islanding detection method. When the real power and reactive power of DG closely matches that of the load, opening the circuit breaker will not result in significant change of frequency and voltage. The load values for which the islanding detection method fails to detect islanding is called as Non-Detection Zone (NDZ) [5]. For this passive method NDZ is given by (1) and (2) [4]. The variables f_{min}, f_{max} and V_{min}, V_{max} are the minimum and maximum limit settings of the protective relay for frequency and voltage. The variables f_g and V are the grid frequency and voltage at the PCC. The NDZ is given by the real and reactive power mismatch ΔP and ΔQ. In many countries like India, the operating frequency varies in wide range requiring relay to have a broader minimum and maximum limit settings. Hence this passive scheme has a large NDZ. Due to this drawback various schemes that can be grouped under different methods are proposed in literature.

$$Q_f\left(\frac{f_{min}}{f_g}-\frac{f_g}{f_{min}}\right)\leq\frac{\Delta Q}{P_{load}}\leq Q_f\left(\frac{f_{max}}{f_g}-\frac{f_g}{f_{max}}\right) \quad (1)$$

$$\left(\frac{V}{Vmax}\right)^2-1\leq\frac{\Delta P}{P_{load}}\leq\left(\frac{V}{Vmin}\right)^2-1 \quad (2)$$

IV. EXISTING SCHEMES

Since conventional relays cannot detect islanding instant in all cases several islanding detection schemes are proposed in literature. They can be classified broadly based on the DG type on which it is implemented, namely inverter and rotating machine.

A. In inverter based DGs

Existing schemes can be classified as active, passive and communication based methods. Passive method relies on monitoring frequency and voltage of the system and does not affect the power output of DG. Schemes in passive method include voltage phase jump [6], voltage harmonic monitoring [6], current harmonic monitoring [7], Rate of Change of Frequency (ROCOF) [8]. Through the adaptation of passive schemes it is only possible to reduce the NDZ but it cannot be eliminated completely. Schemes in active method are based on perturbation in inverter output like cyclic change in real or reactive power [9], active frequency drift [10], sliding mode or slip-mode frequency shift [11], Sandia frequency shift or active frequency drift with positive feedback [11], impedance estimation [11], detection of impedance at a specific frequency or monitoring of harmonic distortion [12], Sandia voltage shift [3], frequency jump [3]. Active method is intrusive in nature i.e. the method involves intentional perturbation in inverter output hence suffer from power quality degradation. Methods like General Electric (GE) positive feedback technique [13] overcome the problem of NDZ and power quality degradation but it affects the system stability. Schemes involving communication between utility and DG can avoid the problems discussed above but reliability of communication link and the setup cost make them less attractive.

B. In rotating machine DGs

Rotating machines directly connected to grid are much more capable to maintain an island than the inverter based DGs. Techniques to detect islanding instant for such system can again be classified as passive, active, communication based schemes. Communication based schemes are same as the schemes in inverter based DGs. Passive schemes includes

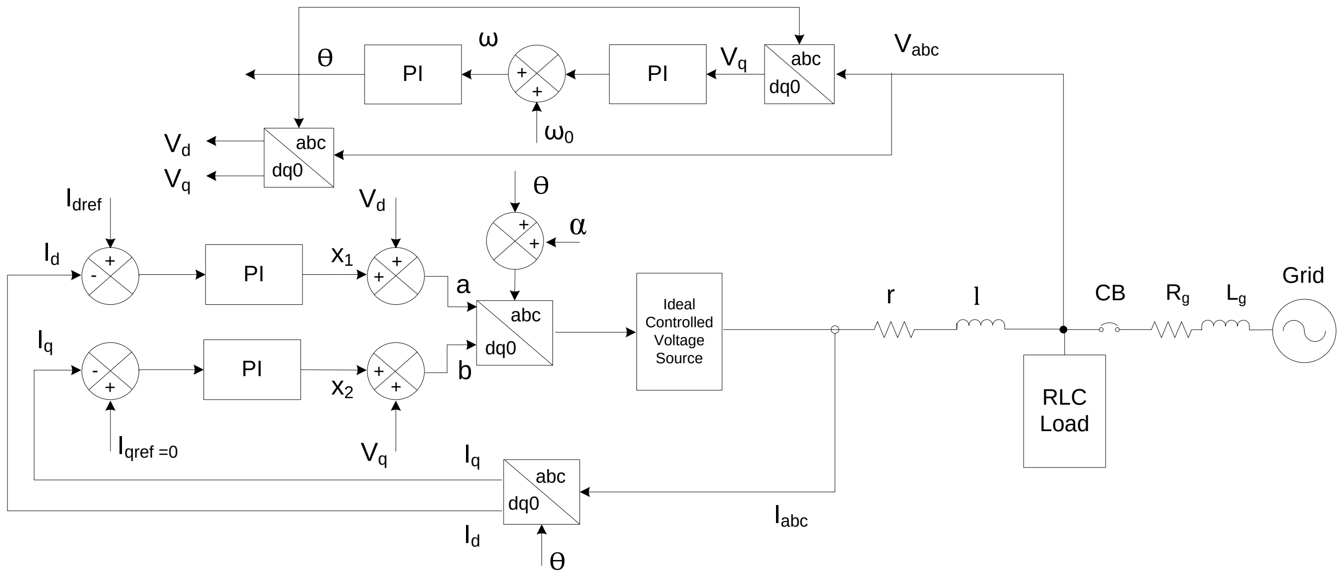


Fig. 3. PLL and Controller inside DG control system

monitoring the deviations in voltage, frequency, $\frac{df}{dt}$ and phase shift of voltage at DG terminal [14]. Active detection schemes include calculation of impedance from voltages and currents measured at the DG terminals and injecting low-frequency interharmonic currents [14]. Active schemes have negligible NDZ but disturbs the quality of power delivered to load.

V. MODEL AND STATE SPACE EQUATION

A. Test System

Shown in Fig. 2 is the block diagram of the test system [13] with inverter based distributed generation connected to the grid. A constant voltage DC supply is chosen as the DG source. A PWM (Pulse Width-Modulator) three phase voltage source inverter transforms dc to ac. A three phase balanced parallel RLC circuit of 2.5 quality factor (QF) resonant at frequency of 60 Hz is chosen as the load as it is considered to be the worst case scenario for islandng detection [15]. The measured three phase voltages V_a, V_b, V_c at PCC and line current I_a, I_b, I_c is transformed from abc domain to dq0 through dqo transformation (referred hereafter as direct dq0 transformtion). A simple PI current controller in dq0 domain controls the output line current. A constant current control scheme [13] is implemented with reactive current reference (I_{qref}) being zero. This is set to avoid reactive power generation from DG. Synchronous reference frame phase locked loop (SRF-PLL) [16] synchronizes the DG with grid. CB is the circuit breaker between DG and main grid.

B. Mathematical Model

For reducing complexity average model of inverter is employed. The PWM signal generator, the switching power electronics devices like Insulated Gate Bipolar Transistors (IGBTs) and the dc source are replaced by controlled voltage sources [17]. Grid is modeled as a Thevenin voltage source behind Thevenin impedance. The linearized state space equation of the system is derived for both grid connected and islanded mode from the differential equations of the system (appendix). The parameter used in this paper is shown in Table. I in appendix. The worst case scenario of exact power match between DG generation and local demand is chosen as the operating point for linearizing the system.

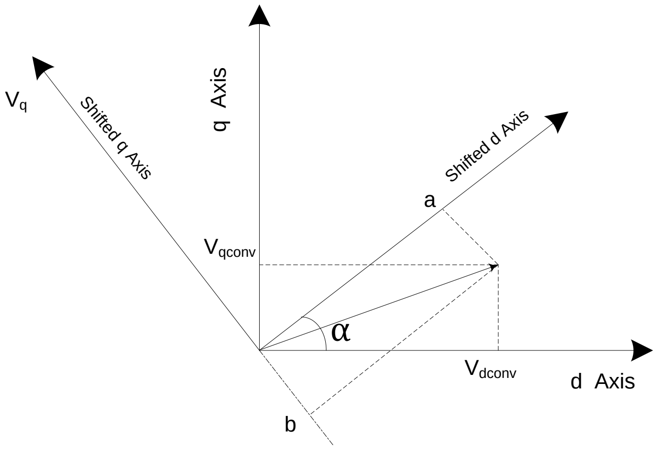


Fig. 4. V_{conv} phasor and its components in dq axis and shifted dq axis

VI. PROPOSED SCHEME

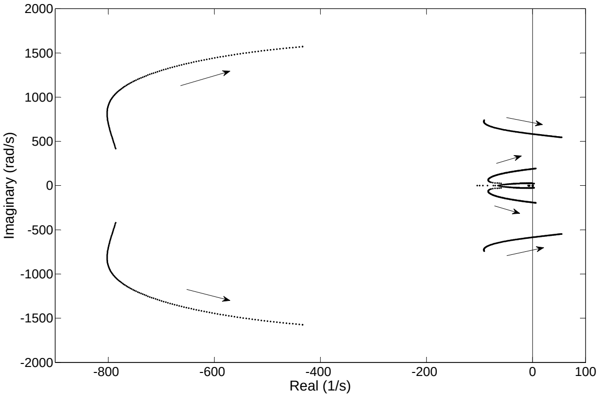
The operating principle is based on pushing the frequency at PCC out of normal operating range when the DG is islanded. In this technique this is achieved by pushing the dominant eigenvalues to the right half of s-plane when transitioning from grid connected mode to islanded mode. An intentional difference in angle α between the direct and inverse dq0 transformation is introduced. This angle difference induces a shift in reference frame for inverse dq0 transformation from the direct dq0 transformation. Shown in Fig. 4 is the effect of shifting the reference frame. If a and b are the voltage applied by converter (V_{conv}) in shifted frame then voltage applied by converter in dq frame can be equivalently written as,

$$V_{dconv} = a\cos\alpha - b\sin\alpha \tag{3}$$

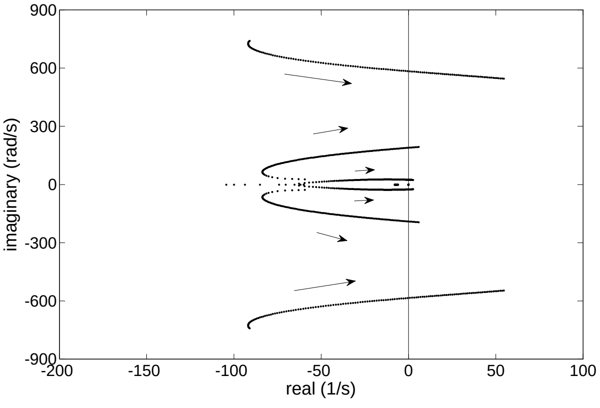
$$V_{qconv} = a\sin\alpha + b\cos\alpha \tag{4}$$

Now dynamics of I_d and I_q individually depends on both V_d and V_q (refer appendix) creating a coupling effect in control action. This dependency pushes the system to instability when the DG is islanded.

In order to find the value for α for which the islanded system is unstable, eigenvalue loci for increasing value of α from 0 rad is plotted as shown in Fig.5. For plotting, state space matrix A is obtained after linearizing the system. As shown in Fig. 5b the dominant eigenvalue of the islanded system moves towards the right half of s-plane as α increases. For α= 0.86 rad, couple of eigenvalues crosses the right half of s-plane and hence for α above 0.86 rad the islanded system is unstable.



(a) All eigenvalues



(b) Dominant eigenvalues

Fig. 5. Loci of eigenvalues for increasing value of α. Arrows indicate the direction of loci for increasing α

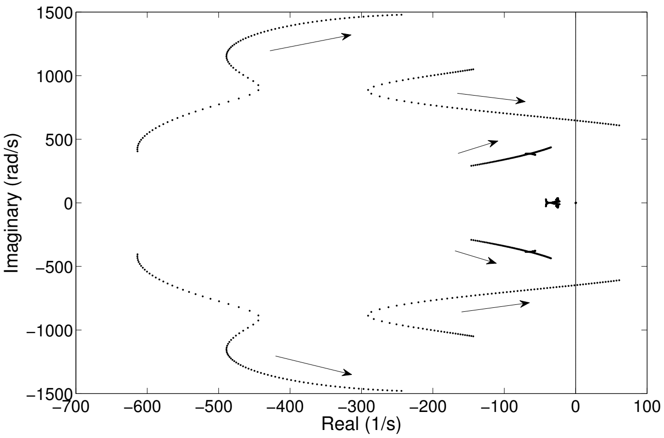


Fig. 6. Loci of eigenvalue of the system in grid connected mode crossing the imaginary axis at α=1.45 rad

It has to be shown that this technique does not make the DG unstable in grid connected operation to avoid maloperation. The state space equation for grid connected mode can be obtained from differential equations shown in appendix. Shown in Fig. 6 is the plot of loci of eigenvalue for grid connected system for increasing value of α from 0 rad. The eigenvalue enters the right half of s-plane only at $\alpha = 1.45$ rad. This implies that the grid connected system is stable till $\alpha = 1.45$ rad. Thus the value of α can take a value between 0.86 and 1.45 rad for successful implementation of this technique. The lesser value of α is preferred as it gives the best transient performance of DG.

VII. SIMULATION

The simulation of the sample system with nonlinearities considered, is performed in Simulink. The parameter used for Simulink simulation in pu. is same as that of the one used for plotting eigenvalues. The system which is in steady state operation is islanded at 5 s. The frequency of voltage at PCC as observed by PLL is shown in Fig. 7. For $\alpha = 0$ rad the frequency settles back to nominal grid frequency after islanding but for $\alpha = 1$ rad the frequency becomes unstable after islanding. This corroborates with the results of small signal stability.

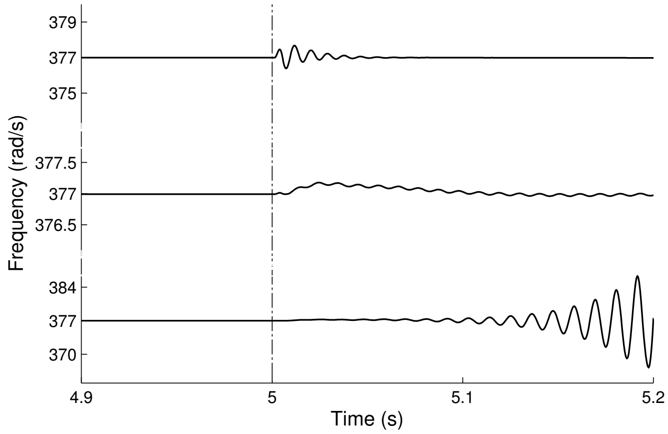


Fig. 7. Frequency at PCC as measured by PLL for α= 0 rad (top), α= 0.7 rad (middle), α= 1 rad (bottom)

VIII. STABILITY

Stability impact of positive feedback schemes is a major issue as the grid is not an infinite source. The positive feedback scheme proposed in report [13] cannot be applied when the grid impedance is 1 pu because of stability issues. The technique proposed in this paper is found out to be stable from the small signal stability analysis for grid impedance of 1 pu and even higher. Shown in Fig. 8 is the plot with grid resistance and reactance as coordinate axis. The shaded region represents stable region when $\alpha = 1$. From the figure it is clearly seen that the practical grid impedance value falls within the stable region.

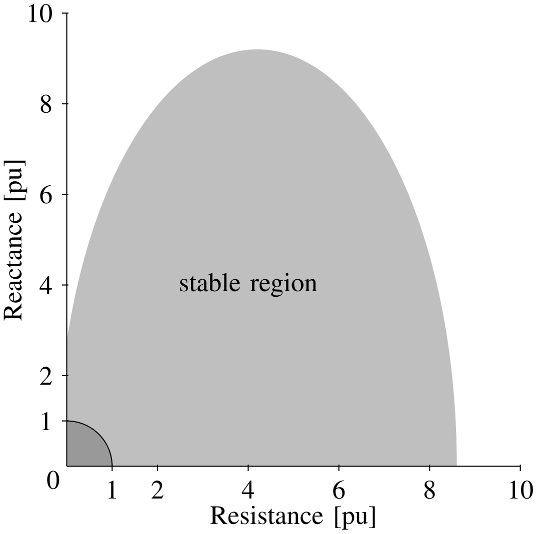


Fig. 8. Light shaded region indicates stable space and dark shade represents 0 to 100 % grid impedance area

IX. CONCLUSION

This paper discussed a new islanding detection technique. The advantage of the proposed scheme is that unlike active method it does not induce any power quality problems as this scheme does not perturb inverter output. Mathematical investigation proves that the NDZ is zero at least when $Q_f \leq 2.5$. The trade off in implementing this scheme will be the dynamic response of the system in normal grid connected operation. The work can be enhanced by designing control system in such a way that transient response is not sacrificed by finding other means to make the islanded system unstable. The work can be extended even to rotating machine based DGs. The voltage regulator in synchronous machines is one such potential application where islanding detection based on control system design can help.

APPENDIX

With reference to Fig. 3, x_1 and x_2 are the outputs of PI controller. k_1, k_3 are the proportional constants while k_2, k_4 are integral constants of current controllers. R, L, C and Q_f are the values of resistance, inductance, capacitance and quality factor of parallel RLC load. l and r are the inductance and resistance between DG and PCC while L_g and R_g are the equivalent grid inductance and grid resistance viewed from PCC. V_d, V_q and V_{dconv}, V_{qconv} are the d (direct) and q (quadrature) axis voltages at PCC and DG terminal respectively. I_d, I_q and I_{gd}, I_{gq} are the d and q axis DG line currents and grid currents. I_{Ld} and I_{Lq} are the d and q axis load inductor currents. ω is the frequency as observed by PLL. I_{ref} and I_{qref} are the d and q axis reference currents. All units are in per unit except frequency. The mathematical description of the model is given by,

TABLE I
PARAMETERS

Parameter	Value
k_1	0.3
k_2	20
k_3	0.3
k_4	20
k_{p1}	60
k_{p2}	1400
R	1 pu
L	1.06 $\times 10^{-3}$ pu
C	6.63 $\times 10^{-3}$ pu
L_g	4.48 $\times 10^{-4}$ pu
R_g	0.089 pu
I_{dref}	1 pu
I_{qref}	0 pu

$$\frac{dx_1}{dt} = k_2(I_{dref} - I_d) + k_1\frac{d(I_{dref} - I_d)}{dt}$$
$$\frac{dx_2}{dt} = k_4(I_{qref} - I_q) + k_3\frac{d(I_{qref} - I_q)}{dt}$$
$$\frac{dI_d}{dt} = (V_{dconv} - V_d + l\omega I_q - rI_d)\frac{1}{l}$$
$$\frac{dI_q}{dt} = (V_{qconv} - V_q - l\omega I_d - rI_q)\frac{1}{l}$$

From Fig. 3,

$$a = x_1 + V_d \tag{5}$$
$$b = x_2 + V_q \tag{6}$$

I_d, I_q can be rewritten from (3), (4), (5) and (6)

$$\frac{dI_d}{dt} = ((x_1 + V_d)\cos\alpha - (x_2 + V_q)\sin\alpha - V_d + l\omega I_q - rI_d)\frac{1}{l} \tag{7}$$
$$\frac{dI_q}{dt} = ((x_1 + V_d)\sin\alpha + (x_2 + V_q)\cos\alpha - V_q - l\omega I_d - rI_q)\frac{1}{l} \tag{8}$$

(7) and (8) indicates that dynamics of I_d depends on both V_d and V_q, dynamics of I_q also depends on both V_d and V_q

$$\frac{dV_d}{dt} = \frac{I_d}{C} + \omega V_q - \frac{V_d}{RC} - \frac{I_{Ld}}{C} + \frac{I_{gd}}{C}$$
$$\frac{dV_q}{dt} = \frac{I_q}{C} - \omega V_d - \frac{V_q}{RC} - \frac{I_{Lq}}{C} + \frac{I_{gq}}{C}$$
$$\frac{dI_{Ld}}{dt} = \frac{V_d}{L} + \omega I_{Lq}$$

$$\frac{dI_{Lq}}{dt} = \frac{V_q}{L} - \omega I_{Ld}$$
$$\frac{d\omega}{dt} = k_{p2}V_q + k_{p1}\frac{dV_d}{dt}$$

For deriving A matrix in islanded mode I_{gd}, I_{gq} are made zero and for deriving A matrix in grid connected mode,

$$\frac{dI_{gd}}{dt} = (V_{gd} - V_d + L_g(\omega I_{gq} - R_g I_{gd})\frac{1}{L_g}$$
$$\frac{dI_{gq}}{dt} = (V_{gq} - V_q - L_g(\omega I_{gd} - R_g I_{gq})\frac{1}{L_g}$$

where V_{gd} and V_{gq} are d and q axis grid voltages.

REFERENCES

[1] J. Driesen and R. Belmans, "Distributed generation: challenges and possible solutions," in *Power Engineering Society General Meeting, 2006. IEEE.* IEEE, 2006, pp. 8–pp.

[2] F. Katiraei, M. Iravani, and P. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *Power Delivery, IEEE Transactions on*, vol. 20, no. 1, pp. 248–257, 2005.

[3] I. PVPS, "Evaluation of islanding detection methods for photovoltaic utility-interactive power systems," *Report IEA PVPS T5-09*, 2002.

[4] F. Wang, C. Zhang, and Z. Mi, "Anti-islanding detection and protection for grid connected pv system using instantaneous power theory," in *Industrial and Information Systems, 2009. IIS'09. International Conference on.* IEEE, 2009, pp. 413–416.

[5] Z. Ye, A. Kolwalkar, Y. Zhang, P. Du, and R. Walling, "Evaluation of anti-islanding schemes based on nondetection zone concept," *Power Electronics, IEEE Transactions on*, vol. 19, no. 5, pp. 1171–1176, 2004.

[6] H. Kobayashi, K. Takigawa, E. Hashimoto, A. Kitamura, and H. Matsuda, "Method for preventing islanding phenomenon on utility grid with a number of small scale pv systems," in *Photovoltaic Specialists Conference, 1991., Conference Record of the Twenty Second IEEE.* IEEE, 1991, pp. 695–700.

[7] F. De Mango, M. Liserre, A. D. Aquila, and A. Pigazo, "Overview of anti-islanding algorithms for pv systems. part i: Passive methods," in *Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International.* IEEE, 2006, pp. 1878–1883.

[8] S. Salman and D. King, "Monitoring changes in system variables due to islanding condition and those due to disturbances at the utilities' network," in *Transmission and Distribution Conference, 1999 IEEE*, vol. 2. IEEE, 1999, pp. 460–465.

[9] M. ElNozahy and M. Salama, "Technical impacts of grid-connected photovoltaic systems on electrical networksa review," *Journal of Renewable and Sustainable Energy*, vol. 5, p. 032702, 2013.

[10] M. Ciobotaru, V. G. Agelidis, R. Teodorescu, and F. Blaabjerg, "Accurate and less-disturbing active antiislanding method based on pll for grid-connected converters," *Power Electronics, IEEE Transactions on*, vol. 25, no. 6, pp. 1576–1584, 2010.

[11] M. Ropp, M. Begovic, and A. Rohatgi, "Prevention of islanding in grid-connected photovoltaic systems," *Progress in Photovoltaics: Research and Applications*, vol. 7, no. 1, pp. 39–59, 1999.

[12] Z. Ye, L. Li, L. Garces, C. Wang, R. Zhang, M. Dame, R. Walling, and N. Miller, "A new family of active antiislanding schemes based on dq implementation for grid-connected inverters," in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, vol. 1. IEEE, 2004, pp. 235–241.

[13] Z. Ye, R. Walling, L. Garces, R. Zhou, L. Li, and T. Wang, *Study and development of anti-islanding control for grid-connected inverters*. National Renewable Energy Laboratory, 2004.

[14] J. Mulhausen, J. Schaefer, M. Mynam, A. Guzmán, and M. Donolo, "Anti-islanding today, successful islanding in the future," in *Protective Relay Engineers, 2010 63rd Annual Conference for.* IEEE, 2010, pp. 1–8.

[15] S. Gonzalez, R. Bonn, and J. Ginn, "Removing barriers to utility interconnected photovoltaic inverters," in *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE.* IEEE, 2000, pp. 1691–1694.

[16] S.-K. Chung, "A phase tracking system for three phase utility interface inverters," *Power Electronics, IEEE Transactions on*, vol. 15, no. 3, pp. 431–438, 2000.

[17] X. Wang and W. Freitas, "Impact of positive-feedback anti-islanding methods on small-signal stability of inverter-based distributed generation," *Energy Conversion, IEEE Transactions on*, vol. 23, no. 3, pp. 923–931, 2008.