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Energy Procedia 117 (2017) 600–606

Energy Procedia

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1st International Conference on Power Engineering, Computing and Control, PECCON-2017, 2-4 March 2017, VIT University, Chennai Campus

Load sharing control of parallel operated single phase inverters

P.Monica[a]*, M.Kowsalya[b], P.C.Tejaswi[c]

[a]*Research scholar, School of Electrical engineering, VIT University, Vellore-632014, India*
[b]*Professor, School of Electrical engineering, VIT University, Vellore-632014, India*
[c]*M.Tech, School of Electrical engineering, VIT University, Vellore-632014, India*

Abstract

The parallel operation of inverter for distributed generation application that operates under different load conditions was investigated in this paper. A dual loop control in combination with conventional droop control was developed to control the module of inverter independently. The focus of the work is to attain proper load sharing among inverters through a simple yet efficient control strategy. The independent communication less control is achieved. Simulation is carried out in MATLAB/Simulink environment active and reactive power sharing of inverters were presented as simulation results.

Peer-review under responsibility of the scientific committee of the 1st International Conference on Power Engineering, Computing and CONtrol.

Keywords: Parallel Inverter; Distributed control; Droop control; Dual loop control;

1. Introduction

The growing energy crisis and the adverse effect of fossil fuel, necessitates the need for augmentation of power generation via renewable energy sources. The energy sources like solar-PV, wind turbine and fuel cells are largely used in a distributed network to meet the load demand which can be of either serving loads locally or injecting a clean power to utility grid/main grid. This can be termed as microgrid / minigrid [1]. The distributed energy sources are equipped with a power electronic interface like a DC/AC converter so as to integrate with the load, besides replacing a bulky and lossy transformers. The microgrid can be operated on grid and off conditions, termed as islanded and grid connected modes respectively [2]. Critical customer requirements such as increased power level at

* Corresponding author. Tel.: +91-8297721022.
E-mail address: monica.p2015@vit.ac.in

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10.1016/j.egypro.2017.05.156

the output, reliability, expandability can be attained through parallel operation of DG with its power electronic interface [3]. Different architectural patterns of microgrid were suggested in the literature [4]. The structure of microgrid that serves the load demand of commercial and residential customers forming a class of microgrid as "Utility microgrid". Since the structure does not dictate the size, scale and growth rate of microgrid, proves to be a prerogative factor in microgrid research. The enigma of phase difference at the output affects the power quality issues like load sharing capability, harmonics due to circulating currents, voltage regulation. Hence, a control strategy that pulls off the power quality issues effectively is needed.

Review of different control strategies were inoculated in the literature [5]. The centralized architecture of microgrid constitutes a control mechanism at remote centre and are destined to serve concentrated loads. The aspects of resilience and reliability are in stake, during fault conditions [6]. The Hierarchical control architecture of microgrid put forth the scope of control and communication bandwidth between different layers of control as challenge [7]. The decentralized control architecture of microgrid, the DG could follow a prerogative approach in critical load management without communication pertaining to the capability of DGs [8]. The decentralized control supports the top notched qualities of microgrid like autonomy, compatibility, stability, flexibility, scalability, economics and peer to peer model in terms of control and operation.

In decentralized control, the droop control mechanism proved to be prolific and efficient in terms of independent control and power sharing in parallel inverter [9]. Eventually the droop concept arose the behaviour of synchronous generator whose frequency varies with load demand [10]. Now a days, augmentation of uneven loads poses problems of power quality, especially in balancing the active and reactive power among the inverter units [11]. A Virtual impedance or resistive loop which shares the harmonic current dynamically was proposed in [12]. The control of parallel units based on critical computation of the harmonic currents using algorithm was proposed in [13] whose system stability is at stake. Based on the core theory of conventional droop strategy, modified droop strategy evolved with auxiliary loops being added and constraints of the droop included to tackle dynamic load problem [14-17]. A universal droop controller was designed irrespective of the variation in output impedance with the use of absolute quantity as a feedback [18]. The bounded characteristics of droop in combination with zero gain property was proposed in [19]. Nevertheless all the control techniques requires complex computation of harmonic currents and addition of loops, with inherent trade-off between the voltage regulation and stability. Although conventional droop based control of parallel units inherits regulation and stability problem, the same with uneven loads was seldom addressed in the literature either without any auxiliary loops added to the control structure or with simple computations and control loop.

The paper seeks to provide a simple dual loop feedback control strategy based on the conventional droop reference for parallel inverter. The advantages of the proposed technique can be summarized as: Accurate load sharing with simple control logic, low THD with reduced impact of circulating current, simple design of tie line for parallel operation. Since the focus is on inverter stage control, the simulation is carried out on single phase inverter with the combination of droop and PI controller. The active and reactive power sharing under equal and unequal load were establishes as results. The Paper is organized as follows: Section 2 provides the system overview .Section 3 gives the control design of the system's Individual module. The simulation results were presented in the section 4.

2. System overview

The structure of parallel inverter in the islanded microgrid is shown in Fig 1[20]. The model assumes micro sources whose equivalent output is a constant dc source fed to a power electronic interface like an inverter. The inverters feeding independent load are connected in parallel with a tie line inductor.

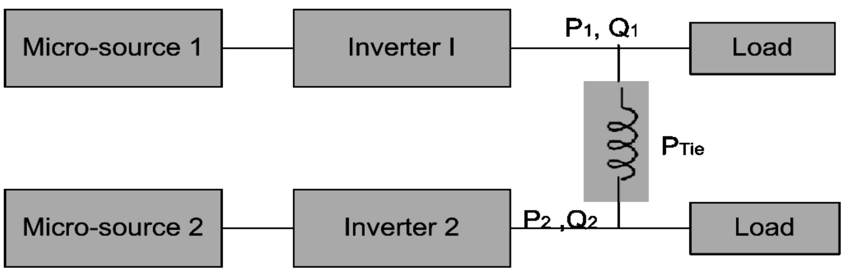

Fig 1. System of parallel Inverter feeding independent load [20]

The standard single phase H- bridge inverter with L_f, R_f that provide a self-supporting filtering is considered. The complete setup is connected in parallel to analyse the load sharing with both equal and unequal load conditions for microgrid application. The Load sharing analysis is carried out by efficient control strategy that involves three stages i) Reference generation ii) Dual loop feedback control for individual module of inverter ii) Tie line design for parallel connection.

3. Control design

3.1. Reference generation

The voltage source inverter which is relatively a stiff source, experiences large circulating current when they are connected in parallel. This affects the real and reactive regulation in the system causing a drop in voltage and frequency. Droop control strategy that mimics the behaviour of synchronous generator to regulate the voltage and frequency. This technique is carried out by predetermining the droop coefficients m, n from the drooping characteristics of voltage and frequency with respect to real and reactive power [9]. The Fig 2a and Fig 2b represents the droop control block and droop characteristics. The equations governing the droop control is given as

$$f^* = f - mP \tag{1}$$

$$V^* = V - nQ \tag{2}$$

Although the conventional droop control has a trade-off between voltage regulation and stability, combined control of droop and the PI mechanism implemented in the closed loop feedback exhibits better response and has the improves stability.

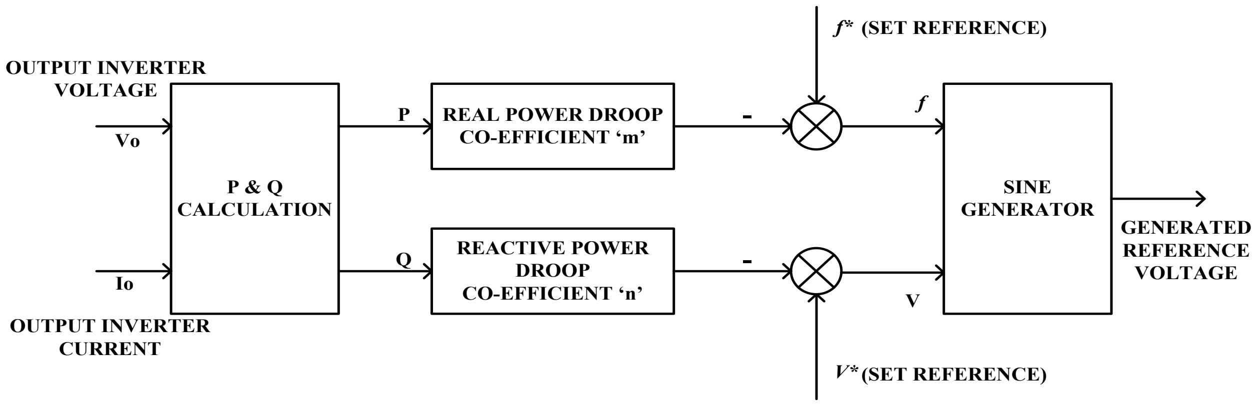

Fig 2.a. Conventional droop control [3]

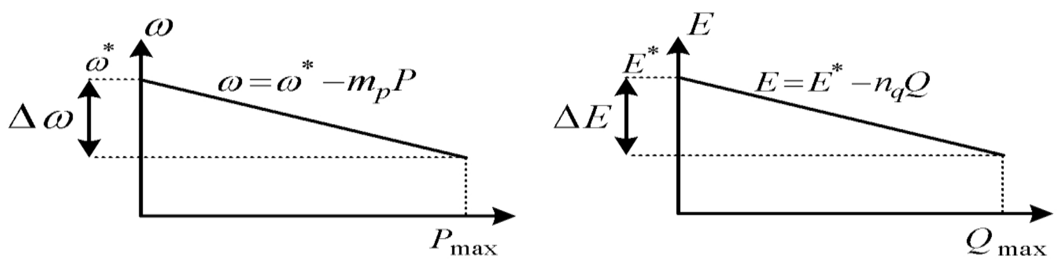

Fig 2.b. Droop characteristics [3]

3.2. Proposed Dual Loop Control

The Control design was based on instantaneous feedback of current and voltage of the filter components [21]. Transfer function approach was followed for the design of compensation with a PI controller for outer and inner loops. The outer voltage loop regulates the fundamental frequency component of output voltage at an expense of stability of the system. A most probable effective solution is to design an inner current compensation loop that provides a feedback of the filter inductor current. The inner current feedback of inductor current helps for compensation against the harmonics and stabilizing the system. The Fig 3 shows the dual loop control block diagram of an individual inverter.

3.2.1. Inner current control

The Design of inner current control loop aims at improving the response by synthesizing the sinusoidal component of capacitor current fed back for error processing. The compensating constraints are modeled based on change in capacitor current.

The transfer function of the current control is derived from control block as

$$\frac{i_0}{i_{ref}} = \frac{G_i\, K_{pwm}}{(sL+r)(sCR+1)+R+G_i.K_{pwm}\ R^2} \tag{3}$$

Where G_i is the compensation with PI controller whose transfer function is $G_i = K_p + \frac{K_i}{s}$

3.2.2. Outer Voltage Loop

The voltage regulation is carried out by dual feedback of output voltage at the capacitor that tends to improve the stability of the system by stabilizing the capacitor voltage and by processing the voltage deviation comparable at the voltage reference generated through droop control. The error voltage is being processed by a PI controller whose compensator gain is G_v.

The transfer function of the output voltage with the inner loops being processed is derived as

$$\frac{\hat{V}_0}{\hat{V}_{ref}} = \frac{K_p\, L_l C_f V_{dc} S^3 + (C_f\ R_L K_p V_{dc} + K_i V_{dc} L_l C_f) S^2 + K_i C_f R_l S}{L_f C_f L_l S^4 + (R_l L_f C_f + K_p L_l C_f V_{dc}) S^3 + (L_f + C_f R_l K_p V_{dc} + K_i\ V_{dc} L_l C_f) + (1 + K_i C_f R_l) S} \tag{4}$$

The inner voltage feedback loop of output voltage to the filter inductance improves the fast transient response of the system.

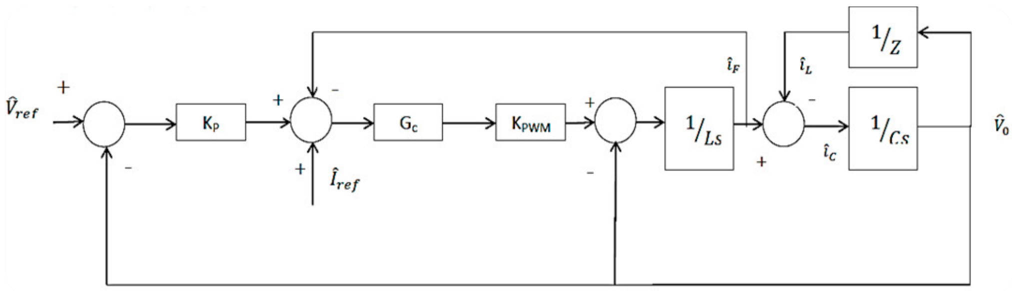

Fig 3. Dual loop control diagram of single inverter

3.3. Tie line design for parallel operation of inverters

The Inverters parallel operation needs an optimal tie line design for the synchronization of phase angle. The Power control through tie line equation [20] helps accurate power sharing independent of the output impedance in unequal inverter rating. The power difference due to unequal rating of inverter is neutralized by the power exchange through the tie line design. This helps for the frequency restoration by shifting the droop slope line to the predefined slope line of inverter.

$$P_{inv1} = P_{inv2} + P_{tie} \tag{5}$$

P and q are the active and reactive power v_1 and v_2 are the voltages at inverter end.

$$p = \frac{v_1 * v_2 * sin\delta}{X} \tag{6}$$

$$q = \frac{v_1 * (v_1 - v_2 cos\delta)}{X} \tag{7}$$

Where p and q are the active and reactive power v_1 and v_2 are the voltages at inverter end and δ is the angle between the voltages.

$$\frac{p}{q} = \frac{v_2 * sin\delta}{v_1 - v_2 cos\delta} \quad (8)$$

The ratio of $^p/_q$ should be constant. For inverter $v_1 = v_2$ and $\frac{d}{d\delta}\left(\frac{p}{q}\right) = 0$where $P_{tie}$is Constant.

$$\frac{d}{d\delta}\left(\frac{p}{q}\right) = \frac{d}{d\delta}\left(\frac{v_2 * sin\delta}{v_1 - v_2 cos\delta}\right) \quad (9)$$

The equation provides the δ in which the tie has needs to be designed.

4) Simulation results and discussion

The simulation is carried out in Matlab environment whose parameters are shown in table below.

Table 1. Simulation parameters

Simulation Parameters	
L_{f1}, L_{f2}	$700\mu H$
C_{f1}, C_{f2}	$20\mu F$
n	2.84
m	0.02
Switching frequency	15*KHz*
$frequency$	60*Hz*
Load impedances,	*12+j0.3768 ohms, 12 ohms*
Tie-line	*1.7mH*
Current Loop	K_p*=0.2,* K_i*=10*
Voltage Loop	K_p*=500*
Output Voltage V_0	*84 V r.m.s Volts*

4.1 Individual Inverter

The system with controller has 0.06% of voltage THD and 0.08% 0f current THD. The system produces negligible distortion with linear load. The voltage and current wave form is shown as in Fig 4. for resistive Load and inductive load.

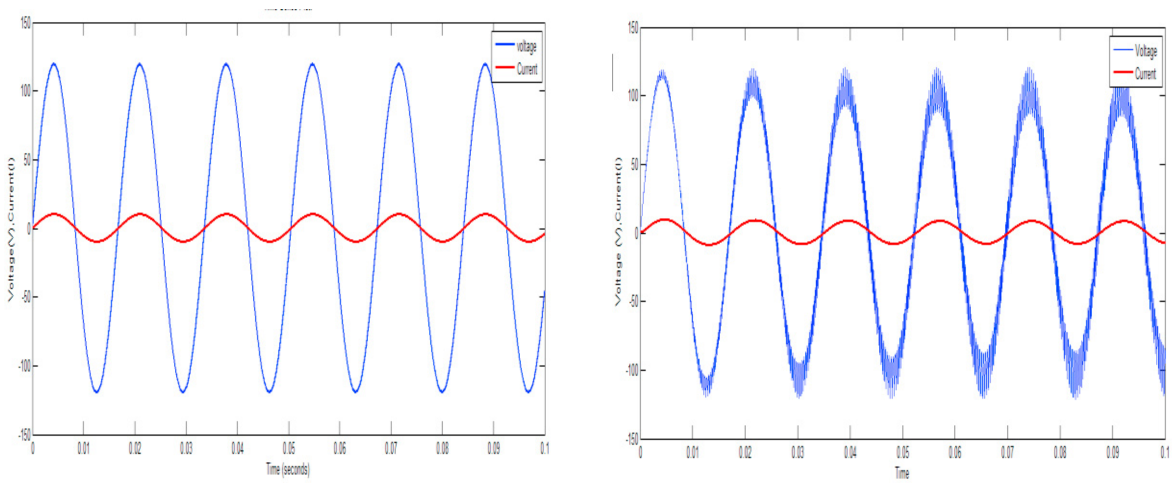

Fig 4. Voltage and Current waveform for Resistive and inductive load

4.2. Parallel operated inverters

4.2.1. Power sharing under even Load conditions

When the inverters operate under even load condition with an impedance of 12+j0.3768, and inductance of L=1mh. Simulation results of the active and reactive power sharing in the inverters with an independent control of each module are as follows:

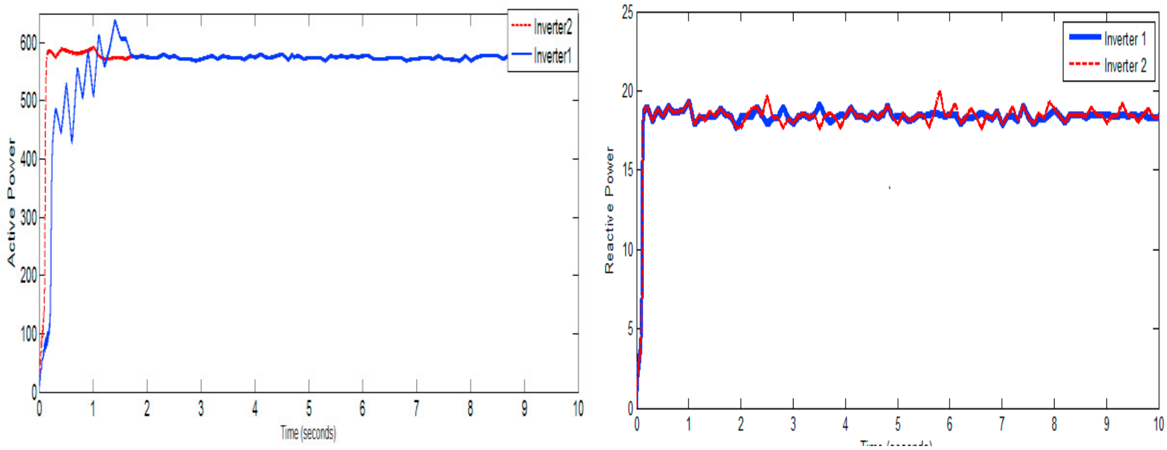

Fig.5. Active and reactive power under even load condition

4.2.2. Power sharing under uneven load conditions

Under uneven load condition load conditions, the inverter 1 is loaded with R- load of 12 ohms and inverter 2 is loaded with RL load of 12+j0.3768. The tie line design of 1.7 mh holds good and facilitates for power sharing in parallel operated inverters. The inverters share power in proportion with the tie line design. The simulation results are as follows:

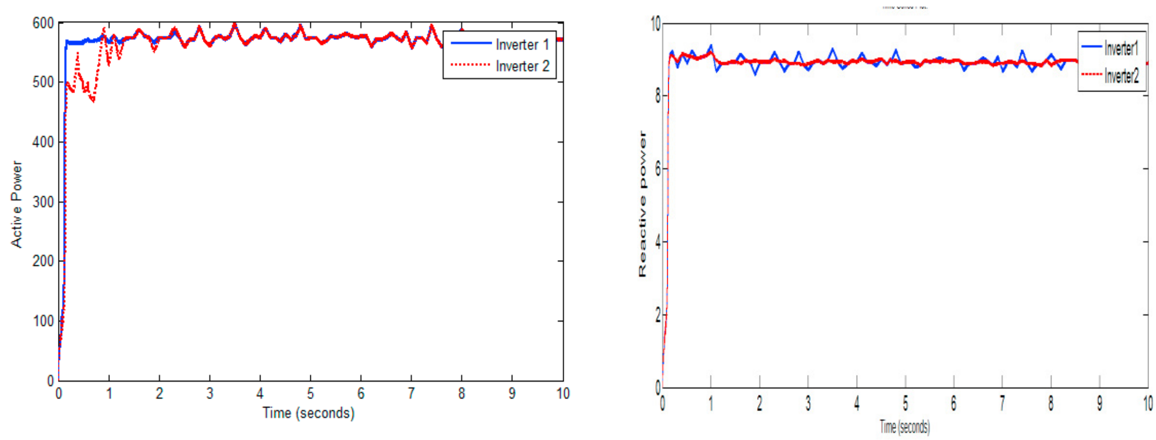

Fig.6. Active and reactive power under uneven load condition

Although the tie line inductor in parallel connection constitutes for power loss in the system, the simple parallel connection helps for active power sharing effectively provided the control loop design is appropriate.

Conclusion

The parallel inverter stage control in a distributed environment was investigated in this paper with even and uneven loading conditions. The system bears the privilege of simpler control and compensation with a combination of droop and dual loop control. The simple tie line design proved to be prolific in parallel operation. Load sharing of inverters was in proportion to their rating irrespective of tie line inductor design, which tends to reduce the impact of circulating current during parallel operation. The simulation results shows that the control strategy performs well for similar rating of inverter. The system befits for low voltage application in the distributed environment of microgrid that gained huge popularity.

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