ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

Analysis and Control of Parallel Connected Single Phase Voltage Source Inverters

I.Mumtaj[#1], S.Archana[#2]

[#1]PG Scholar, [#2] Phd Scholar, EEE Department, College of Engineering, Guindy,

Anna University, Chennai-25.

Abstract: This work focuses on analysis and design a parallel-connected single phase voltage source inverters. Inverters are in parallel to provide system redundancy and high reliability. A natural problem in parallel-connected inverters is that the load is commonly shared among them. It is anticipated to use the droop control for power sharing among the inverters. The control technique of the inverters is based on frequency and voltage droops based on the information that is obtainable locally at the inverter and does not need control interconnections. Also it is proposed to develop a control strategy for parallel connected single phase voltage source inverters, which can poise the current distribution among the parallel-connected inverters with no interconnected communication lines.

Keywords: Parallel connected inverters, droop control

I. INTRODUCTION

Inverters produce an AC output waveform from a DC source. The major applications of the inverters are adjustable speed drives (ASD), uninterruptible power supplies (UPS), active filters, Flexible AC transmission systems (FACTS), voltage compensators, and photovoltaic generators.

To provide reliable power under scheduled and unscheduled outages requires an uninterruptible power supply (UPS) which can be easily expanded to meet the needs of a growing demand. A system should posses fault tolerant control and include the capability for redundancy. These goals can be met by connecting smaller inverters in parallel. A control scheme is designed to allow them to operate independently yet still share the load. We have developed a control technique for operating two or more single phase inverter modules in parallel with no auxiliary interconnections. Parallel operating systems of voltage source inverters with other inverters or with the utility source are sensitive to disturbances from the load or other sources and can easily be damaged by over current.

Thus attention should be given to the system design of parallel operating inverters. Types of system configuration, control methods, and means of protection against failure are summarized, and several methods are proposed. Features and problems of these systems are discussed.

The parallel operation of voltage source inverters (VSIs) is a configuration that allows the processed load power to be shared among the converters, creating redundant systems and making the power expansion flexible. These characteristics have led to the use of this configuration in an uninterruptible power supply (UPS), mainly to build a redundant and modular system. In applications for UPS, the inverters must operate in parallel independently of each other, which requires an appropriate control strategy that ensures the system operation.

II. PARALLEL CONNECTION OF INVERTERS

Nowadays, more and more distributed generation and renewable energy sources, e.g. wind, solar and tidal power, are connected to the public grid via power inverters. They often form micro grids before being connected to the public grid. Due to the availability of high current power electronic devices, it is inevitable that several inverters are needed to be connected in parallel for high-power and/or low-cost applications. Inverters are also often connected in parallel to provide system redundancy and high reliability, which is important for critical customers. A natural problem for parallel-connected inverters is that how the load is shared among them. A key technique is to use the droop control, which is widely used in conventional power generation

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

systems. The advantage is that no external communication mechanism is needed among the inverters.

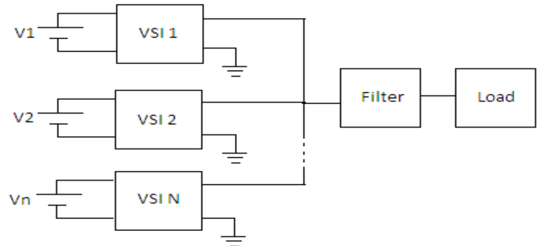


Fig.1 circuit diagram of "N" inverters connected in parallel

III. Control Of Parallel Connected Inverters

When two or more inverters operate in parallel, the following features must be achieved:

- amplitude, frequency and phase synchronization among the output voltages of inverters
- proper current distribution according to the capacities,
- flexibility and
- hot-swap feature at any time.

The conventional control strategies for the parallel-connected inverters can be classified into two types;

- Active load sharing/current distribution
- Droop control.

A. Active Load Sharing / Current Distribution Type

The object of the active current distribution control is to generate a reference current for each parallel-connected inverter and it can be subdivided into;

- Current Limit Control (CLC)
- Master-Slave Control (MSC)
- Average Current Sharing (ACS) / Distributed Logical Control (DLC)
- Circular Chain Control (3C)

In CLC mode, all the modules should have the same configuration and each module tracks the average current of all the modules to achieve an equal current distribution. Perfect and equal current distribution can be achieved by using DSP based control for voltage and current controller and by tracking the averaged inductor current of the inverters. Thus the system stability and robustness can be improved. [15]

In MSC method, one inverter is specified as the master, and all others are as the slaves. The master inverter supplies a reference current to the slave inverters. Thus the master module is responsible for the output voltage regulation. In such a system, if the master module fails, the system will shut down. This is a major drawback. This can be partially overcome by introducing a separate current-controlled PWM inverter unit to generate the distributing current nearly independent for the slave inverters. Hence, precise current division between the inverters are very much important. This strategy is easy to implement in parallel operation of UPS Or, in other case, another module can take the role of master in case of main master unit fails. Control scheme can be of dedicated, rotary or high-crest current type. [16]

In the MSC and CLC methods, the output currents of all parallel-connected inverters must be collected, and the number of parallel-connected inverters must be pre-known. If one of the parallel-connected inverters fails, the parallel-connected system will fail. This problem can be overcome by DLC mode where redundancy is also achievable.

In ACS mode, individual control circuit is used for each inverter. Current control mode is used to control its output current and to trace the same average reference current. When defect is found in any module, others can still operate in parallel. It can also be used as power-sharing technique where each inverter controls the active and reactive power flow in order to match the average active power of the system.[18]

In 3C mode, the successive module tracks the current of its previous one to achieve an equal current distribution, and the first module tracks the last one to form a circular chain connection. The output voltage and current of each inverter can also be varied and internally controlled to achieve a fast dynamic response.[17]

IV. Droop Control Method

The droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as Wireless Control (WC) with no interconnection between the inverters. In this case, inverters are generally operated in the voltage-mode control and the phase & amplitude of the inverter's output voltage are the control parameters. This control is defined in

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities. This technique is then improved for non-linear load where harmonic components can be shared properly. Impact of line impedance on reactive power sharing in the conventional frequency/voltage droop concept is further enhanced in to make the controller ideally suited for distributed ac power supply systems.[2]

We know that the active and reactive power transmitted across a lossless line are:

$$P = (V_1V_2 / X) \sin \delta \qquad (1)$$

$$Q = (V_2 (V_2 – V_1 \cos \delta)) / X \qquad (2)$$

Since the power angle "δ" is typically small, we can simplify this further by using the approximations Sin δ ≈ δ and Cos δ = 1:

$$\delta \approx PX / V_1V_2 \qquad (3)$$

$$(V_2 – V_1) \approx QX/V_2 \qquad (4)$$

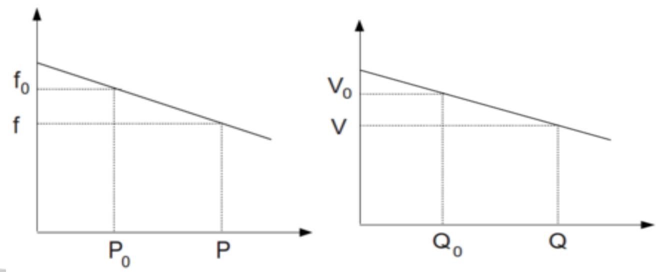
From the above, we can see that active power has a large influence on the power angle and reactive power has a large influence on the voltage difference. Restated, by controlling active and reactive power, we can also control the power angle and voltage. We also know from the swing equation that frequency is related to the power angle, so by controlling active power, we can therefore control frequency. [7]

This forms the basis of frequency and voltage droop control where active and reactive power are adjusted according to linear characteristics, based on the following control equations:

$$f = f_0 – K_p (P – P_0) \qquad (5)$$

$$V = V_0 – K_q (Q – Q_0) \qquad (6)$$

These two equations are plotted in the characteristics below:



(a) **(b)**

Fig.2. (a) Frequency droop characteristic **(b) Voltage droop characteristic**

The frequency droop characteristic above can be interpreted as follows: when frequency falls from f_0 to f, the power output of the generating unit is allowed to increase from P_0 to P. A falling frequency indicates an increase in loading and a requirement for more active power. Multiple parallel units with the same droop characteristic can respond to the fall in frequency by increasing their active power outputs simultaneously. The increase in active power output will counteract the reduction in frequency and the units will settle at active power outputs and frequency at a steady-state point on the droop characteristic. The droop characteristic therefore allows multiple units to share load without the units fighting each other to control the load . [7]

Similarly in the Voltage droop characteristic above can be interpreted as follows: when Voltage falls from V_0 to V, the reactive power output of the generating unit is allowed to increase from Q_0 to Q. A falling Voltage indicates a requirement for more reactive power. Multiple parallel units with the same droop characteristic can respond to the fall in voltage by increasing their reactive power outputs simultaneously. The increase in reactive power output will counteract the reduction in voltage.[7]

A. Block Diagram Of Droop Control Method

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

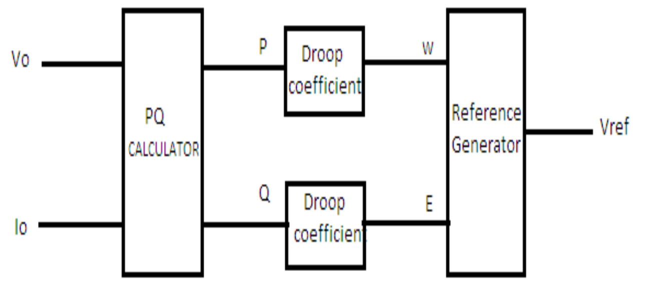


Fig.3.Block Diagram of Droop Control Method

Here the reference voltage is generated by a droop control method.

Reference voltage equation is ,

$$V_{ref} = E \sin \omega t \qquad (7)$$

$$E = E^{*} - nQ \qquad (8)$$

And $$\omega = \omega^{*} - mP \qquad (9)$$

After generating the reference voltage , V_{ref} is compared with output voltage(v_o) then the error signal is controlled by the PI Controller. The output from the PI controller is compared with the repeating sequence to produce the switching pulses for the inverter. The total circuit model of the two parallel connected inverter with droop control is shown in fig.4

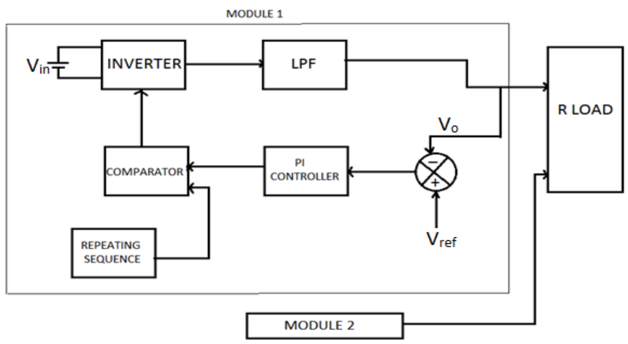


Fig..4. Circuit model of the two parallel connected inverter with droop control

Advantages of droop control method

- Improves the power sharing performance.
- Eliminate the circulating current of parallel operation.

B.Voltage Mode Control

The voltage-mode control scheme is shown in Fig. 5. Here the inverter output voltage that is to be regulated is sensed and fed back through a resistive voltage divider. It is then compared with a precision external reference voltage, V_{ref} in a voltage error amplifier. The error amplifier produces a control voltage that is compared to a constant-amplitude saw tooth waveform. The comparator or the PWM Modulator produces a PWM signal that is fed to drivers of controllable switches in the inverter. [19]

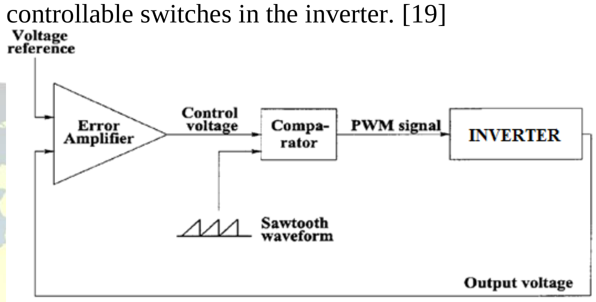


Fig. 5. Schematic diagram for voltage mode control

The major characteristics of this design are that there is a single voltage feedback path, with pulse- width modulation performed by comparing the voltage error signal with a constant ramp waveform. Current limiting must be done separately.

Advantages of Voltage mode control method,

- Simple hardware implementation and flexibility is the greatest advantage of voltage mode control scheme.
- The error amplifier keeps a fast track of changes in the converter output voltage. Thus, it provides good load regulation, that is, regulation against variations in the load.
- A large-amplitude ramp waveform provides good noise margin for a stable modulation process.
- A low-impedance power output provides better cross-regulation for multiple output supplies.

Disadvantages of Voltage mode control method,

This scheme has a poor line regulation i.e. regulation against variations in the input voltage. It is delayed since any change in the input voltage must manifest itself in the converter output before it can be corrected.

To alleviate this problem, the voltage-mode control scheme is sometimes augmented by a so called voltage-feed forward path.

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

IV. MODELLING AND SIMULATION

Table.1. Parameter values used in Simulation

PARAMETERS	RANGE
Input voltage	100V
Switching Frequency	25 KHz
Cut 0ff Frequency	19.5 KHz
Filter Inductor	408 µH
Filter Capacitor	163 nF
Load Resistor	50 Ω
Power rating	162

A.SIMULATION CIRCUIT

A. *Simulation Circuit*

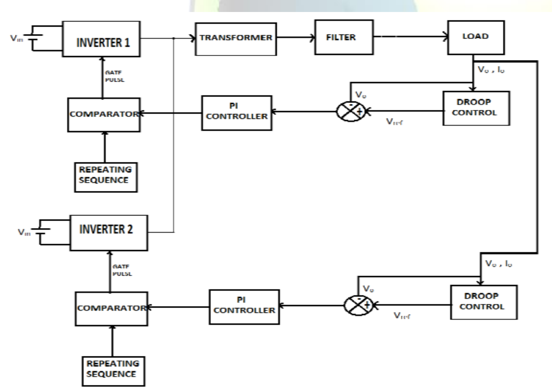


Fig.6. Simulation Circuit of Two Parallel connected Inverters with droop control

The overall circuit diagram of two parallel connected inverters with droop control is shown in fig.6. Here the reference voltage is calculated by the droop control method from the output of inverters. This reference voltaage is compared with the output voltage to produce the gate pulse for each inverter.

In droop control method, the real power and reactive power are calculated from the V_0 and I_0 is shown in fig.7 to calculate the E and ω by the equation(8) and (9) and these are fed into the reference generator to generate the reference voltage by the equation (7).

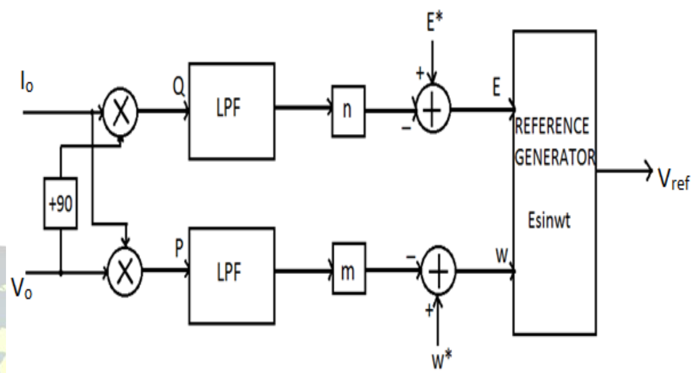


Fig.7.Simulation Circuit of droop control

In voltage mode control method, the reference voltage is not generated from the output of inverters, so directly we set here any value as reference voltage, then compared with the output voltage of inverters to produce the gate pulses for each inverter shown in fig.8.

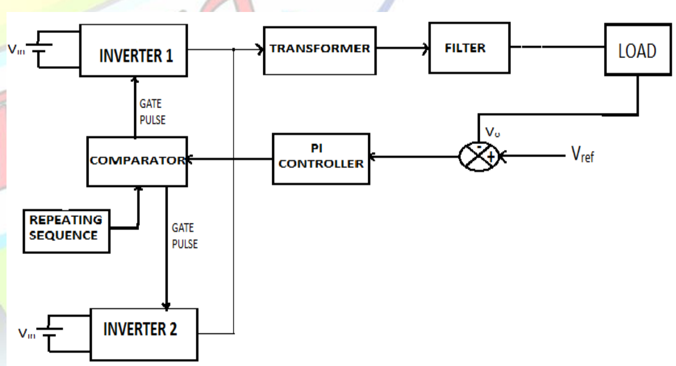


Fig.8.Simulation Circuit of Two Parallel connected Inverters with Voltage Mode control

B.Simulation Results

Here the input voltage applied is 100V and the range of switching frquency is 25KHz. The cutoff frequency to design a filter is 19.5KHz, the value of filter inductor and capacitor are 408µH and 165nF respectively. The load resistor is 50Ω and so the output voltage is 90V and the output current is 1.8 A. The power rating is 162W.

The output voltage and current waveform when two inverters are connected in parallel with open loop is shown

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

in below. The current from the both inverters are same as shown in fig. 10.

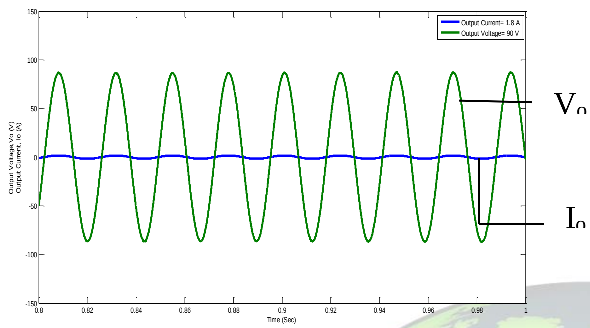


Fig.9. Output Voltage and Current waveform of two parallel connected inverter with open loop contol

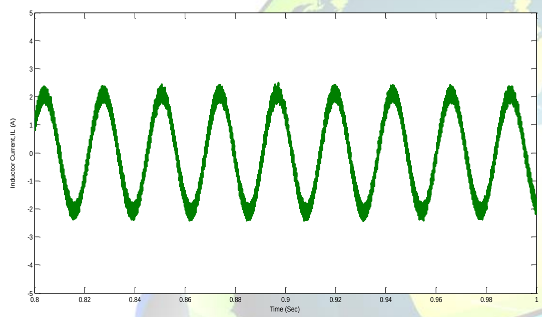


Fig.10. Inductor Current waveform of two parallel connected inverter with open loop control

The reference voltage from the droop contol is 90V is shown in below. From this we get the gate pulse for inverters is also shown in fig.12.

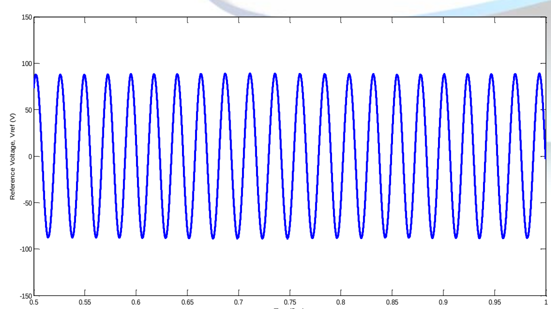


Fig.11. Reference Voltage waveform generated by droop contol

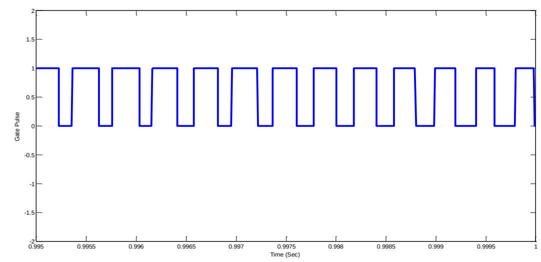


Fig.12.Gate Pulse waveform

The output voltage and output current waveform of two parallel connected inverter withdroop control is shown in below. The waveform of real and reactive power from the droop control is shown in fig.15.

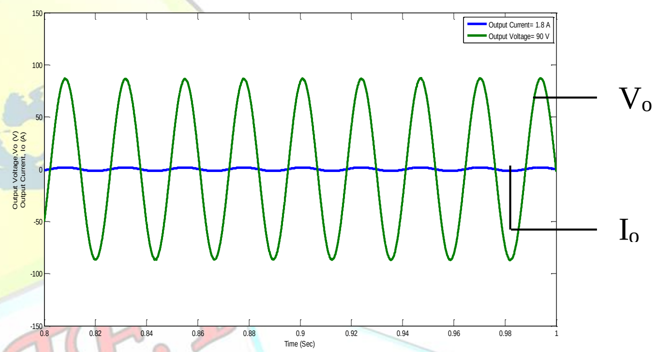


Fig.13. Output Voltage and Current waveform of two parallel connected inverter with droop contol

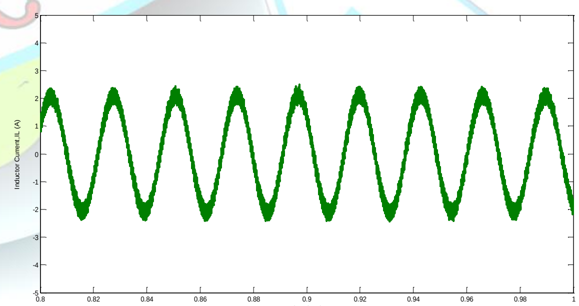


Fig.14. Inductor Current waveform of two parallel connected inverter with droop contol

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

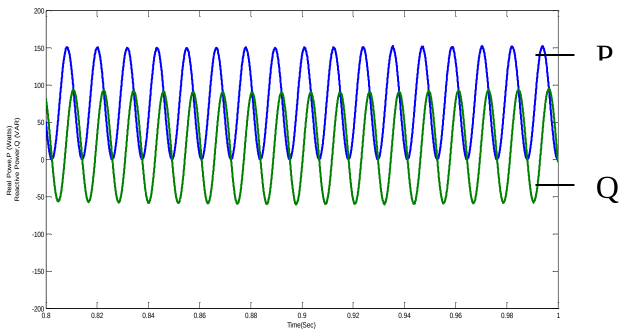


Fig.15. Active and Reactive Power waveform of two parallel connected inverter with droop contol

The output voltage and current of two parallel connected inverter with voltage mode control is same as that of droop control is shown in below.

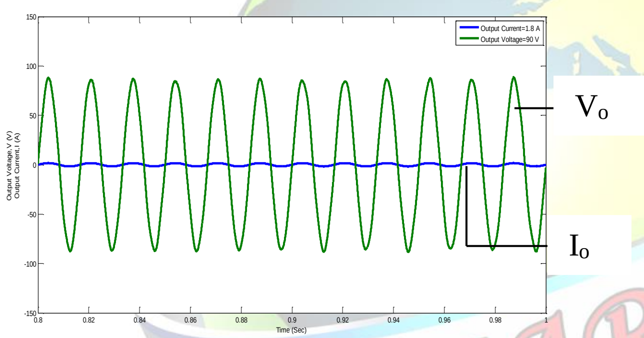


Fig.16. Output Voltage and Current waveform of two parallel connected inverter with Voltage mode contol

In droop control and in voltage mode control, if the voltages are different for both inverters, the output will be regulated according with reference voltage. And which can balance the current distribution among the parallel-connected inverters with no interconnected communication lines.

V. Conclusion

This paper described a method to effectively control inverters without any form of signal communication. It had developed a droop control scheme that meets the equal power sharing without control signal communication between parallel-connected inverters. A key feature of the control scheme is that it used feedback of only those variables that can be measured locally at the inverter and does not need communication of control signals between the inverters. This was essential for the operation of large ac systems, where distances between inverters make communication impractical. It was also important in high-reliability UPS systems where system operation can be maintained in the face of a communication breakdown. Real and reactive power sharing between inverters could be achieved by controlling two independent quantities-the power angle, and the fundamental inverter voltage magnitude**.** And also voltage mode control scheme was applied for the parallel connected inverters. Simulation results obtained with the control scheme were also presented.

References

1. Mukul C. Chandorkar, Deepakraj M.Divan, and Rambabu Adapa," *Control of Parallel Connected Inverters in Standalone ac Supply Systems*" IEEE Transactions On Industry Applications, Vol. 29, No. 1, January/February 1993.
2. Karel De Brabandere, Bruno Bolsens, Jeroen Van den Keybus,Achim Woyte, Johan Driesen, and Ronnie Belmans, "A Voltage and Frequency Droop Control Method for Parallel Inverters" IEEE Transactions on Power Electronics, Vol. 22, No. 4, July 2007
3. Soeren Baekhoej Kjaer, John K. Pedersen and Frede Blaabjerg*," A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules"* IEEE Transactions On Industry Applications, Vol. 41, No. 5, September/October 2005.
4. Uffe Borup, Frede Blaabjerg, and Prasad N. Enjeti*, "Sharing of Nonlinear Load in Parallel-Connected Three-Phase Converters"* IEEE Transactions On Industry Applications, Vol. 37, No. 6, November/December 2001.
5. Telles B. Lazzarin, Guilherme A. T. Bauer and Ivo Barbi, *"A Control Strategy for Parallel Operation of Single Phase Voltage Source Inverters "* IEEE Transactions On Industry Applications 2009.
6. Telles B. Lazzarin, Guilherme A. T. Bauer, and Ivo Barbi, *"A Control Strategy for Parallel Operation of Single-Phase Voltage Source Inverters: Analysis, Design and Experimental Results"* IEEE Transactions On Industrial Electronics, Vol. 60, No. 6, June 2013.
7. *Chunsheng Wu, Hua Liao, Zilong Yang, Yibo Wang, Honghua Xu "Voltage and Frequency Control of Inverters Connected in Parallel Forming a Micro-Grid"* International Conference on Power System Technology, 2010.
8. *M.A.A. Younis. A. Rahim and S. Mekhilef "* Distributed Generation With Parallel Connected Inverter" IEEE Transactions ICIEA 2009.
9. Shungang Xu, Jinping Wang, and Jianping Xu, *"A Current Decoupling Parallel Control Strategy of Single-Phase Inverter With Voltage and Current Dual Closed-Loop Feedback"* IEEE Transactions on Industrial Electronics, Vol. 60, No. 4, April 2013.

ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 2, Issue 4, April 2015

10. Zhilei Yao and Lan Xiao, *"Control of Single-Phase Grid-Connected Inverters With Nonlinear Loads"* IEEE Transactions on Industrial Electronics, VOL. 60, NO. 4, April 2013.

11. Telles B. Lazzarin, Guilherme A. T. Bauer, and Ivo Barbi*,"A Control Strategy for Parallel Operation of Single-Phase Voltage Source Inverters: Analysis, Design and Experimental Results"* , IEEE Transactions on Industrial Electronics, Vol. 60, No. 6, June 2013.

12. Shungang Xu, Jinping Wang, and Jianping Xu, *"A Current Decoupling Parallel Control Strategy of Single-Phase Inverter With Voltage and Current Dual Closed-Loop Feedback*" IEEE Transactions On Industrial Electronics, Vol. 60, No. 4, April 2013.

13. Rathnayake,T.S. ; RukshanK.T. ; Rupasinghe,R.A.T.J.K. ;Ruwanthika,R.M.M. ; Karunadasa,J.P. *"Design and simulation of single phase active current harmonic filter Circuit",* IEEE Transactions on Power and Computing Technologies, 2014.

14. Dasgupta, S. ; Sahoo, S.K. ; Panda, S.K. *"Single-Phase Inverter Control Techniques for Interfacing Renewable Energy Sources With Microgrid—Part I: Parallel-Connected Inverter Topology With Active and Reactive Power Flow Control Along With Grid Current Shaping"*, IEEE Transactions on Power Electronics,Volume:26,2011.

15. Xunwei Yu and Zhenhua Jiang *"Dynamic current limiting control of voltage source inverters"* IEEE Transactions on Electric Machines and Drives, May 2009.

16. Borrega, M. ; Marroyo, L. ; Gonzalez, R. ; Balda, J. ; Agorreta, J.L. *"Modeling and Control of a Master–Slave PV Inverter With N-Paralleled Inverters and Three-Phase Three-Limb Inductors*" IEEE Transactions on Power Electronics, Volume:28, Issue:6, 2013.

17. Piboonwattanakit, K. ; Khan-ngern, W. *"Design of the Two Parallel Inverter Modules by Circular Chain Control Technique"* IEEE Transactions on Power Electronics and Drive Systems, 2007.

18. Roslan, A.M. ; Ahmed, K.H. ; Finney, S.J. ; Williams,B.W. *"Improved Instantaneous Average Current-Sharing Control Scheme for Parallel-Connected Inverter Considering Line Impedance Impact in Microgrid Networks"* IEEE Transactions on Power Electronics, Volume:26, Issue:3, 2011.

19. Kai-Cheung Juang ; Chiang, S.J. ; *Xiao, W.M. "A grid-tied flyback-based PV inverter with BCM variable frequency voltage mode control"* IEEE Transaction on Intelligent Signal Processing and Communications Systems (ISPACS), 2012.