ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Special Issue 1, December 2013

Droop Control of Parallel Inverters with LCL Filter and Virtual Output Impedance

Anuroop.P.V[1], Prof.K.Radhakrishnan[2], A. Saravana Kumar[3]

M.Tech Student, Dept. of EEE, Mar Athanasius College Of Engineering, Kothamangalam, Kerala, India[1]

Professor, Dept. of EEE, Mar Athanasius College Of Engineering, Kothamangalam, Kerala, India[2]

CDAC, Thiruvananthapuram, India.[3]

Abstract: Because of the acute shortage of conventional energy resources, renewable energy harness is gaining attention. Voltage source inverter forms the interface to feed the power from the renewable source to utility. In order to increase the modularity of the system, the use of several parallel inverters of reduced rating is preferred. An effective control strategy to maintain the amplitude and frequency of output voltages of each inverter at the specified values is necessary to avoid circulating currents and to share load currents proportionally. This paper presents a simple and effective droop control strategy for two three phase inverters to operate in stand-alone manner.

Keywords:Active damping, droop control, virtual output impedance, circulating current, LCL filter

I. INTRODUCTION

Distributed generation means the production of power close to the point of consumption. IEA (International Energy Agency) defines distributed generation *as "Distributed generation is a generating plant serving a customer on-site, or providing support to a distribution network, and connected to the grid at distribution level voltages"*. Since the depletion of fossil fuel are rapid and demand for electrical power is ever increasing, the interconnection of distributed generation units (DGs) including wind turbines, photovoltaic (PV) etc., are gaining importance, as in [1]. Centralized power generation plants are inefficient due to significant amount of energy loss as heat to the environment.

Distributed generation has many advantages compared to the centralized generation, such as, high reliability, less pollution, high efficiency, and easy installation as explained in [2]. All the DGs are parallel connected to an ac common bus through inverters or ac-to-ac converters, the common bus is then connected to the utility/grid. In distributed generation several inverters are connected in parallel in order to increase the modularity and reliability of the system. The control strategy of these inverters should hold the voltage and frequency of the grid with in specified limits. The control strategy for the inverter units can be designed either with communication or without communication between the inverter units. When inverter units are at considerable distance, communication between the inverter units is not reliable.

This paper starts with a review of the different control strategies, followed by detailed description of control based on conventional droop control. A suitable LCL filter is designed with active damping to avoid resonance related stability problems. This paper explains the parallel operation of two 7-KVA inverters connected in parallel with conventional droop control.

II. REVIEW OF CONTROL STRATEGIES

The control techniques for parallel operation can be broadly classified in to two, with communication link and without communication link. All these are detailed in [3]-[5].

A. Control techniques with communication link

1) Concentrated control method

In concentrated control method an independent parallel control unit detects frequency and phase of main bus to generate synchronization pulses to each inverter. The PLL circuit is used to ensure synchronism of frequency and phase. Parallel control unit detects total load current I, divided by the number of operating inverters, n, as current reference to each inverter. When each parallel unit, controlled by a synchronization signal, has negligible deference in frequency and phase between each other, the current error of each unit is resulting from voltage amplitude difference.

2) Distributed control method

In distributed control the control action between the central controller and the local controllers is divided through a frequency partition. The central controller ensures proper following of a reference voltage. The signal to local units is only the low-frequency part of the drive signal. This can be transmitted through a communication link of limited bandwidth. But the failures in the data bus cause the whole system to shut down.

3) Combined control

Combined control method is a combination of average power control and droop control. Since the calculation of the average powers is required, its implementation is difficult and it has a slow dynamic response. There is a larger error in the distribution of power between the inverters than the previous techniques. Here also low band width communication signals are used.

4) Current distribution control

The current distribution controls are

a) Master slave control.
b) Auto master slave control.
c) Center limit control.
d) Circular chain control.
e) Instantaneous current control.

The master-slave and central mode control techniques are the popular current-sharing control methods, even though there isn't a true redundancy. A failure in the master or in the central unit will shut down the whole system. The master–slave control is similar to concentrated control. The difference is that only the master unit has enabled the PLL, which provides a constant sinusoidal output voltage synchronized in frequency and phase with the critical bus voltage. In the master slave control, one inverter is the master, and all others are slaves. The master inverter supplies a reference current to the slave inverters there by the output voltage regulation. A partial redundancy can be achieved by adding a separate current-controlled pwm inverter unit to generate the distributing current independent of the slave inverters.

In center limit control mode, all the modules should have the same configuration. For equal current sharing, each module tracks the average current. Good current distribution can be achieved with the help of a DSP-based control for the voltage and current controller and by tracking the average inductor current of the modules. In the circular chain control mode, the successive module tracks the current of the previous module to achieve an equal current distribution, and the first module tracks the last one to form a circular chain. The output voltage and current of each inverter can also be internally controlled to achieve a fast dynamic response.

B. Control techniques without communication link

To achieve good power sharing and wireless communication between inverters the most popular approach is voltage and frequency droop control for active and reactive power regulation. The conventional droop method is based on the principle that the phase and the amplitude of the inverter can be used to control active and reactive power flow. The new load sharing is determined by frequency and voltage droop characteristics.

III. DROOP CONTROL

Droop control is a decentralized control strategy for the inverters of the distributed generation, where the controller regulates the active power output according to the frequency deviation. Similarly it adjusts the reactive power output according to the voltage deviation.A typical transmission line with resistive and reactive impedances can be shown as in Fig.1. The power is flowing from point A to point B. The Phasor diagram can be drawn as in fig. 2.

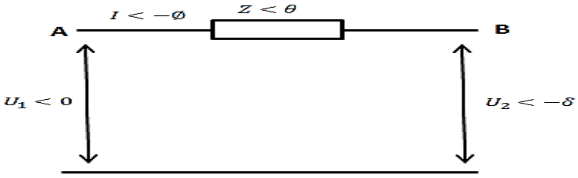


Fig.1. Power flow through a transmission line

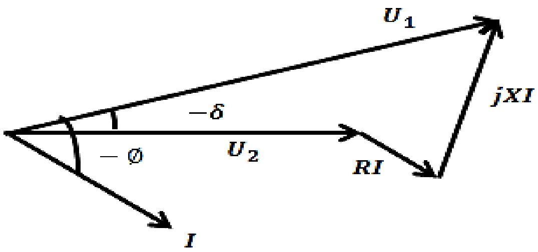


Fig.2. Phasor diagram.

The active and reactive power flowing in to a line can be calculated using the following expressions,
Active power, P, is

$$P = \frac{{U_1}^2}{Z} cos\theta - \frac{U_1U_2}{Z}\cos(\theta + \delta) \qquad (1)$$

Reactive power,Q, is

$$Q = \frac{{U_1}^2}{Z} sin\theta - \frac{U_1U_2}{Z}\sin(\theta + \delta) \qquad (2)$$

From $Ze^{j\Theta} = R + jX$, the above equations can be written as,

$$P = \frac{U_1}{R^2 + X^2}[R(U_1 - U_2cos\delta) + U_2Xsin\delta] \qquad (3)$$

$$Q = \frac{U_1}{R^2 + X^2}[-U_2Rsin\delta + X(U_1 - U_2cos\delta)] \qquad (4)$$

From (3) and (4) the following expressions can be mathematically derived as in [2].

$$U_2sin\delta = \frac{XP - RQ}{U_1} \qquad (5)$$

$$U_1 - U_2cos\delta = \frac{RP + XQ}{U_1} \qquad (6)$$

Where X and R are the transmission line inductive reactance and resistance respectively. For a long overhead transmission line X >> R. Therefore R can be neglected. If the power angle is small, then,
Sin $\delta = \delta$
Cos $\delta = 1$
Hence from (5) &(6)

$$\delta \cong \frac{XP}{U_1U_2} \qquad (7)$$

$$U_1 - U_2 \cong \frac{XQ}{U_1} \qquad (8)$$

For X >> R, small power angle δ and small voltage difference U_1-U_2, the power angle depends on P, while the voltage difference depends on Q. Hence the angle δ can be controlled by controlling P, and the inverter voltage U_1 is controllable through Q. Control of frequency dynamically controls the power angle and, hence, the real power flow. Thus, by the independent control of P and Q , frequency and amplitude of the grid are determined. This forms the basis for frequency and voltage droop regulation specified in [6]-[12]. The frequency and voltage droop equations can be written from Fig. 3 as follows,

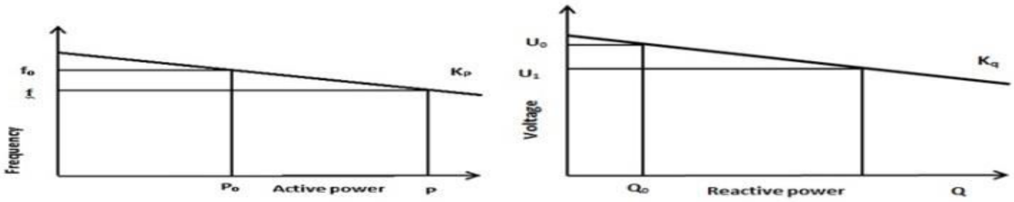


Fig.3. Frequency and voltage droop characteristics

The frequency and voltage droop equations can be written from Fig. 3 and Fig.4 as,

$$f - f_0 = -k_p(P - P_0) \qquad (9)$$

$$U_1 - U_0 = -k_q(Q - Q_0) \qquad (10)$$

Where f_0 and U_0 are nominal frequency and nominal grid voltage respectively, and P_0 and Q_0 are the setpoints for active and reactive power of the inverter. K_p and K_q are the droop coefficients. This is classic droop control approach that is applicable only to a long transmission line. When the load increases, a single inverter module can not meet the requirement. In such cases two or more inverters are to be connected in parallel. Inverter has a unique value of open circuit frequency and voltage. Therefore large circulating currents would result, if they were simply paralleled without additional control. This problem is solved by introducing an artificial droop in the inverter frequency and voltage. The droop characterics of two inverters with different rating is shown in fig. 4. To ensure proper load sharing, the droop coefficients for inverters with different ratingsare selected as follows:

$$KP_1.S_1. = KP_2. S_2 = ... = KP_n. S_n \qquad (11)$$

$$KQ_1 . S_1 = KQ_2. S_2 = ... = KQ_n. S_n \qquad (12)$$

Where S_1 , S_2 . . . S_n are the apparent power ratings of the inverters. The voltage and frequency droop characteristics for inverters with different ratings are shown in fig. 4.

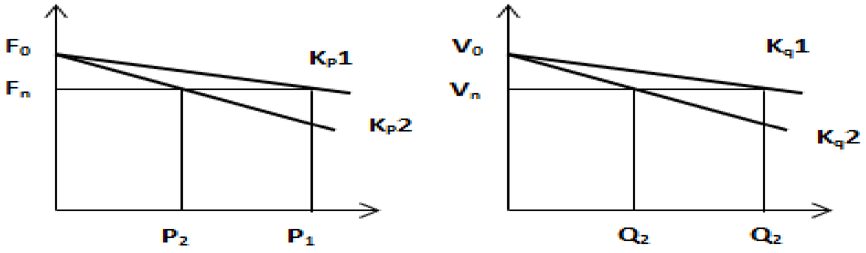


Fig.4. Droop characteristics of two inverters in parallel with different ratings

IV. SYSTEM MODELLING

The active power flows from the leading voltage side to the lagging voltage side and the reactive power flows from the higher voltage side to the lower voltage side. Hence, both active and reactive power can be controlled by controlling the phase and magnitude of the fundamental component of the converter voltage. When inverters are connected in parallel the output voltage and frequency of output should be equal. Otherwise there will be circulating current. Hence developing a control strategy is very important. A constant switching frequency control scheme is used in this paper, so that filter design is easy. The two control loops are outer voltage control loop and inner current control loop. The outer voltage control loop is assigned with a proportional controller and the current control loop is assigned with a PI controller. The internal loops are designed to achieve short settling times and fast harmonic tracking, whereas the outer loop for optimum regulation and stability. Obviously internal loop could be designed to be faster than the outer loop. The inverters are connected to the grid and load draws power from the grid. Inverters share the total load, according to their capacity. The current sharing is determined by the droop characteristics. Two inverters feeding a three phase load is shown in fig.5.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Special Issue 1, December 2013

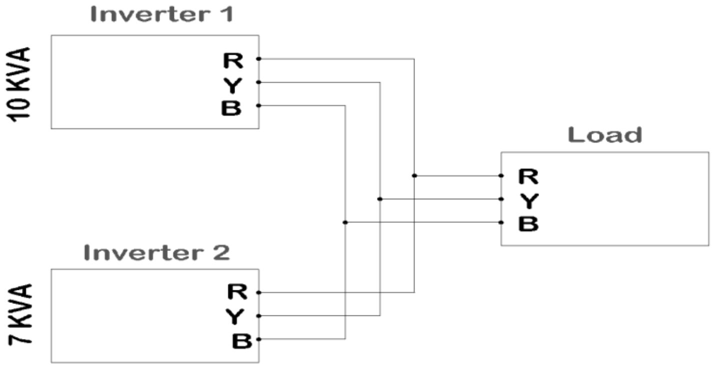


Fig.5. Inverters in parallel.

Each inverter has LCL filter at the output and it is shown in fig. 6.Overall control system for an inverter is shown in fig. 8. Inverter current, I_{inv}, the grid current, I_{grid}, and capacitor voltage V_{cap} are measured and it is used to control the firing pulse to the inverter bridge. Three-phase IGBT bridge converter is used as inverter. The DC input is derived from the photo voltaic panel with the help of a DC –DC converter. The DC input is assumed to be constant. Other parallel connected inverter will have the same configuration. In contrast to the conventional control strategies based on synchronous reference frame, a control strategy is analysed and developed in stationary reference frame using Clarke's transformation.

Here the active and reactive powers are calculated as,

$$P = V_\alpha I_\alpha + V_\beta I_\beta \qquad (13)$$

$$Q = V_\alpha I_\beta - V_\beta I_\alpha \qquad (14)$$

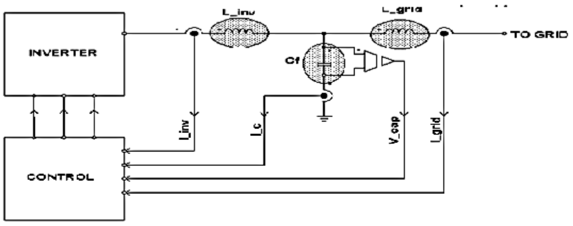


Fig.6. Single inverter with LCL filter and control.

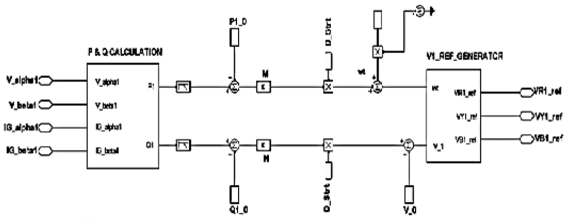


Fig.7. Droop implementation and voltage reference generation

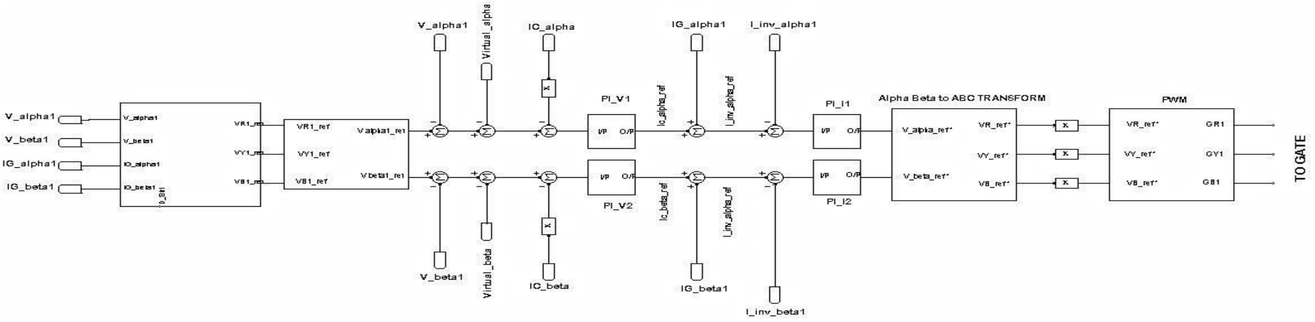


Fig.8.Control system

Droop logic is implemented using equations 13& 14. Reference voltage generation using the droop logic is shown in fig. 7. Overall control system is shown in fig. 9.

Droop Coefficients, K_{p1} and K_{q1}.

$$k_p = \frac{-\Delta\omega}{P_{max}} \tag{15}$$

$$k_q = \frac{\Delta V}{2Q_{max}} \tag{16}$$

The maximum variation in frequency is set as 5%.Therefore,

$$\Delta\omega = 2\pi \times f_0 \times 0.05$$

Where f_0 is the nominal frequency. For a 7 KVA inverter maximum active power is selected as, Pmax = 5500 W

The value of K_p can be obtained using equation (15).The maximum variation in output voltage ΔV is taken as 10% of nominal voltage. The nominal voltage is 240 V and maximum reactive power,
Qmax = 4330 VAR

The value of K_q can be obtained using equation (16). The value of the output filter inductance is related with the switching frequency in order to achieve a limited harmonic distortion at the input current or to limit the current ripple generated mainly due to the PWM switching of the inverter. The selection of the ripple current is a trade-off among inductor size, IGBT switching and conduction losses and inductor losses. The resonance frequency is selected in a range between 10 times the nominal frequency and one half of the switching frequency. Here the nominal frequency is 50 Hz and switching frequency is 10 KHz. The filter inductances and capacitance value can be calculated as follows.
Rated current,

$$I = \frac{KVA}{\sqrt{3} \times V_L} \tag{17}$$

Maximum ripple current, ΔI=10% of rated current (18)
The base impedance,

$$Z_b = \frac{{V_g}^2}{P} \tag{19}$$

Base capacitance,

$$C_b = \frac{1}{\omega Z_b} \tag{20}$$

To limit the capacitor power drawn, the capacitance is selected as 5% of base capacitance as in [13]. Using (19) and (20), the filter capacitance, C_f, is calculated. The inverter side inductance is selected as follows.

$$L_{inv} = \frac{V_{DC}}{8\sqrt{3}\Delta I \times F_{sw}} \tag{21}$$

The grid side inductance, L_g,

$$L_g = r.Li \tag{22}$$

Where 'r' is a factor, linking converter side inductance and grid side inductance.
Ripple attenuation factor, R,

$$R = \frac{1}{\left|1 + r\left[1 - L_{inv}C_f{\omega_{sw}}^2\right]\right|} \tag{23}$$

Consider a ripple attenuation factor of 5%. From (23), 'r' can be calculated and by substituting the value of 'r' in (22) the grid side inductance can be obtained by methods specified in [14]-[16].

The resonance frequency is,

$$F_{res} = \frac{1}{2\pi}\sqrt{\frac{L_g + L_{inv}}{L_g.L_{inv}.C_f}} \tag{24}$$

The resonance frequency should be between 10 times the nominal frequency and half of the switching frequency. This is between the specified limits. To eliminate the problems of instability caused by resonance, active damping is used. The damping resistance value is calculated as,

$$R_d \geq \frac{1}{3.C_f.\omega_{res}} \qquad (25)$$

The voltage control loop is assigned with a proportional controller. The time constant ‘τv’ of P controller is taken as 100µs. For the voltage controller, the proportional gain, ‘K_{pv}’ is,

$$K_{pv} = \frac{C_f}{\tau_v} (26)$$

For the current control loop a PI controller is assigned. The time constant for the current control loop is 100µs. For the current controller the proportional and integral gains are,

$$K_{Pi} = \frac{L_g + L_i}{\tau_i} \qquad (27)$$

$$K_{Ii} = \frac{R_g + R_I}{\tau_i} \qquad (28)$$

Where, R_g is the parasitic resistance of grid side inductor and Ri is the parasitic resistance of invertor side inductor. $R_g + R_i = 0.001\Omega$. Active damping is preferred rather than simple passive damping. Active damping coefficient K_D,

$$K_D = \frac{R_d(L_g + L_i)}{L_g} \qquad (29)$$

V. SIMULATION RESULTS

The system parameters selected for the calculation of the filter components of the inverter with LCL configuration, with an output rating of 10 KVA, is given in the Table 1. The output phase voltage is shown in Fig.9. The load current for 7 KW load is shown in fig.10. From Fig.11 and Fig.12 it is clear that the load current is shared equally between the two inverters. R-phase voltage and current is shown in Fig.13.The grid phase voltage obtained is sinusoidal with peak amplitude of 338V at 50 Hz frequency. Output voltage and current during a sudden load change at 0.02s is shown in Fig.14 and Fig.15 respectively.

Table.1.Simulation Parameters

Plant capacity	7 KVA +10 KVA
Maximum active power	5500 + 8000 W
Maximum reactive power	4330 + 6000 VAR
Nominal frequency	50Hz
Nominal output phase voltage	240V
Maximum Δω	5%
Maximum ΔV	10%
Switching frequency	10 KHz
L_{i1}	5.56 mH
L_{g1}	0.956 mH
C_{f1}	5.1 µF

L_{i2}	3.9 mH
L_{g2}	0.656 mH
C_{f2}	7.4 µF
R_d	4.223Ω
K_{D1}	28.2
K_{D2}	20.83
T_v	1 ms
T_i	100 µs
Load resistance	21.053Ω
$R_{VIRUTAL\ 1}$	3
$R_{VIRUTAL\ 2}$	2

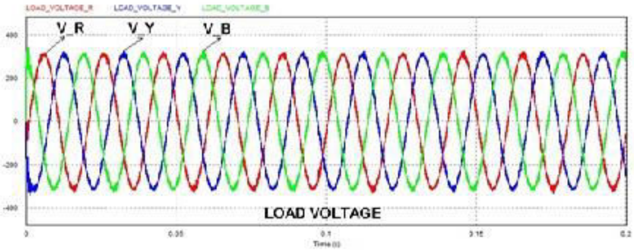


Fig.10.Output phase voltage

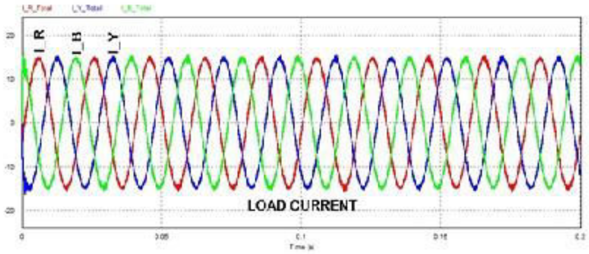
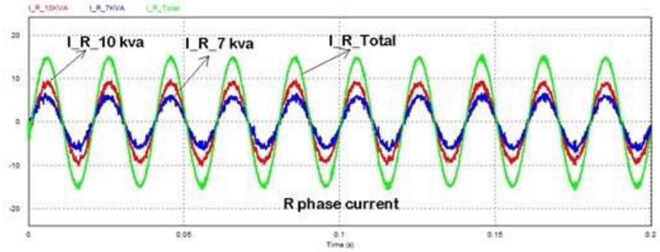


Fig.11.Load Current



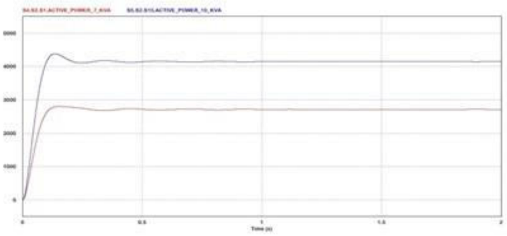


Fig.12. Inverteroutput currentand Load current(R-phase)**Fig.13.**Load Sharing

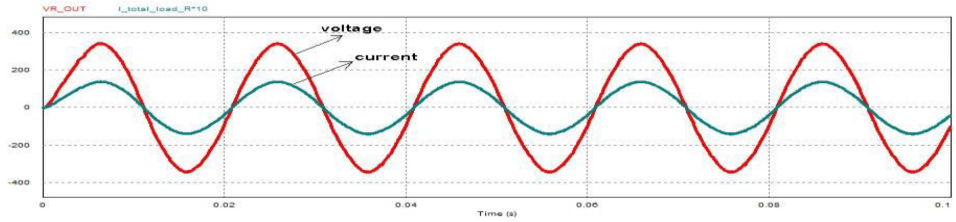


Fig.14.R-Phase Voltage and Curren

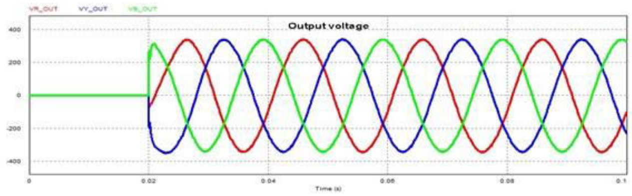


Fig.15. Phase voltage during transient.

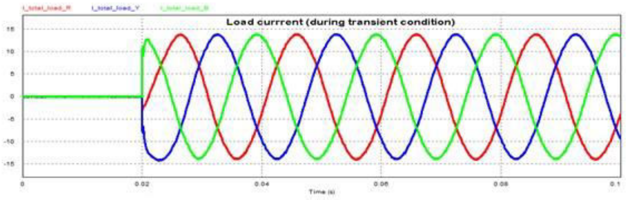


Fig.16. Load current during transient

VI. RESULT

Two different inverters are connected in parallel, based on the classic droop control logic, without any inter-connection between them. Control logic described here ensures proper current sharing between the parallel connected inverters. Steady state and transient properties of the system is studied. Simulation result shows that the system has good steady state and transient stability.

VII. CONCLUSION

The need of a control strategy which strictly holds the amplitude, phase and frequency of output voltages of inverters at the same values in order to avoid circulating currents through inverter modules and make them share load currents equally even during transients is studied and simulated in this work .This work describes the design and simulation of a control scheme for parallel connected inverters operating in island mode in a micro grid. Control logic for inverters assigned with a LCL filter at the output is presented here. The LCL filter attenuates the harmonics generated due to switching of IGBTs better than L or LC filter.

REFERENCES

[1] Josep M. Guerrero, Nestor Berbel, Jose Matas, Jorge L. Sosa' , and Luis Garcia de Vicufia, “Droop Control Method with Virtual Output Impedance for Parallel Operation of Uninterruptible Power Supply Systems in a Microgrid” IEEE Trans. on Neural Networks, vol. 4, pp. 570-578, July 1993.

[2] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen and R. Belmans, K.U.Leuven, “A Voltage and Frequency Droop Control Method for Parallel Inverters”. 2004 35th Annual IEEE Power Electronics Specialists Conference Aachen, Germany, 2004.

[3] YANG Xiu, ZONG Xiang, YANG Fei, ZANG Hai-yang, “A research on droop control strategy and simulation for the micro-grid”.

[4] DuanShanxu, Meng Yu, XiongJian, Kang Yong, Chen Jian, “Parallel Operation Control Technique of Voltage Source Inverters in UPS”, IEEE 1999 International Conference on Power Electronics and Drive Systems,July 1999.
[5] M. C. Chandorkar, D. M. Divan, and R. Adapa, “Control of parallel connected inverters in standalone ac supply systems,” IEEE Transactions on Industrial Applications, volume 29, no. 1, February 1993.
[6] Takao Kawabata, Shigenori Higashino, “Parallel operation of voltage source inverters,” IEEE Transactions on Industrial Applications., volume 24, no. 2, April 1988.
[7] JieFeng Hu, JianGuo Zhu, Glenn Platt, “A Droop Control Strategy of Parallel-Inverter-Based Microgrid”, Proceedings of 2011 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, Sydney, Australia, December, 2011.
[8] M. C. Chandorkar, D. M. Divan, Y. Hu, and B. Barnajee, “Novel architectures and control for distributed UPS systems,” in Proceedings IEEE APEC,1994
[9] Chien-Liang Chen, Jih-Sheng Lai, Yu-Bin Wang, Sung-Yeul Park, and Hide Miwa. “Design and control for lcl-based inverters with both grid-tie and standalone parallel operations”
[10] Samuel VasconcelosAraújo, Alfred Engler, Fernando Luiz Marcelo Antunes. “LCL Filter design for grid-connected NPC inverters in offshore wind turbines”. The 7th International Conference on Power Electronics October, 2007 EXCO Korea.
[11] UffeBorup, FredeBlaabjerg, and Prasad N. Enjeti, “Sharing of nonlinear load in parallel-connected three-phase converters”. IEEE Transactions on Industry Applications, December 2001.
[12] JiaYaoqin, Liu Dingkun, Pan Shengkui, “Improved Droop Control of Parallel Inverter System in Standalone Microgrid”. 8th International Conference on Power Electronics - ECCE Asia. June, 2011, TheShillaJeju, Korea.
[13] Chien-Liang Chen, Jih-Sheng Lai, Yu-Bin Wang, Sung-Yeul Park, and Hide Miwa. “Design and Control for LCL-Based Inverters with Both Grid-Tie and Standalone Parallel Operations”.
[14] Jiri Lettl, Jan Bauer, and Libor Linhart. “Comparison of Different Filter Types for Grid Connected Inverter”. PIERS Proceedings, Marrakesh, MOROCCO, March, 2011.
[15] T. Loix, K. De Brabandere, J. Driesen, R. Belmans. “A Three-Phase Voltage and Frequency Droop Control Scheme for Parallel Inverters”. The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON) November, 2007, Taipei, Taiwan
[16] GuzmánDíaz, Cristina González-Morán, , Javier Gómez-Aleixandre, ,and Alberto Diez, “Scheduling of droop coefficients for frequencyand voltage regulation in isolated microgrids”.IEEE Transactions On Power Systems, Volume 25, February 2010.