Frequency and Voltage Droop Control of Parallel Inverters in Microgrid

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***Abstract*—The distributed generation units are connected to microgrid through an interfacing inverter. Interfaced inverter plays main role in the operating performance of microgrid. In this paper, interfaced parallel inverter control using an P-F/Q-V droop control was investigated, when microgrid operated in islanded mode. In islanding mode the inverter droop control should maintain voltage and frequency stability. The droop control for parallel inverters is implemented and the proportional load sharing is obtained from each individual inverter. Droop control of inverter is simulated on Matlab/Simulink, the results indicate droop control has a significant effect on balancing the voltage magnitude, frequency and power sharing.**

***Keywords*—droopcontrol, inverters parallel operation, microgrid , proportional power sharing.**

I. INTRODUCTION

In recent years, in order to solve the power shortage and environmental pollution problems using traditional fossil fuels, the development and the use of solar, wind and other polluting renewable energy is increasingly subject to people's attention[1].Power electronics rapid development for distributed power supply, has opened up a new path for the renewable energy. With multiple distributed generation units in microgrid can be operated in grid or islanded mode. In islanding mode utilizing multiple distributed power inverter parallel way to achieve high capacity and redundant power supply, can greatly improve the reliability of the power supply system[2].With respect to a single high power inverters, the use of multiple inverters in parallel to expand the supply capacity of the system has many advantages.Among them, the most prominent advantage is to achieve a stable and reliable redundant power[3].Parallel inverter technology improves the operational reliability of the inverter and widely used in the distributed generation systems and high frequency modular UPS. However, the parallel operation of inverter is difficult, all parallel inverter inverter should be synchronized, otherwise the burden on the inverter is more and may cause the system to collapse, causing the power supply interruption[6]. The inverter parallel operation control, generally divided into centralized control[7], master slave control[8], decentralized control based on communication lines interaction control and no interconnecting lines interaction control[13]. Droop control is a non contact signal line independent control technology, it does not need signal line interconnection between the inverters. technology[5].Particularly in islanding operation, grid power utility support is lost, microgrid should rely on their own capacity to maintain the regulation of voltage and frequency [4]. The use of droop control using P-F/Q-V for inverter does not require communication between inverters. In this paper, droop control for parallel inverter in microgrid is implemented for proportional load sharing.

II. DROOP CONTROL INTRODUCTION AND SYSTEM IMPLEMENTATION

Figure 1 Consider an ac bus connected to an inverter equivalent circuit is shown in figure 6.Inverter output voltage is $E\angle\delta$,the common load terminal voltage is $V\angle 0$,the output of the inverter and a common load end through the inverter connected to the output impedance. the total inverter output impedance is set as $Z\angle\theta$,which itself includes an inverter output impedance $Z_b\angle\theta_b$ and the line impedance is $Z_L\angle\theta_L$.

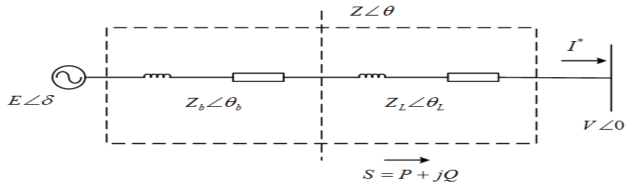

Fig.1.Three phase inverter equivalent circuit

The DG unit output power is:

$$P + jQ = \bar{S} = V\bar{I}^* = V\left(\frac{Ee^{j\theta} - V}{Ze^{j\theta}}\right)^* \tag{1}$$

Output current is:

$$\bar{I} = \frac{Ee^{j(\delta-\theta)} - Ve^{-j\theta}}{Z} \tag{2}$$

Dg unit output of active and reactive power are as follows:

$$P = \frac{V}{R^2 + X^2}[R(E\cos\delta - V) + XE\sin\delta \tag{3}$$

$$Q=\frac{V}{R^2+X^2}[X(E\cos\delta-V)-RE\sin\delta \tag{4}$$

Suppose the inverter output impedance resistive component is negligible, the inverter output voltage and ac bus voltage is very small, namely $\theta=90^0$, δ is very small, thus $\sin\delta=\delta,\cos\delta=1$,the output power is given by[14]:

$$\omega=\omega^*-m(P-P^*) \tag{5}$$

$$V=V^*-n(Q-Q^*) \tag{6}$$

The inverter no-load output voltage amplitude and frequency are V^*,ω^*,active and reactive droop co-efficients are m,n [10]. The inverter rated output active and reactive power are P^*,Q^*.

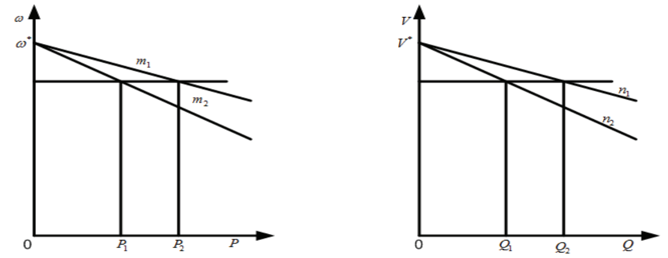

Fig.2. Droop control curve

Figure 3 shows the microgrid consisting of two inverters connected in parallel with common load. Two 3KVA three phase inverter are connected in parallel. SPWM scheme is used in the three phase inverter with a switching frequency of 10KHz[12].

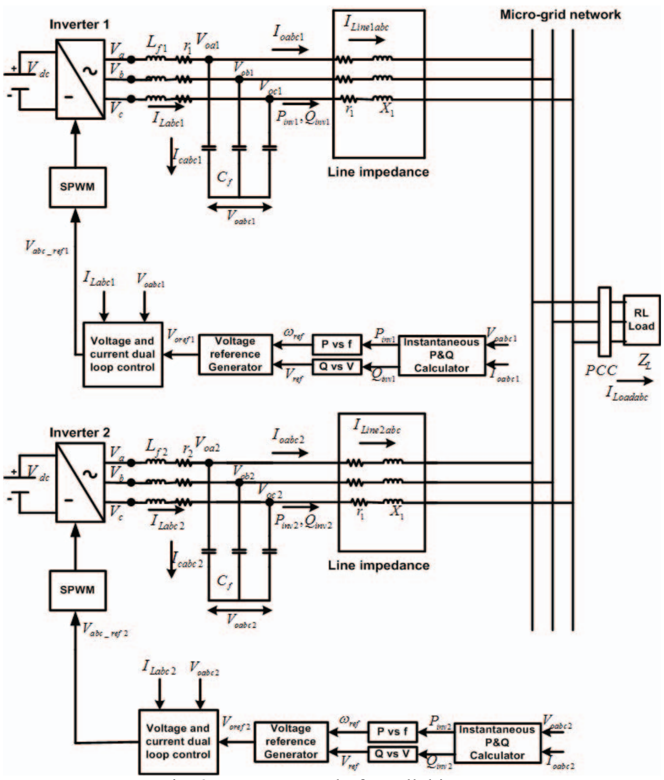

Fig. 3. Droop control of parallel inverter

III. Droop control of three phase inverter

A. Three phase inverter dq model

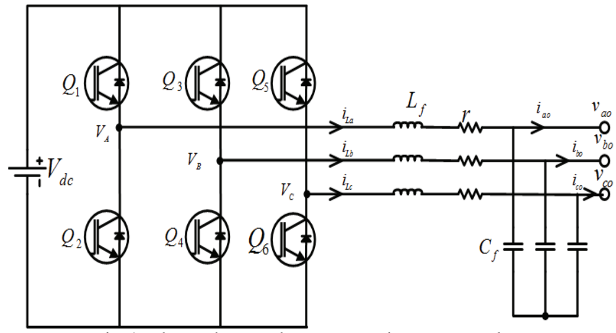

Fig.4. Three phase voltage source inverter topology

Three phase voltage source inverter with three phase full bridge topology the details of the structure as shown in the figure 4.

V_{dc} input voltage ,L_f filter inductor ,r filter inductor equivalent resistance, C_f filter capacitor, from left to right in order to define *A,B,C* three phase inverter bridge arm. Inverter leg midpoint voltage V_A, V_B, V_C. Inverter output terminal voltage v_{ao}, v_{bo}, v_{co}. Three phase inductor current respectively i_{La}, i_{Lb}, i_{Lc}. Load side three phase inverter output current[6].According to Kirchhoff's voltage and current law can be obtained as:

$$\begin{aligned}
V_A-v_{ao}&=L_f\frac{di_{La}}{dt}+ri_{La}\\
V_B-v_{bo}&=L_f\frac{di_{Lb}}{dt}+ri_{Lb}\\
V_c-v_{co}&=L_f\frac{di_{Lc}}{dt}+ri_{Lc}\\
i_{La}-i_{ao}&=C_f\frac{dv_{ao}}{dt}\\
i_{La}-i_{bo}&=C_f\frac{dv_{bo}}{dt}\\
i_{Lc}-i_{co}&=C_f\frac{dv_{co}}{dt}
\end{aligned} \tag{7}$$

According to the principle of equal amplitude conversion, its transformation matrix is:

$$T_{abc-\alpha\beta}=\frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix} \tag{8}$$

Clark inverse transform, its transformation matrix is:

$$T_{\alpha\beta-abc}=\begin{bmatrix}1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix} \tag{9}$$

three phase voltage source inverter $\alpha\beta$ equation of state two phase stationary co-ordinate system:

$$\frac{d}{dt}\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ v_{o\alpha} \\ v_{o\beta} \end{bmatrix} = \begin{bmatrix} -\frac{r}{L_f} & 0 & -\frac{1}{L_f} & 0 \\ 0 & -\frac{r}{L_f} & 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & 0 & 0 & 0 \\ 0 & \frac{1}{C_f} & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ v_{o\alpha} \\ v_{o\beta} \end{bmatrix} + \begin{bmatrix} 0 & 0 & \frac{1}{L_f} & 0 \\ 0 & 0 & 0 & \frac{1}{L_f} \\ -\frac{1}{C_f} & 0 & 0 & 0 \\ 0 & -\frac{1}{C_f} & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{o\alpha} \\ i_{o\beta} \\ v_{\alpha} \\ v_{\beta} \end{bmatrix} \tag{10}$$

According to the principle of equal amplitude transformation ,αβ two phase rotating co-ordinate transformation matrix is:

$$T_{\alpha\beta-dq} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \tag{11}$$

$$\frac{d}{dt}\begin{bmatrix} v_{od} \\ v_{oq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} 0 & \omega & \frac{1}{C_f} & 0 \\ -\omega & 0 & 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & 0 & -\frac{r}{L_f} & \omega \\ 0 & -\frac{1}{L_f} & -\omega & -\frac{r}{L_f} \end{bmatrix} \begin{bmatrix} v_{od} \\ v_{oq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} + \begin{bmatrix} -\frac{1}{C_f} i_{od} \\ -\frac{1}{C_f} i_{oq} \\ \frac{v_d}{L_f} \\ \frac{v_q}{L_f} \end{bmatrix} \tag{12}$$

Equation(12) is the three phase voltage source inverter dq mathematical model in two phase rotating co-ordinate system.

B. LC filter design:

To eliminate high frequency harmonics and switching noise during the operation of a three phase inverter an LC filter is used[12]. It is a second order filter having attenuation of -40db/decade. The cut off frequency of the filter is given by

$$f_c = \frac{1}{(2\pi\sqrt{L_f C_f})} \tag{13}$$

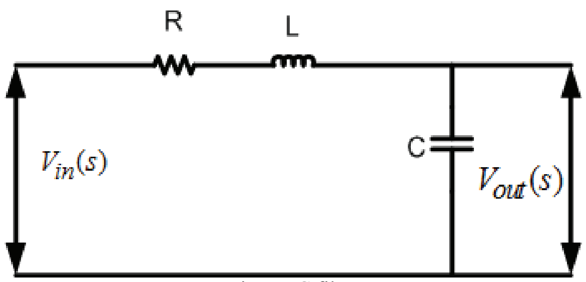

Fig.5. LC filter

$$\frac{V_{out}}{V_{in}} = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}} \tag{14}$$

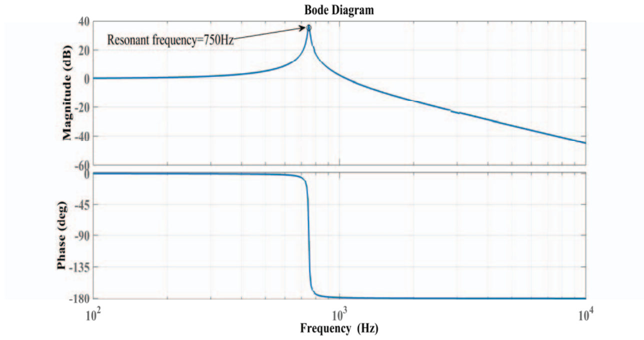

Fig.6.LC filter bode plot

C. Current and voltage loop

Inverter voltage and current double closed loop block diagram is as shown in the figure 7. Outer voltage makes the inverter output voltage reference tracking loop for output power given. Inner current loop to improve the dynamic response of the system to enhance the system's anti disturbance ability and provide over current protection[10],[11].

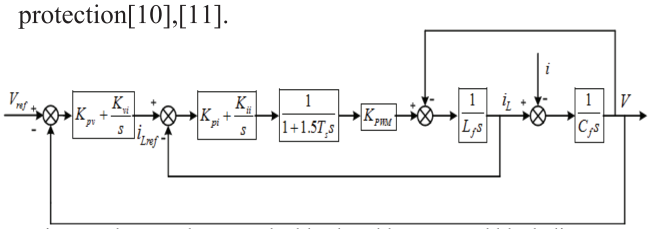

Fig.7. Voltage and current double closed loop control block diagram

Current loop design: The inner current controller has two phase rotating co-ordinate system decoupled, in the design of the loop d-axis and q-axis current control respectively .Figure 8 shows the block diagram of the current loop.

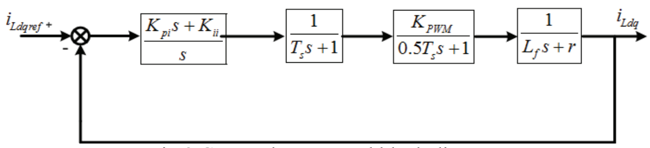

Fig.8.Current loop control block diagram

where, T_s is a current loop sampling period, K_{ip} and K_{ii} PI parameters corresponding to the current loop, *1/(1+0.5T_ss)* on behalf of inertia pwm control, *1/(1+T_ss)* for the current sampling delay and K_{pwm} amplification factor of the converter. The open loop transfer function given by:

$$G_{oi} = \frac{K_{PWM} K_{ii} (1 + \frac{K_{ip}}{K_{ii}} s)}{rs(1 + 1.5T_s r)(1 + \frac{L_f}{r} s)} \tag{15}$$

The closed loop transfer function of the current loop is:

$$G_{ci}=\frac{G_{oi}(s)}{1+G_{oi}(s)}=\frac{\dfrac{K_{PWM}K_{ii}}{1.5T_s r}}{s^2+\dfrac{1}{1.5T_s}s+\dfrac{K_{PWM}K_{ii}}{1.5T_s r}} \tag{16}$$

the equation(16) expressed as a standard form:

$$G_{ci}=\frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2} \tag{17}$$

$$\xi=\frac{1}{2}\sqrt{\frac{r}{1.5K_{PWM}K_{ii}T_s}}=0.707,\omega_n=\sqrt{\frac{K_{PWM}K_{ii}}{1.5T_s r}} \tag{18}$$

$$K_{ii}=\frac{r}{3T_s K_{PWM}},K_{ip}=\frac{L_f}{3T_s K_{PWM}} \tag{19}$$

By equation(19) is the current loop PI regulator control parameter calculation and we get K_{ii}=1.90,K_{ip}=0.02857.

Voltage loop design: The outer voltage controller has two phase rotating co-ordinate system decoupled, in the design of the loop d-axis and q-axis voltage control respectively .Figure 9 shows the block diagram of the voltage loop.

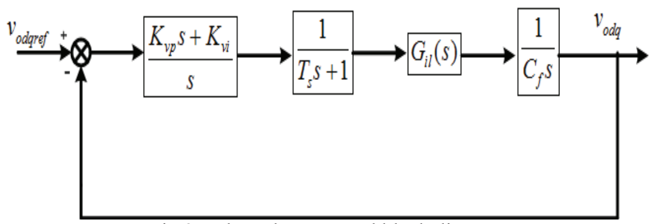

Fig.9.Voltage loop control block diagram

The voltage loop bandwidth is given by:

$$h_u=\frac{K_{vp}}{4T_s K_{vi}} \tag{20}$$

$$\frac{K_{vi}}{C}=\frac{h_u+1}{32h_u^2T_s^2} \tag{21}$$

Take the bandwidth h_u=2.

$$K_{vi}=\frac{1.5C}{64T_s^2}=35.15 \tag{22}$$

$$K_{vp}=\frac{1.5C}{10T_s}=0.0225 \tag{23}$$

IV. SIMULATION RESULTS OF DROOP CONTROLLED PARALLEL INVERTERS

In order to verify the droop control method for parallel inverters in microgrid,Matlab/Simulink platform is used to build the two inverters parallel simulation models. Two inverters are connected in parallel of rating 3kva each. Droop co-efficients of m=0.0015rad/s/W,n=0.001/Var/W and line impedance of R=0.642Ω,X=0.083Ω. Power sharing of each inverters investigated with load P_{Load}=2000W,Q_{Load}=5VAR. Each inverter is able to share the load proportionally with respect to the load, active power of P1=997W,P2=994W and reactive power of Q1=2.5VAR,Q2=2.2VAR as shown in fig10,11. Voltage, current and frequency are in the stable limit at PCC for the given load as shown fig 12,13,14.

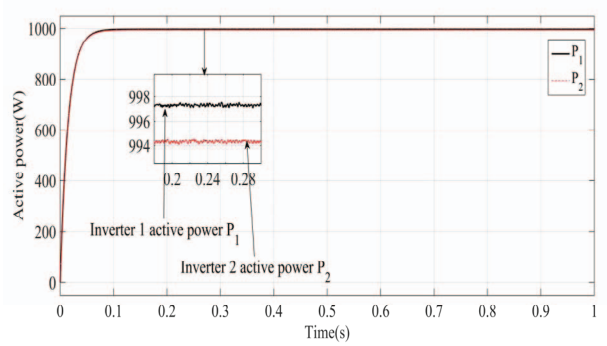

Fig.10.Active power waveforms of inverters

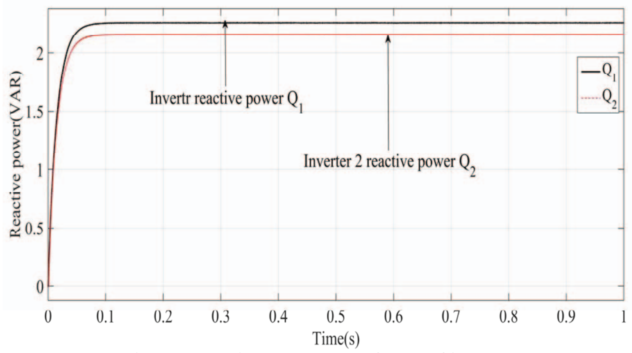

Fig.11. Reactive power waveforms of inverters

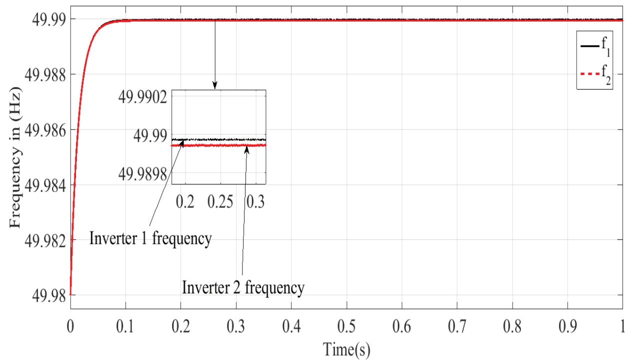

Fig.12.Frequency waveforms of inverters

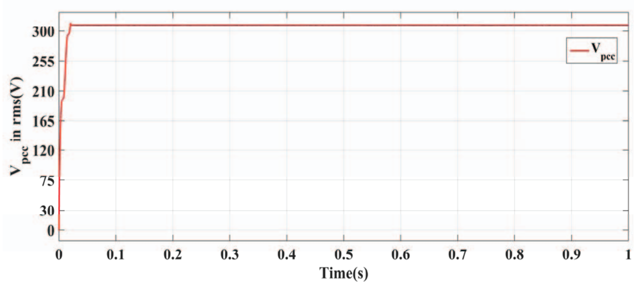

Fig.13. Voltage at PCC(RMS)

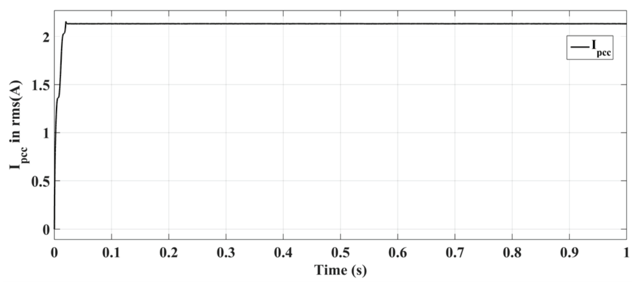

Fig.14.Current at PCC(RMS)

V. DROOP CONTROL OF THREE PHASE INVERTER

The droop control of parallel inverters in microgrid is done in Matlab/Simulink. Voltage and current loop are designed for microgrid parallel inverters. By using droop control proportional load sharing is obtained from each inverter in microgrid, without using any communication. Simulation results show that droop control method can effectively provide required power to the load ensuring the system voltage drops and frequency are in the stable limit. By using droop control proportional load sharing is obtained from each inverter in microgrid, without using any communication. Simulation results show that droop control method can effectively provide required power to the load ensuring the system voltage drops and frequency are in the stable limit.

REFERENCES

[1] H.Farhangi, "The path of the smart grid", *IEEE Power Energy Mag.,* vol 8, no.1, pp.18-28, Jan/Feb.2010.

[2] R.Lasseter, "Microgrids", in *Power Engineering Society Winter Meeting.* 2002. *IEEE*, vol.1, 2002, pp.305-308.

[3] M.Chandorkar, D.Divan, and R.Adapa, "Control of parallel connected inverters in standalone AC supply systems", *IEEE Tranactions on Industry Applications*, vol. 29, no.1, pp.136-143, Jan/Feb 1993.

[4] Y.W.Li and C.kao, "An accurate power control strategy for power electronics interfaced distributed generation units operating in voltage

[5] Y.B.Byn, T.G.Koo, K.Y.Joe, E.S.Kim, J.I.Seo, and D.H.Kim, "Parallel operation of three phase UPS inverters by wirless load sharing control", in Proc.22nd, *Int. Telecommun. Energy conf.*, 2000, pp.526-532.

[6] T.F.Wu, Y.K.Chen ,and Y.H.Huang, "3C strategy for inverters in parallel operation achieving and equal current distribution", *IEEE Trans.Ind.Electron*.,vol.47,no.2,pp.273281,Apr.2000.

[7] Y.Pei, G.Jiang, X.Yang and Z.Wang, "Auto master slave control technique of parallel inverters in distributed ac power systems and UPS", *in Pro. IEEE Power Electron. Spec. Conf.,* 2004, pp.2050-2053.

[8] J.C.Vasquez, J.M.Guerrero, A.Luna, P.Rodriguez, and R.Teodorescu, "Adaptive droop control applied to voltage source inverters operating in grid connected and islanded modes", *IEEE Trans. on Industrial electronics,* vol 56, pp.4088-4096, 2009.

[9] J.M.Guerrero, L.G.DeVicuna, J.Matas, M.Castilla, and J.Miret, "A wirless controller to enhance dynamic performance of parallel inverters in distributed generations systems", *IEEE Trans. on Power Electronics,* vol.19, pp.1205-1213, 2004.

[10] K.H.Ahmed, S.J.Finney and B.W.Willams, "Passive filter design for three phase inverter interfacing in distributed generation", Compatibility in Power Electronics,CPE,pp.1-9.

[11] J.M.Guerrero,J.C.Vasquez,J.Matas,L.G.Vicuna,andM.Castilla,"Hierarchical control of droop-controlled AC and DC microgrids- a general approach toward standardization, "*IEEE Trans. Ind. electron*.,vol.58,no.1pp.158-166,Jan2011.

[12] K.H.Ahmed, S.J.Finney and B.W.Willams, "Passive filter design for three phase inverter interfacing in distributed generation", Compatibility in Power Electronics,CPE,pp.1-9.

[13] C.N.Rowe, T.J.Summers, R.E.Betz, D.J.Cornforth, and T.G.Moore, "Arctan power-frequency droop for improved microgrid stability", *IEEE Trans. on Power Electron.,* vol 28, no.8, pp.3747-3759, Aug.2013.

[14] Q.C.Zhong, "Robust droop droop controller for accurate proportional load sharing among inverters operated in parallel", *IEEE Trans.Ind.Electron.,* vol 60, no.4, pp.1281-1290, Apr..2013.