Dynamic Modeling of Microgrid for Grid Connected and Intentional Islanding Operation

Rinu J Vijayan, Subrahmanyam Ch, Ranjit Roy

Abstract—**Microgrid is defined as the cluster of multiple distributed generators (DGs) such as renewable energy sources that supply electrical energy. The connection of microgrid is in parallel with the main grid. When microgrid is isolated from remainder of the utility system, it is said to be in intentional islanding mode. In this mode, DG inverter system operates in voltage control mode to provide constant voltage to the local load. During grid connected mode, the Microgrid operates in constant current control mode to supply preset power to the main grid. The main contribution of this paper is summarized as**

1) **Design of a network based control scheme for inverter based sources, which provides proper current control during grid connected mode and voltage control during islanding mode.**
2) **Development of an algorithm for intentional islanding detection and synchronization controller required during grid reconnection.**
3) **Dynamic modeling and simulation are conducted to show system behavior under proposed method using SIMULINK.**

From the simulation results using Simulink dynamic models, it can be shown that these controllers provide the microgrid with a deterministic and reliable connection to the grid.

Index Terms—**Distributed generation (DG), grid connected operation, intentional islanding operation and islanding detection, microgrid, synchronization, voltage source converter (VSC)**

I. INTRODUCTION

POWER SYSTEMS are experiencing tremendous growth in the field of distributed generation because of economic benefits, environmental concern, reliability requirement etc. Mainly the DGs include wind turbines, photovoltaic cells, micro turbines and fuel cells. The DG is a voltage source inverter with an output low pass filter supplying the load [1]. The microgrid configuration [2] with the control strategy is shown in Fig. 1.

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The flexibility and control needed by microgrid with the main grid is achieved with the help of power electronic interfaces [3]. During grid connected mode the controller has to supply the preset power to the main grid. In this mode the inverters use the signal of main grid as reference. Thus in grid connected mode the system operates in stiff synchronization with main grid in current control mode.

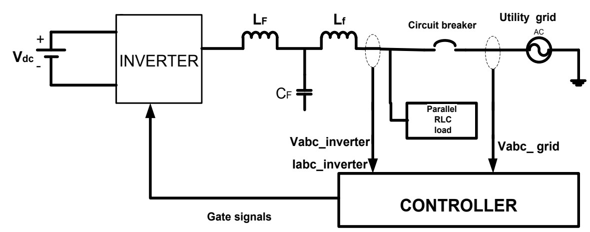

Fig. 1. Microgrid configuration with controller

When the microgrid is isolated from the main grid i.e. intentional islanding operation, the controller is designed so as to supply constant voltage to the local sensitive loads [4], [5]. In this autonomous mode, the main grid reference is not available; therefore a new reference is required to continue good power quality generation. The new reference is found out by using phase locked loop (DQ-PLL) and PI controller [6], [7]. In order to transfer from current control to voltage control mode, detection of transition from grid connected to intentional islanding mode is necessary. This is achieved by using an intentional islanding detection algorithm [4]. After islanding operation, the DGs are connected back to grid. At this instant of grid reconnection, re-closure algorithm has to be established to achieve synchronization [4], [9].

II. CONTROL TECHNIQUES FOR INVERTER

The voltage and current control loop has been implemented by using PI controllers working on the D-Q synchronous reference frame. AC quantities are converted in to DC synchronous reference frame by Parks Transformation. Correspondingly all reference quantities become DC in nature, so that simple PI controllers would be sufficient to yield zero steady state error.

A. DQ- PLL structure

For unity power factor operation i.e. Grid current reference to be in phase with grid voltage, estimation of phase angle is a

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necessity. The phase angle and frequency at point of common coupling (PCC) is determined by using a DQ-PLL structure shown in Fig. 2. The PLL structure analogy comprises of a voltage controlled oscillator, an integrator and a phase detector [6], [7]. Phase estimation is achieved by synchronization of the oscillating waveform generated by oscillator with the measured waveform.

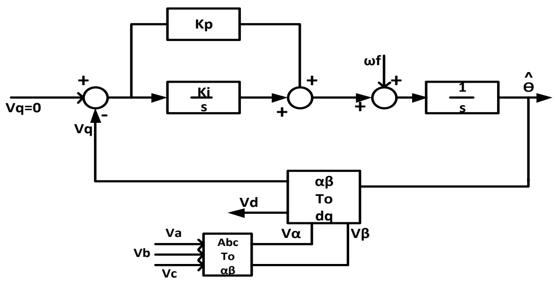

Fig. 2. DQ-PLL structure

The DQ-PLL structure consists of a Clarke's transformation, Park's transformation, PI regulator and an integrator. The expression for the d- axis component and the q-axis component fed to the PI controller is given as

$$V_q = V_\alpha \sin\hat{\theta} + V_\beta \cos\hat{\theta} \quad (1)$$

$$V_q = V\cos\theta\sin\hat{\theta} - V\sin\theta\cos\hat{\theta} \quad (2)$$

$$V_q = -V\sin(\theta - \hat{\theta}) \quad (3)$$

$$V_d = V\cos(\theta - \hat{\theta}) \quad (4)$$

The realization of lock in PLL relies on regulating the quadrature component (3) of rotating reference frame to zero using the PI controller. When θ generated by oscillator approximates $\hat{\theta}$, the PLL will be locked. The value of V_d as shown in (4) will become V i.e. At the instant, when lock is realized, the direct axis component gives the magnitude of the voltage [8].

B. Current control

In grid connected mode the magnitude and frequency of the microgrid terminal voltages are imposed by the grid voltage. Current controller is designed to provide constant current output during grid connected operation [12], [13]. Control System shown in Fig. 3 is used to accomplish current control. In the strategy proposed here, the VSC line current is made controllable by a dedicated scheme and through the control of VSC terminal voltage. The inverter AC output current is transformed in to DC quantity in synchronous rotating frame by Park's transformation. The direct and quadrature components are compared with the reference quantities and the error signal is passed to the PI controller to generate the voltage references [10]. The inverter terminal voltage is considered as a disturbance and hence fed forward to compensate it [1].

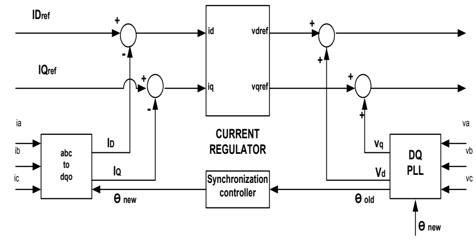

Fig. 3. Block diagram of current controller

Finally the DC reference quantities added with terminal voltages are transformed back to stationary frame by Inverse Park's Transformation. Thereafter it is used to generate the gate pulses by SPWM technique [4].

C. Voltage control

In this control the microgrid will provide constant voltage to the load [10]. This control scheme makes use of both current regulator as well as voltage regulator. The control works on the principle of voltage regulation through current compensation [12], [13]. Fig. 4 represents the voltage control scheme. The converter output voltage is controlled by a synchronous reference frame closed loop voltage controller. Its output is transferred in to a closed loop current regulator which is further transformed in to stationary frame, and then the space vector PWM generates the gating signals of the IGBTs.

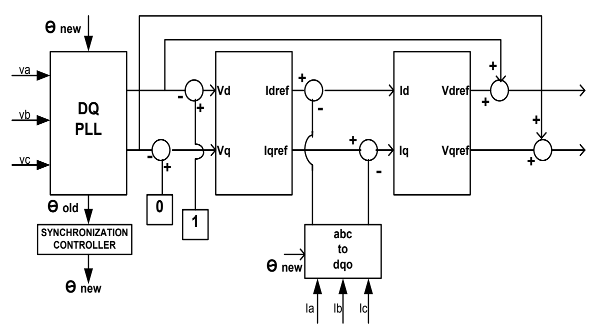

Fig. 4. Block diagram of voltage controller

As shown in Fig. 4, the filter output line voltage is transformed in to dc quantities by DQ-PLL structure. The direct and quadrature quantities are forced to follow their corresponding reference values by using voltage regulator. The current references generated by voltage regulator are compared with the dc values of load currents and the error is compensated by current regulator. The output of current regulator provides the reference voltage signal.

D. Intentional islanding detection algorithm

Parameters which are used to determine the state of grid is voltage and frequency. Fig. 5 indicates the algorithm developed to accomplish the detection of intentional islanding. Under deficient grid voltage conditions, the main switch is turned off and disconnects the main grid from the utility. This switching causes transients in voltage and frequency [11]. Therefore tracking of system voltage magnitude and frequency indicates the transition switching between grid connected and islanding mode, and vice versa.

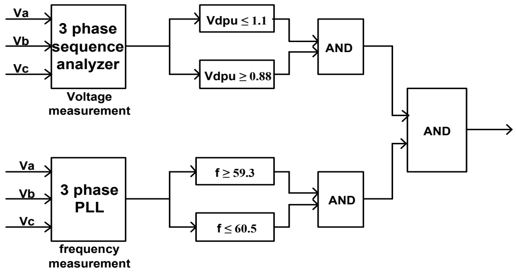

Fig. 5. Proposed algorithm for intentional islanding detection

Voltage magnitude and frequency measurement is achieved with the help of three phase sequence analyzer and DQ-PLL [8]. According to this algorithm, values of frequency and voltage magnitude are constrained to particular limit. During transition from grid connected to islanding operation, the voltage and frequency parameters get shifted from this constrained range as shown in Fig. 13. This sends a logical high output to the switch, which switches the inverter to the suitable control accordingly.

E. Resynchronization controller algorithm

Islanded operation can change its operational mode to grid connected operation by reconnection to the grid, which is referred as synchronization [9]. Synchronization is achieved by using the phase difference between islanded microgrid and utility grid insuring a transient free operation. The microgrid continues to operate in the islanding mode until both systems are synchronized. Thus synchronization controller ensures the microgrid to operate in stiff synchronization with the utility grid [5].

When paralleling microgrid with utility grid, it is necessary to have the same phase angle for both of them. By closing the breaker at PCC, the two individual systems begin to have parallel operation. In order to achieve stiff synchronization with the utility grid during grid reconnection, synchronization controller is used. The algorithm used here [4] is to determine the new phase angle at which both the microgrid and utility grid have to operate.

The algorithm is as follows

1) suppose the phase difference between the grid and inverter voltages is given by

$$\theta = \angle V_G - \angle V_I \tag{5}$$

$$k = V_{Ia}V_{Ga} + V_{Ib}V_{Gb} + V_{Ic}V_{Gc} \tag{6}$$

$$= \frac{3}{2}[\cos(\theta)] \tag{7}$$

$$g = V_{Ia}V_{Gb} + V_{Ib}V_{Gc} + V_{Ic}V_{Ga} \tag{8}$$

$$= \frac{3}{4}[-\cos(\theta) + \sqrt{3}\sin(\theta)] \tag{9}$$

Using the variables k and g, $\sin(\theta)$ can be found as

$$\sin(\theta) = \frac{\frac{4}{3}g + \frac{2}{3}k}{\sqrt{3}} \tag{10}$$

The control circuit in Fig. 6 depicts how $\sin(\theta)$ is determined from grid and inverter voltages, which has to be synchronized.

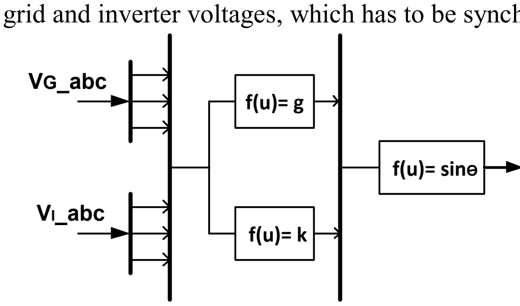

Fig. 6. Control circuit to determine $\sin(\theta)$.

$$\frac{I_d}{V_{in}} = \frac{\frac{s^2C_LL_LR_L + sL_L + R_L}{s}}{s^4(L_fL_LC_LL_LR_L) + s^3L_LL_fL_L + s^2R_L\left(L_fL_F + L_L(C_FL_F + C_LL_F + C_LL_f)\right) + s(L_fL_L + L_LL_F) + R_L(L_F + L_f + L_L)} \tag{11}$$

$$T(s) = \frac{s^3 + 8.72*10^3s^2 + 6.51*10^7s + 4.03*10^9}{s^4 + 9.46*10^3s^3 + 1.04*10^8s^2 + 3.31*10^{11}s + 3.22*10^{12}} \tag{12}$$

$$T(s) = \frac{s^4 + 8.79*10^3s^3 + 6.56*10^7s^2 + 8.06*10^9s + 6.45*10^7}{s^5 + 1.42*10^4s^4 + 1.46*10^8s^3 + 6.44*10^{11}s^2 + 3.49*10^{13}s + 2.79*10^{11}} \tag{13}$$

(L_F=1mH, L_f= 0.5mH, C_F=31μF, L_L= 4.584mH, C_L=1.535mF, K_{P1}=0.8, K_{I1}=50, K_{P2}=1.24, K_{I2}=0.02)

III. DESIGN OF PI CONTROLLER

A. Current control transfer function

Current control scheme is needed during grid connected operation. The block diagram of current controlled operation is shown in Fig. 7. The inverter is modeled with an ideal gain G_I=1. In order to obtain the transfer function of the filter and the load block, the designed LCL filter and RLC load circuit must be taken in to consideration. Fig. 8 depicts the circuit diagram of LCL filter and RLC load. The transfer function of the LCL filter and the RLC load remains the same for voltage control transfer function also.

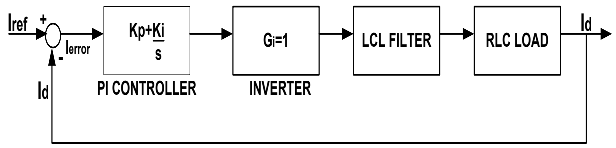

Fig. 7. Block diagram of current controlled inverter

Correspondingly transfer function of PI controller block is given as

$$C(S) = K_P + \frac{K_I}{S} \tag{14}$$

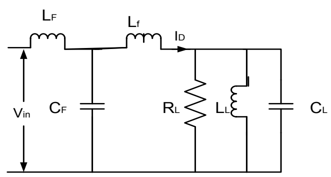

Fig. 8. LCL filter and parallel RLC load circuit

The steps to obtain transfer function [12] of this stage are given below.

1) For the parallel RLC load, the equivalent impedance is given as

$$Z_{eq} = \frac{sL_L R_L}{s^2 C_L L_L R_L + sL_L + R_L} \tag{15}$$

2) By using KVL to the meshes, the transfer function is obtained as

$$\frac{I_d}{V_{in}} = \frac{1}{\left(sC_F\left(sL_f + Z_{eq}\right) + 1\right)sL_F + SL_F + Z_{eq}} \tag{16}$$

3) Using (15) and (16) the fourth order transfer function of the filter and load scheme is obtained and is given in (11).

4) The values of K_P and K_I of the PI controller are determined by using Ziegler-Nichols tuning formula [15]. A MATLAB function Ziegler () exists to design PI controllers using the Ziegler–Nichols tuning formulas.

5) The complete transfer function of the block diagram is then obtained by block diagram reduction method and thereafter by substituting the corresponding designed values of the parameters. The transfer function of the current control system is given in (12).

B. Voltage control transfer function

Voltage control scheme is required during islanding mode of operation. Fig. 9 represents the block diagram of voltage controlled operation.

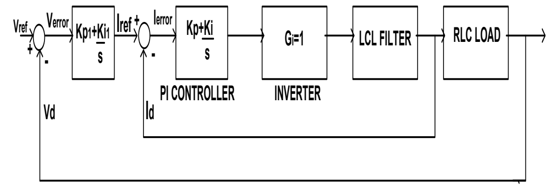

Fig. 9. Block diagram of voltage controlled inverter

This scheme consists of an inner current control loop and an outer voltage control loop. The transfer function of individual blocks, such as PI controller, inverter, filter and load remains the same as in current control transfer function. The same methodology so as to find transfer function in current control scheme is followed here also. The transfer function of the voltage control system hence obtained is given by (13).

C. Current control and voltage control stability

The control method used here has two operating modes, current control and voltage control corresponding to grid connected and intentional islanding operations of microgrid. The stability of the current and voltage controller can be determined by using their transfer functions [14]. Stability analysis is carried out by using the conventional control theory. According to it, the bode plot of the controller transfer function is plotted using the SISO design tool in MATLAB. The positive Gain margin in the bode plots of both the transfer functions of corresponding controllers indicates that the system is stable.

IV. DYNAMIC MODELING AND SIMULATION

A. Simulation results

To investigate microgrid operational modes, the effect of designed current controller, voltage controller, proposed intentional islanding detection algorithm and re-closure algorithm, the MATLAB/SIMULINK is used to develop a time domain simulation model of the study system. Electrical power system components are simulated with a physical modeling product called simpower systems supported by MATLAB. The simulations have been run with the dynamic model shown in Fig. 10 to investigate the behavior of grid connected and intentional islanding mode of operation. Inside the current and voltage regulator blocks, there exist the schemes shown in Fig. 3 and Fig. 4. Similarly inside islanding detection algorithm and resynchronization controller block, there exist the circuit corresponding to Fig. 5 and Fig. 6.

For both the cases the parameters used for simulation is given in the Table I [4]. In the dynamic model depicted here, the inverter is connected through a filter and a circuit breaker to the local load. The simulations are conducted here with the assumption that the irradiation variations are completely absent in this system. Two case studies based on the influence of synchronization controller are conducted to examine the system performance during grid connected and intentional islanding mode.

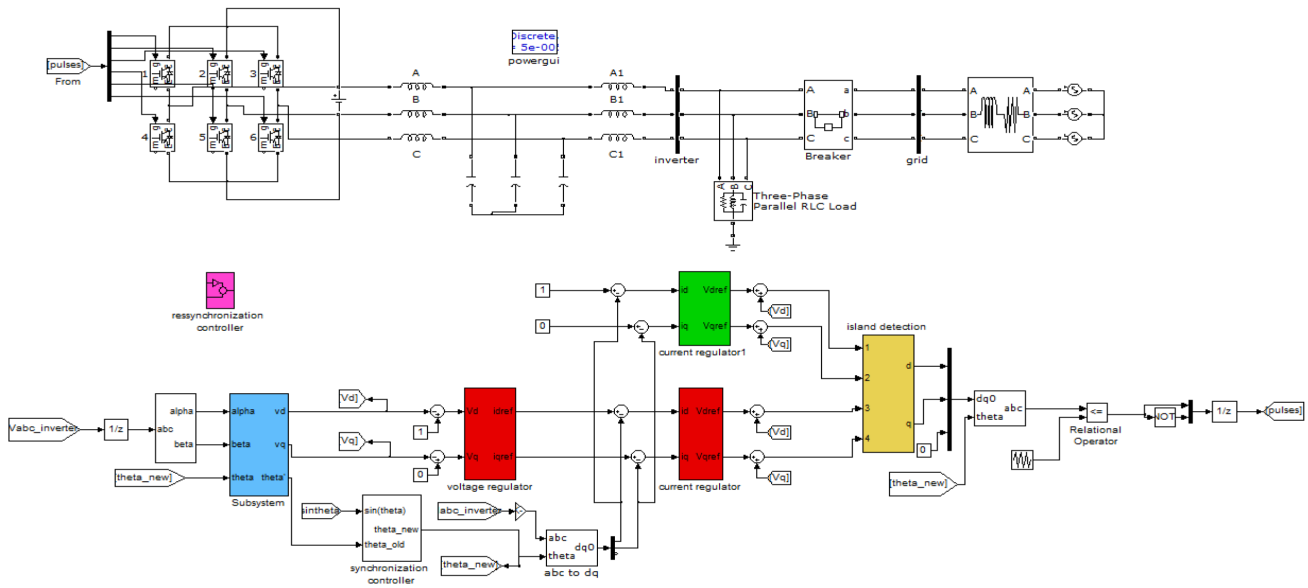

Fig.10. Dynamic model of microgrid with controller.

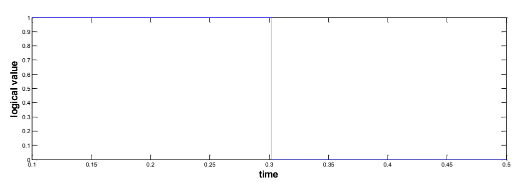

Fig. 11. Transition from grid connected to islanding mode.

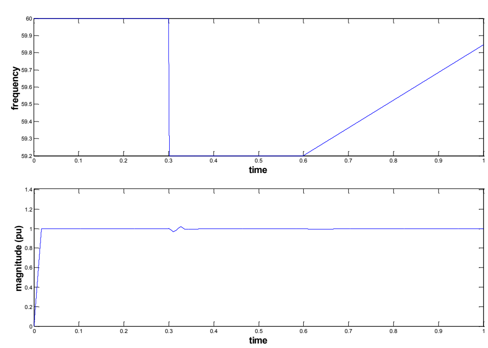

Fig. 12. Variation in parameters during islanding
(a) Frequency (b) Magnitude

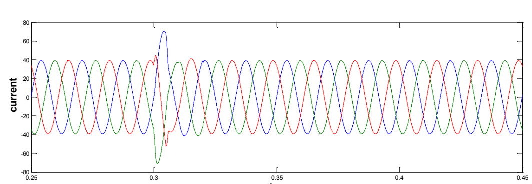

Fig. 13. Line Current without current controller

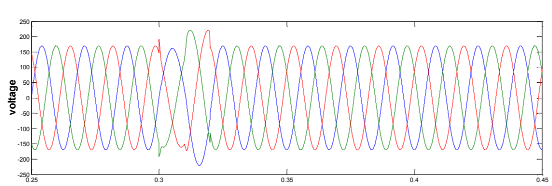

Fig.14(a). Line Voltage without Voltage controller

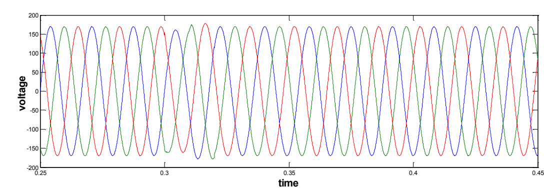

Fig. 14(b). Line Voltage with voltage controller

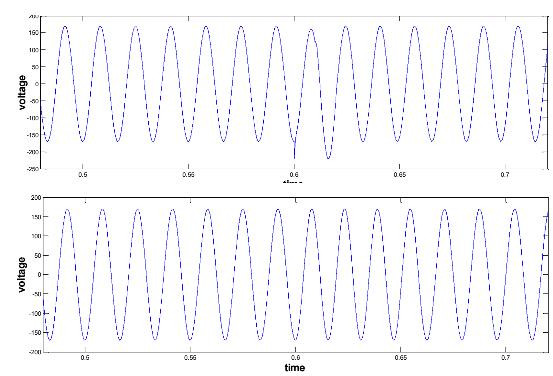

Fig. 15. Phase voltage waveform (a) without re-closure controller (b) with re-closure controller

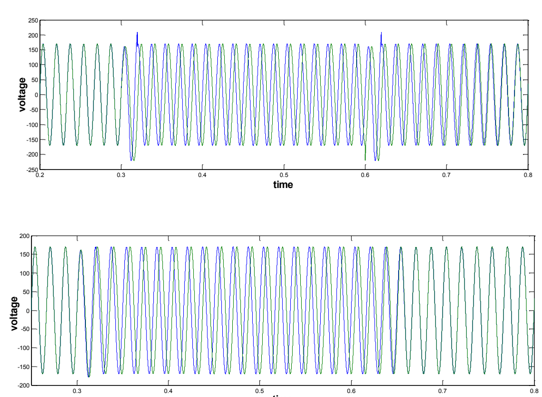

Fig. 16. Synchronization for grid reconnection (a) without re-closure algorithm (b) with re-closure algorithm

B. *Without and with synchronization controller*

At first, simulation was conducted when the microgrid is connected to the utility grid without any synchronization controller. The grid was disconnected by setting the status in three phase circuit breaker as closed initially and transition time at 0.3s. Fig. 13 and Fig. 14(a) show the inverter currents and voltages at the point of common coupling. The occurrence of transients at 0.3s is seen clearly. Occurrence of large transient during the instant of grid reconnection is undesirable. Fig. 15(a) shows the phase voltage at PCC without the implementation of any resynchronization algorithm. Fig. 16(a) shows per phase voltage at both sides of PCC in the absence of resynchronization controller. It can be observed that the system takes longer duration to achieve the synchronization, which is quite undesirable for the loads. Grid current doesn't get influenced under the effect of synchronous controller, as there will not be any supply of current to the load from the utility grid during standalone mode.

The grid was then reconnected at 0.6s. The microgrid continuous to operate in synchronous islanding mode until both the utility system and the microgrid system is resynchronized. Fig. 16(b) shows the synchronization of voltage at both sides of the PCC in the presence of resynchronization controller. On investigating from the beginning of intentional islanding mode, the system achieves synchronization in much less time comparing with that system without synchronization controller. With the implementation of resynchronization controller algorithm, the DG voltage is forced to track the voltage at the grid. On completion of the synchronization, the DG is reconnected to the grid, and the controller will be switched from the voltage to the current control mode. Fig. 15(b) shows the phase voltage with the synchronization algorithm implemented. This graph depicts the effectiveness of resynchronization algorithm in avoiding hard transients during grid reconnection.

TABLE I
DESIGNED VALUES OF PARAMETERS USED FOR SIMULATION

Symbol	Value	Description
L_f	1mH	Filter inductance
C_F	31µF	Filter capacitance
L_F	0.5 mH	Filter inductance
C_L	1.535mF	Load capacitance
L_L	4.585mH	Load inductance
R_L	4.33Ω	Load resistance
V_{dc}	400V	Dc voltage source
R_{grid}	0.1 Ώ	Grid resistance
L_{grid}	0.1mH	Grid inductance
K_p, K_i	1.24, 0.02	Voltage loop PI constant values
K_p, K_i	0.8, 50	Current loop PI constant values
f	60hz	System frequency
f_s	1Khz	Switching frequency
$v_Ø$	120v	Output phase voltage

V. CONCLUSION

Current and voltage Control techniques have been developed for grid connected and intentional islanding modes of operation using PI controllers. An intentional islanding detection algorithm responsible for switching between current control and voltage control is developed using logical operations and proved to be effective. The reconnection algorithm coupled with the synchronization controller enabled the DG to synchronize itself with the grid during grid reconnection. The performance of the microgrid with the proposed controllers and algorithms has been analyzed by conducting simulation on dynamic model using SIMULINK. The simulation results presented here confirms the effectiveness of the control scheme.

REFERENCES

[1] L. Shi, M.Y. Lin Chew. "A review on sustainable design of renewable energy systems," *science direct journal present in Renewable and Sustainable Energy Reviews,* Vol. 16, Issue 1, 2012, pp. 192–207.

[2] Q. Lei, Fang Zheng Peng, Shuitao Yang. "Multi loop control method for high performance microgrid inverter through load voltage and current decoupling with only output voltage feedback," *IEEE Trans. power. Electron,* vol. 26, no. 3, 2011, pp. 953–960.

[3] J. Selvaraj and N. A. Rahim, "Multilevel inverter for grid-connected PV system employing digital PI controller," *IEEE Trans. Ind. Electron.,* vol. 56, no. 1, 2009, pp. 149–158.

[4] I. J. Balaguer, Fang Zheng Peng, Shuitao Yang, Uthane Supatti Qin Lei. "Control for grid connected and intentional islanding modes of operations of distributed power generation," *IEEE Trans. Ind. Electron.,* vol. 56, no. 3, 2009, pp. 726–736.

[5] R. J. Azevedo, G.I. Candela, R. Teodorescu, P.Rodriguez , I.E-Otadui "Microgrid connection management based on an intelligent connection agent," *36th annual conference on IEEE industrial electronics society*, 2010, pp. 3028–3033.

[6] V. Kaura and V. Blasko "Operation of a Phase Locked Loop System under Distorted Utility Conditions," *IEEE Trans. on Ind. Applications,* vol. 33. no. 1,1997, pp. 58–63.

[7] S.A.O. Silva. and E.A.A. Coelho, "Analysis and Design of a Three-Phase PLL Structure for Utility Connected Systems under Distorted Utility Conditions," *in Proc. Conf. Rec. IEEE-CIEP,* 2004, pp. 218–223.

[8] L.N. Aruddha "PLL structure for utility connected systems," *in IEEE 36th IAS annual meeting in industry applications conference* vol. 4,2001, pp. 2655–2660.

[9] C.Cho, J-HongJeon, J-YulKim, S. Kwon, K. Park, S. Kim "Active synchronizing control of a microgrid," IEEE Trans. power. Electron, vol. 26, no. 12, 2009, pp. 3707–3719.

[10] I.Vechiu, A.Llaria, O.Curea, and H.C. Technopôle Izarbel " Control of power converters for microgrid" *in 4th international conference on EVER MONACO ecological vehicles and renewable energies ,* EVER09-181, RE 4 session, 2009.

[11] J. Rocabert, G.Azevedo, I. Candela, R.Teoderescu, P.Rodriguez, J.M. Guerrero, "Intelligent control agent for transient to an island grid," *in IEEE international symposium on Ind. Electron,* 2009, pp. 2223–2228.

[12] Sao, C.K. Lehn, P.W, "Intentional islanding operation of converter fed microgrid," *in IEEE power engineering society general meeting* 2006, pp. 6.

[13] Sao, C.K. Lehn, P.W, "Islanding control of DG in microgrid," *in IEEE power engineering society general meeting 2006,* pp. 6.

[14] M.-T ho, H.zen Wang, "PID controller design with guaranteed gain and phase margins," *ASIAN Journal of control*, vol. 5, no. 3, 2003, pp. 374–381.

[15] D. Xue, Yang. Chen, and D.P. Atherton, *Linear Feedback Control* 2007 chapter 6, pp. 183–225.

[16] M.B. Delghavi, A. Yazdani, "A control strategy for islanded operation of a Distributed Resource (DR) unit," *Power & Energy Society General- Meeting, 2009, PES '09,* IEEE 2009, pp. 1–8.