Vector Control of the Interlinking Converter for the Droop Controlled Power Flow in AC-DC Hybrid Microgrids

R.V.S.E Shravan and C. Vyjayanthi
Department of Electrical and Electronics Engineering
National Institute of Technology Goa
Email: rvsravan91@nitgoa.ac.in, vyju80@gmail.com

***Abstract*—Distributed Generation (DG) units using renewable and non-conventional sources have become a part of modern electrical grids because of their advantages like expandability, flexibility, environmental friendliness, etc. The combination of various DG units along with the loads which can operate both in grid connected and islanded modes form a microgrid. In a microgrid, advanced power electronic interfaces along with appropriate control schemes are required for carrying out essential power conditioning and smooth integration of these DGs to the microgrids, and for further integration of microgrids to the main utility grid. In grid tied mode, where the microgrid is interconnected to utility grid, the DG sources (i.e., renewables like Solar) operate like a current source transferring maximum power to the utility grid, and the conventional sources share the load power based on their generation droop characteristics. However, in islanded mode, each DG is made to act like a controlled voltage source and the power sharing between various DG's is generally made according to their power ratings (using Droop control scheme). This paper investigates issues related to power sharing by various sources belonging to AC and DC sub-microgrids connected to a Utility grid. These AC and DC sub-grids are considered as one unit which operates in connected and islanded modes with Utility grid. AC and DC subgrids inturn are connected to each other through a bi-directional power electronic interface. The main challenge addressed in this paper is to manage power sharing between all these DG sources in the AC and DC subgrids. Towards addressing this problem, a normalization expression taking into account the DC bus voltage and AC bus frequency is considered. Accordingly, control schema is implemented, with the aim of meeting all the loads of both the sub-grids ensuring required power exchange through the bi-directional converter. The validation of the implemented control schemes is tested for various load conditions.**

I. INTRODUCTION

With the growth in renewable sources like roof top Solar PVs, power generation in DC is drastically increasing. Parallely, most of our today's loads are also consuming DC power and are considered efficient aswell. A lot of research is going on towards reducing the conversion losses from DC to AC (our main grid being AC) and making the best utilisation of the generated DC power. This thought process has lead to the development of AC-DC hybrid microgrids, where respective grids are primarily connected to their corresponding load types (i.e. AC loads to AC grid and vice-versa). A microgrid is expected to operate smoothly with and without grid connection and it is a discrete electrical system that ensure affordable, localised and reliable electricity. For the AC microgrid, the voltage and frequency variations are fixed by the main grid (with utility grid acting as infinite bus). The energy thus generated by either of the grids would either be consumed by the local loads or channeled to the mains if there is a surplus. Similarly, within the two grids as well there is exchange of power as per the load requirements. To enable a smooth operation of an AC-DC microgrid, which are expected to be durable and can work efficiently in both grid connected/islanded operation, management of critical/non-critical loads with proper voltage and frequency regulations is required. Continuous tuning of the source outputs is thus needed and can be achieved with or without external communication links. In the grid connected mode, hybrid microgrids control power flow between hybrid microgrids and utility grid through the point of common coupling (PCC). On the other hand, in the islanded mode, hybrid microgrids control power flow between the AC and DC microgrids through an interlinking converter. The frequency in AC microgrids and DC voltage in DC microgrids are maintained stably in acceptable ranges by the interlinking converter [1], [2] . In general, the droop control scheme is widely applied for the control schema of the interlinking converter, because it can be used for sharing power among different sources without communication ([3] - [5]). However, the limitation of the droop control scheme is the existence of steady-state error likely to affect the power quality of sensitive loads [6]. Various methods have been proposed [7], [8] focusing on the line impedance effect and output impedance design, respectively. Marwali et al. [9] and Prodanovic and Green [10], on the other hand, contributed by combining low bandwidth and droop control with some considerations given to non-ideal loads. More emphasis on non-ideal load compensation could be found in [11] and [12], followed by stability improvement of droop control found in [13] and [14]. Other efforts include [15] where different load placements were considered and [16] where different control methods were discussed for multiple converters. These methods were mostly confined to an AC microgrid, which might not be the most efficient since modern sources and loads can either be AC or DC. Forming a DC microgrid [17] might therefore be of interest, as reinforced by recent studies related to stability [18]. In this paper, an improved droop control scheme [19] is presented to remove the steady-state error of the conventional droop control scheme. Vector Control scheme [20] is used to control the interlinking converter using the active power command obtained from the applied droop control scheme. In this study, various load conditions are studied in MATLAB/Simulink environment for testing the performance of the proposed control scheme.

II. HYBRID MICROGRID

An AC-DC hybrid microgrid is formed connecting both AC and DC subgrids through an interlinking converter (IC), both of the subgrids consist of their own generating units, loads, energy storage elements grouped together forming a microgrid. An example hybrid AC-DC microgrid is shown in fig.1.

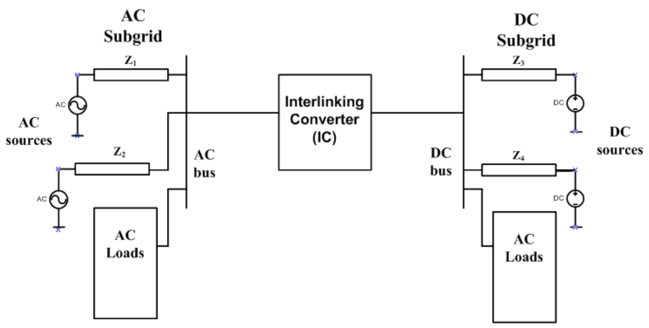

Fig. 1. Example Hybrid AC-DC microgrid

The intention of forming hybrid microgrid is not only to decrease the conversion losses but also to have coordinated power flow between the subgrids whenever required. This power flow should happen in order to share the load seen by either of the subgrids, so that only one subgrid doesnt get loaded. To achieve this, an appropriate droop control technique is applied - so that the load is not met by the nearest source but is shared by both of the subgrids according to their ratings. So, to have this feature of power sharing it is not enough to just have droop controlled sources in the microgrid but the two subgrids when seen wholly as individual sources should also be droop controlled.

III. DROOP CONTROL TECHNIQUE FOR POWER SHARING

As the load on a DC power source increases, the output voltage of the source decreases linearly, similarly frequency and amplitude of the voltage generated by the AC source decreases with increase in active and reactive load, so the power supplied by the source and its output parameters are related with a linear equation which is called Droop equation or Droop characteristics. Eq.(1) and eq.(2) represent the droop equations of the sources in AC and DC subgrids, where m, n, v are droop coefficients, x, y are source number and the intercepts in the equations are the parameters at no load.

$$f_x^* = f_x' + m_x P_x; \quad V_x^* = V_x' + n_x Q_x \tag{1}$$

$$V_{d,y}^* = V_{d,y}' + v_y P_y \tag{2}$$

These are the droop equations used for power sharing between the sources. The AC sources share the total active load in such a way that both the sources operate at same frequency while meeting the load. In case of DC sources, they are made to operate at equal terminal voltage using the above droop equations. However, in case of AC-DC hybrid microgrids, the active power dependent parameters on AC and DC side are frequency and voltage which are the quantities with different dimensions and cannot be equalized directly to have the droop controlled active power sharing.

So in this paper normalized expressions taking into account the DC bus voltage (V) and AC bus frequency (f) are presented which are given in equations (3), (4).

$$f_{pu} = \frac{f - 0.5(f_{max} + f_{min})}{0.5(f_{max} + f_{min})} \tag{3}$$

$$V_{pu} = \frac{V - 0.5(V_{max} + V_{min})}{0.5(V_{max} + V_{min})} \tag{4}$$

Where f_{pu} and V_{pu} are per unitized values of f and V, and f_{max}, f_{min}, V_{max}, and V_{min} are the maximum and minimum values of f and V in which they are allowed to operate.

f_{pu} and V_{pu} are dimensionless quantities. We are aware that in the case of AC droop control technique, the power shared by two AC sources are in proportion of their ratings ensuring both operate at same frequency. Similarly, in DC droop control technique, the power shared by the two DC sources are in proportion of their ratings ensuring connected bus voltage is maintained. Here, in case of AC-DC hybrid microgrids both the perunitised quantities, f_{pu} and V_{pu} are equalized to have the desired droop based power sharing by both AC and DC subgrids.

The way to equalize f_{pu} and V_{pu} is to take the difference of these two quantities and give it to the PI controller whose output will be the amount of active power to be transferred by the interlinking converter from one subgrid to the other. In this way the IC should be controlled according to the load requirements which is explained in next section.

IV. VECTOR CONTROL TECHNIQUE FOR CONTROL OF IC

Hybrid microgrid used for simulation is shown in fig.2.

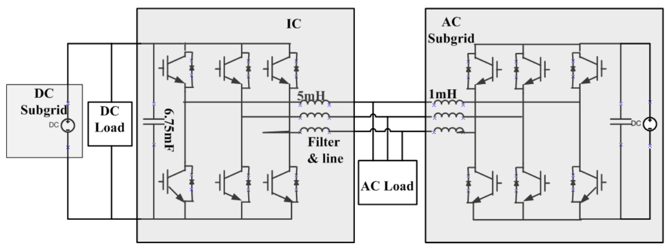

Fig. 2. Simulated Hybrid Microgrid

The active power shared by any of the subgrids should be transferred through IC. Hence, the IC should be controlled in order to transfer the required amount of active power, which is done using vector control technique. Vector Control of IC means, the control of the IC using space vectors of the voltages and currents in rotating reference frame (dq0) in order to get, decoupled active and reactive power control, nearly sinusoidal line currents at any power factor, and also bidirectional flow of current (i.e. from AC to DC side and from DC to AC side also).

Let us consider an IC as shown in fig.3,

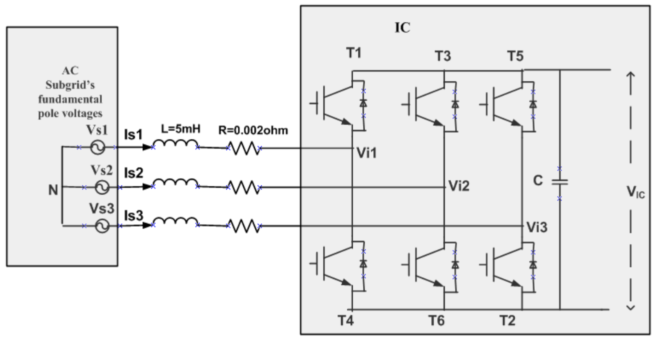

Fig. 3. Interlinking Converter

Consider, V_{s1}, V_{s2}, V_{s3} and I_{s1}, I_{s2}, I_{s3} are per phase AC source fundamental voltages and currents. V_{i1}, V_{i2}, V_{i3} are pole voltages for all three legs of the converter. L and R are line inductance and resistance, V_{IC} is voltage across DC bus capacitance.

By applying KVL on AC side

$$V_{s1} = V_{i1} + L\frac{d_{is1}}{dt} + Ri_{s1} \quad (5)$$

$$V_{s2} = V_{i2} + L\frac{d_{is2}}{dt} + Ri_{s2} \quad (6)$$

$$V_{s3} = V_{i3} + L\frac{d_{is3}}{dt} + Ri_{s3} \quad (7)$$

Now by converting these equations into dq0 frame we get

$$V_{sd} = V_{id} + L\frac{d_{isd}}{dt} - W_s L i_{sq} + Ri_{sd} \quad (8)$$

$$V_{sq} = V_{iq} + L\frac{d_{isq}}{dt} + W_s L i_{sd} + Ri_{sq} \quad (9)$$

The 'θ' used to transform the stationary reference frame (abc) into rotating reference frame or the 'θ' used to get equations (8) and (9) from (5), (6), (7), which is the main feature of vector control technique.

In Vector control method, the stationary reference frame should be rotated in a way such that the source voltage vector V_s is aligned completely on the real power axis i.e. q-axis (here we are considering that q-axis corresponds to the active power and d-axis corresponds to the reactive power), means the speed at which the stationary reference frame should be rotated is such that the source voltage vector V_s aligns completely on q-axis only i.e. the component of the source voltage vector on d-axis is equal to 0.

The advantage that we get after making $V_{sd} = 0$ is we can obtain decoupled or independent control over active and reactive powers.

This can be explained by considering equations (10) and (11),

$$p = \frac{2}{3}(V_{sq}i_{sq} + V_{sd}i_{sd}) \quad (10)$$

$$q = \frac{2}{3}(V_{sq}i_{sd} - V_{sd}i_{sq}) \quad (11)$$

'p' and 'q' are active and reactive powers in dq0 frame.

By putting V_{sd}=0 in the above equations we get,

$$p = \frac{2}{3}(V_{sq}i_{sq}) \quad (12)$$

$$q = \frac{2}{3}(V_{sq}i_{sd}) \quad (13)$$

Now it is clear that as 'V_{sq}' is constant 'p' and 'q' depends on 'i_{sq}' and 'i_{sd}', they can be controlled by controlling 'i_{sq}' and 'i_{sd}' respectively.

Now equations (8) and (9) become

$$0 = V_{id} + L\frac{d_{isd}}{dt} - W_s L i_{sq} + Ri_{sd} \quad (14)$$

$$V_{sq} = V_{iq} + L\frac{d_{isq}}{dt} + W_s L i_{sd} + Ri_{sq} \quad (15)$$

From the above equations we need to obtain pole voltages in dq0 frame i.e. V_{id} and V_{iq} to attain required power transfer at required power factor.

$$V_{id} = -(L\frac{d_{isd}}{dt} - W_s L i_{sq} + Ri_{sd}) \quad (16)$$

$$V_{iq} = V_{sq} - (L\frac{d_{isq}}{dt} + W_s L i_{sd} + Ri_{sq}) \quad (17)$$

and,

$$V_{id} = G.V_{id}^*$$
$$V_{iq} = G.V_{iq}^*$$

Where V_{id}^* and V_{iq}^* are the reference voltage signals in rotating reference frame these need to be reverse transformed into stationary reference frame to obtain control signals V_{i1}^*, V_{i2}^* and V_{i3}^* for the three legs of the converter.

Obtaining these reference signals is not so straight forward as it requires to know the values of currents i_{sq} and i_{sd}, these current values depend upon the active and reactive powers need to be supplied.

AC to DC active power transfer case is presented in this paper considering

$$e = f_{pu} - V_{pu}$$

Where 'e' is given as input to the PI controller, which gives the active power command 'p' thereby deciding the reference value of $i_{sq}(i_{sq}^*)$, the output of the voltage controller gives i_{sq}^*. For AC to DC active power transfer, reactive power command will be 0 therefore $i_{sd}^* = 0$.

Control block diagram of the implementation is given in Fig. 4. Table 1 gives the values of the simulation parameters considered.

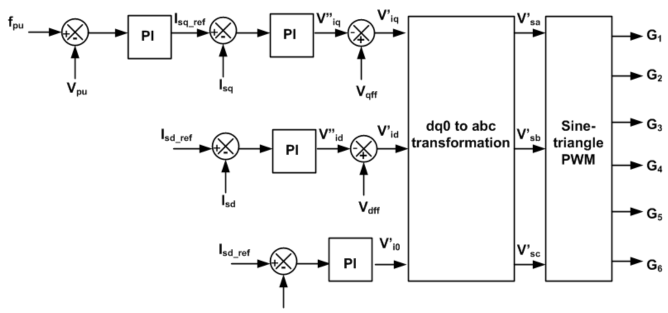

Fig. 4. Control block of IC

TABLE I
SIMULATION PARAMETERS

Parameters	Values
f_{min}	49Hz
f_{max}	51Hz
V_{max}	615V
V_{min}	595V
L	5mH
R	0.002ohm
C(IC)	6.75mF

$$V_{id} = -(L\frac{d_{isd}}{dt} - W_s L i_{sq} + R i_{sd}) \quad (18)$$

$$\Rightarrow V_{id} = (W_s L i_{sq}) - (L\frac{d_{isd}}{dt} + R i_{sd})$$

$$\Rightarrow V_{id} = G(V_{dff} - V_{id}^{"}),$$

where,

$$GV_{dff} = W_s L i_{sq}, GV_{id}^{"} = L\frac{d_{isd}}{dt} + R i_{sd}$$

$$\Rightarrow GV_{id}^{*} = G(V_{dff} - V_{id}^{"})$$

$$\Rightarrow V_{id}^{*} = V_{dff} - V_{id}^{"}$$

and

$$V_{iq} = V_{sq} - (L\frac{d_{isq}}{dt} - W_s L i_{sd} + R i_{sd}) \quad (19)$$

so similarly,

$$V_{id}^{*} = V_{dff} - V_{id}^{"}$$

where,

$$GV_{qff} = V_{sq} - W_s L i_{sd} \quad and$$

$$GV_{iq}^{"} = L\frac{d_{isq}}{dt} + R i_{sq}$$

where

$$V_{dff}, V_{qff}$$

are feed forward terms.

V. Simulation Results

Simulation of a hybrid microgrid with AC and DC subgrids of 10kW rating was carried out in MATLAB/Simulink. the parameters used for simulation are given in Table.1

Where f_{min}, f_{max}, V_{min} and V_{max} are the values of the AC subgrid frequency and DC subgrid voltage at no-load and full-load. Simulation of the hybrid microgrid is done for two cases, (i) full load of 10kW and (ii) half load of 5kW, on DC subgrid, AC subgrid is not loaded in both the cases, power transfer is done from AC subgrid to DC subgrid. DC subgrid voltage should be 595V when a load of 10kW is connected to it and AC subgrid's frequency should be 51 Hz at no load. With the droop control technique applied, both share the load by 5kW each (as their ratings are equal) and their V and f becomes 605V and 50Hz which are equal to the values when a load of 5kW is put on each subgrid individually, simulation result of this case is shown in fig 5 (here x-axis is time in seconds and y-axis in frequency in Hz for upper subplot and voltage in Volts for lower subplot) and fig 6 (here x-axis is time in seconds and y-axis is power from AC subgrid in watt for upper subplot and power from DC subgrid in watt for lower subplot).

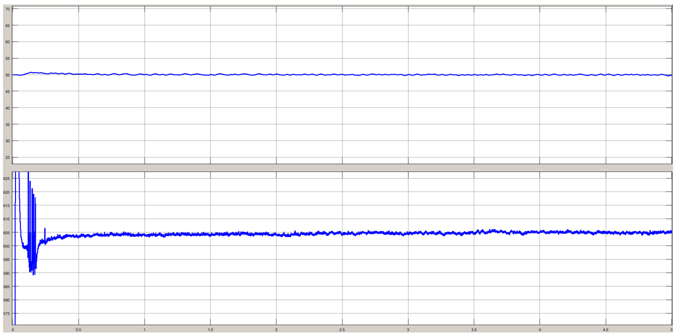

Fig. 5. f and V at full load

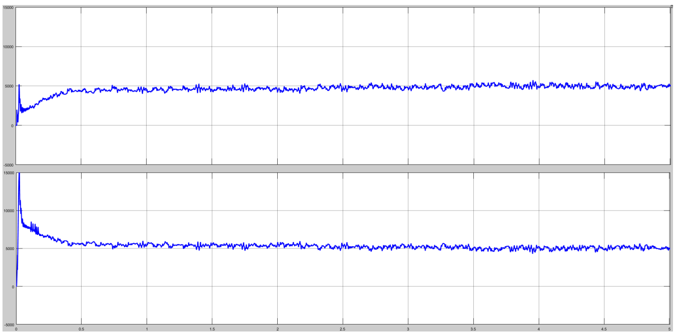

Fig. 6. Pac and Pdc at full load

Similarly when a load of 5kW is put on DC subgrid its V should be 605V but as the subgrids are droop controlled they share the load by 2.5kW each and their V and f becomes 610V and 50.5Hz, which is shown in fig 7 (here x-axis is time in seconds and y-axis is frequency in Hz for upper subplot and voltage in Volts for lower subplot) and fig 8 (here x-axis is time in seconds and y-axis is power from AC subgrid in watt for upper subplot and power from DC subgrid in watt for lower subplot).The power flowing from AC subgrid is transferred through the vector controlled IC.

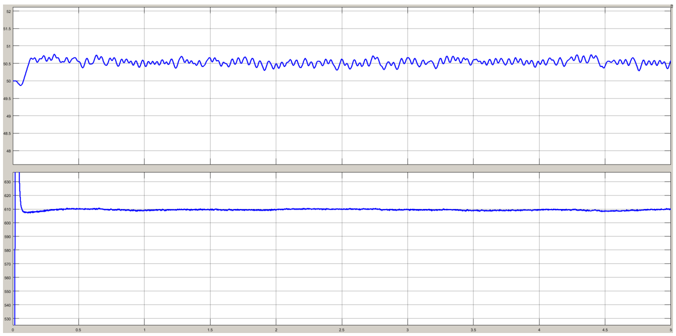

Fig. 7. f and V at half load

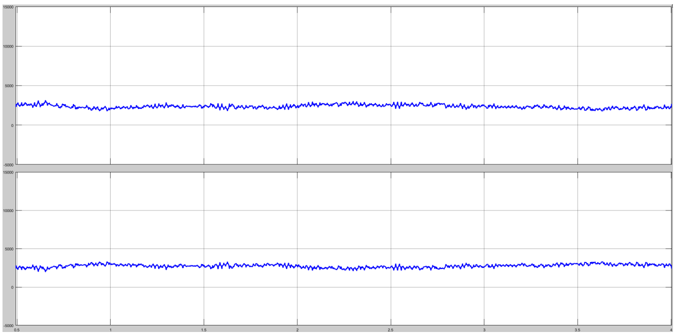

Fig. 8. Pac and Pdc at half load

VI. CONCLUSIONS

Controlled power sharing using the droop control technique in hybrid AC-DC microgrids is simulated in MATLAB/Simulink for two different loading conditions in DC subgrid. The interlinking converter (IC) used for connecting the two subgrids is controlled by vector control technique. The active power command is obtained from the droop control technique which is the input for the vector control technique for obtaining the switching pulses which are used to drive the switches of the interlinking converter allowing it to transfer the required amount of power shared by AC subgrid to DC subgrid. The results obtained show how the two subgrids share the power required by the load.

REFERENCES

[1] X. Liu, P. Wang, and P. C. Loh, A Hybrid AC/DC Microgrid and Its Coordination Control, IEEE Transactions on Smart Grid, vol. 2, no. 2, (2013), pp. 278-286.

[2] C. Wang, X. Li, L. Guo and Y. W. Li, A Nonlinear-Disturbance-Observer-Based DC-Bus Voltage Control for a Hybrid AC/DC Microgrid, IEEE Transactions on Power Electronics, vol. 29, no. 11, (2014), pp. 6162-6177.

[3] H. M. Kim, and T. Kinoshita, A Multiagent System for Microgrid Operation in the Grid-interconnected Mode, Journal of Electrical Engineering & Technology, vol. 5, no. 2, (2010), pp. 246-254.

[4] D. Salomonsson and A. Sannino, Low-Voltage DC Distribution System for Commercial Power Systems with Sensitive Electronic Loads, IEEE Transactions on Power Delivery, vol. 22, no. 3 (2007), pp. 1620-1627.

[5] S. Grillo, V. Musolino, L. Piegari, E. Tironi and C. Tornelli, DC Islands in AC Smart Grids, IEEE Transactions on Power Electronics, vol. 29, no. 1, (2014), pp. 89-98.

[6] J. J. Justo, F. Mwasilu, J. Lee, J. W. Jung, AC-microgrid versus DC-microgrid with distributed energy resources: A review, Renewable and Sustainable Energy Review, vol. 24, (2013), pp. 387-405.

[7] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, Control of parallel inverters in distributed ac power systems with consideration of line impedance effect, IEEE Trans. Ind. Appl., vol. 36, no. 1, pp. 131138, Jan/Feb. 2000.

[8] J. M. Guerrero, L. G. Vicua, J. Matas, M. Castilla, and J. Miret, Output impedance design of parallel-connected UPS inverters with wireless loadsharing control, IEEE Trans. Ind. Electron., vol. 52, no. 4, pp. 1126 1135, Aug. 2005.

[9] M. N. Marwali, J. W. Jung, and A. Keyhani, Control of distributed generation systemsPart II: Load sharing control, IEEE Trans. Power Electron., vol. 19, no. 6, pp. 15511561, Nov. 2004.

[10] M. Prodanovic and T. C. Green, High-quality power generation through distributed control of a power park microgrid, IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 14711482, Oct. 2006.

[11] K. De Brabandere, B. Bolsens, J. Van Den Keybus, A. Woyte, J. Driesen, and R. Belmans, A voltage and frequency droop control method for parallel inverters, IEEE Trans. Power Electron., vol. 22, no. 4, pp. 1107 1115, Jul. 2007.

[12] T. L. Lee and P. T. Cheng, Design of a new cooperative harmonic filtering strategy for distributed generation interface converters in an islanding network, IEEE Trans. Power Electron., vol. 22, no. 5, pp. 19191927, Sep. 2007.

[13] Y. Mohamed and E. F. El-Saadany, Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids, IEEE Trans. Power Electron., vol. 23, no. 6, pp. 28062816, Nov. 2008.

[14] R. Majumder, B. Chaudhuri, A. Ghosh, R. Majumder, G. Ledwich, and F. Zare, Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop, IEEE Trans. Power Syst., vol. 25, no. 2, pp. 796808, May 2010.

[15] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, Load sharing and power quality enhanced operation of a distributed microgrid, IET Renew. Power Gener., vol. 3, no. 2, pp. 109119, Jun. 2009.

[16] J. M. Guerrero, L. Hang, and J. Uceda, Control of distributed uninterruptible power supply systems, IEEE Trans. Ind. Electron., vol. 55, no. 8, pp. 28452859, Aug. 2008.

[17] B. K. Johnson, R. H. Lasseter, F. L. Alvarado, and R. Adapa, Expandable multiterminal dc systems based on voltage droop, IEEE Trans. Power Del., vol. 8, no. 4, pp. 19261932, Oct. 1993.

[18] K. Kurohane, T. Senjyu, A. Yona, N. Urasaki, T. Goya and T. Funabashi, A hybrid smart AC/DC power system, IEEE Transactions on Smart Grid, vol. 1, no. 2, (2014), pp. 199-204.

[19] P. C. Loh, D. Li, Y. K. Chai and F. Blaabjerg, Autonomous Operation of Hybrid Microgrid with AC and DC Subgrids, IEEE Transactions on Power Electron, vol. 28, no. 5, (2013), pp. 2214-2223.

[20] J S SIVA PRASAD, TUSHAR BHAVSAR, RAJESH GHOSH and G NARAYANAN, vector Control of Three Phase AC/DC Front End Converter,Sadhana vol 33. , October, 2008,pp 591-613.