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Research Article

New Approach for Modeling of Robust Droop Control for Equal Load Sharing between Parallel Operated Inverters

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ABSTRACT

This paper proposes a new approach for robust droop control with the objective of equivalent power sharing between parallel inverters in islanded microgrid as well as stability, using close loop voltage and current controller. The past droop controller uses conventional (PI) close loop voltage and current controller. The approach for proposed controller is it uses PR controller for close loop voltage and current control in modeling of robust droop control. The simulated results shows improve stability of frequency reference by limiting the frequency error, improved voltage quality and also exhibit equal power sharing between two parallel inverter considering different output impedence.

Keywords: Microgrid, Robust Droop Control, Controller

Introduction

These days, increasingly Distributed Generation (DG) and renewable energy assets, e.g., wind, sun and tidal strength, are connected to the public grid through electricity inverters. They often form microgrids before being related to the general public grid.[1–4] Because of the availability of high current power electronic devices, it is inevitable that many inverters area unit required to be operated in parallel for dynamic and/or affordable applications. One more reason is that parallel-operated inverters offer system redundancy and high dependableness required by essential customers. A natural drawback for parallel-operated inverters is a way to share the load among them. A key technique is to use the droop management,[5–13] that is wide employed in standard power generation systems.[14] The advantage is that no external communication mechanism is required among the inverters,[10,15] This allows sensible sharing for linear and/or nonlinear masses,[10,16–20] In some cases, external communication means that area unit still adopted for load sharing[21] and restoring the microgrid voltage and frequency.[3,9]

Alternatively, microgrid management in associate islanded mode is complex than grid connected mode. The voltage and frequency of the microgrid are supported by the first grid if it is among the grid connected mode. On the other way, the voltage and frequency management and even electricity management is done by microgrid in islanded mode. The incidence of power mismatch among the DG units, unbalanced load voltages and frequency deviations results into existence of circulating current. Therefore, this is utmost requirement of an efficient controller to manage voltage and frequency balance. The controller also provides acceptable strength sharing amongst DG units in islanded mode operation.[22]

The essential objective of an islanded mode is to stay up precise power sharing among numerous DG. Whenever the operation of microgrid shifted to island mode, potential difference, E and frequency, ω are thought-about to be maintained with many inverters operating in parallel and sharing the load. These inverters act to control the voltage, amplitude and frequency and having completely different mode of operation like alternative converter.[23] The controller also provides the specified current required. However, the problem of power quality.[24] that contributed by the existence of transient circulating current in line electric resistance[25] can result in the system instability, so will harmful for the inverters[26] because of twin of the output voltage. In an islanded microgrid, loads should be properly shared by multiple DG units. Generally, the management techniques for operation of inverters in islanded microgrid operation will be split into 2 categories; droop management techniques[27,28] and active load sharing techniques.[29,30] For improving the accuracy of sharing of linear and nonlinear loads, it was mentioned in[32,33] that the output impedance of inverters play very important role in power sharing. The droop control has different forms for different types of output impedance.[32,34,35] The Q-V and P-ω droop is used when the output impedance is inductive; the Q-ω and P-V droop is used when the output impedance is resistive; P-ω and Q-V droop is used when the output impedance is capacitive.

This paper aims to expand the strategy of robust droop controlled which[31] deals with conventional PI control for voltage and current loop, for LV network based microgrid. It will retain the frequency reference of 50Hz in parallel-connected inverters considering RL line electric resistance. The modeling of robust droop controller proposed is further developed so that it can be applied to inverters with capacitive and resistive output impedance to achieve accurate sharing of both real and reactive power. The simulation studies are performed to verify and analyze the potential of the proposed controller against the conventional robust droop controller.

Droop Control Theory

In Microgrid, the system reliability and stability is achieved only by the voltage regulation when more microsources are interconnected. This voltage regulation damps the reactive power oscillations and voltage.

In a complex power system, when multiple DGs are connected to the microgrid, the power sharing among them is made properly with the help of a control strategy called droop control. Droop control also enables the system to disconnect smoothly and reconnect routinely to the complex power system.

The role of droop control in power sharing is that it control the real power on the basis of frequency droop control and it controls the reactive power on the basis of voltage control. The voltage and frequency can be manipulated by regulating the real and reactive power of the system.

The basic conventional droop control equation can be given by

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{1}$$

$$Q = \frac{V_1^2}{X} - \frac{V_1 V_2}{X} \cos\delta \tag{2}$$

For above equations, resistance (R) is neglected for an overhead transmission lines as it is much lower than inductance (L). Also the power angle δ is lesser, therefore sin δ = δ and cos δ = 1.

$$\delta = \frac{XP}{V_1 V_2} \tag{3}$$

$$V_1 - V_2 \cong \frac{XQ}{V_1} \tag{4}$$

Hence from above equations (3&4), it is clear that the power angle δ can be controlled by regulating real power P. Also the voltage V_1 can be controlled through reactive power Q. Dynamically, the frequency control leads to regulate the power angle and this in turn controls the real power flow. Finally, the frequency and voltage amplitude of the microgrid are manipulated by adjusting the real and reactive power autonomously. As a result, the frequency and voltage droop regulation can be determined as:

The relationship between real power frequency and reactive power voltage can be given as:-

$$f = f_o + k_p(P + P_o) \tag{5}$$

$$V = V_o + k_q(Q - Q_o) \tag{6}$$

For equal load sharing, the conventional droop controller equations are

$$V_i = V^* - n_i P_i \tag{7}$$

$$\omega_i = \omega^* + m_i Q_i \tag{8}$$

Where

f, V= The frequency and voltage at a new operating point

P, Q= Active and reactive power at a new operating point

f_o , V_o = Base frequency and voltage;

P_o ,Q_o = Temporary set points for the real and reactive power;

k_p ,k_q = Droop Constant.

ω^*= rated frequency.

Active and Reactive Power Theory in Low Voltage Microgrid

In LV microgrid, where R>>X, Power dispatch equations is given by:-

$$P = \frac{V_1}{R^2 + X^2}\left[R * (V_1 - V_2 * \cos\delta) + X * V_2 \sin\delta\right] \tag{9}$$

$$Q = \frac{V_1}{R^2 + X^2}\left[- R * V_2 \sin\delta + X * (V_1 - V_2 * \cos\delta\right] \tag{10}$$

In case of Low Voltage (LV) distribution line, R>>X, so in LV network where R>>X, equations 7 & 8 are reduced to 9 & 10 and is given by:-

$$P \cong \frac{V_1^2}{R} - \frac{V_1 * V_2}{R} \qquad (11)$$

$$Q \cong -\frac{V_1 * V_2}{R}\delta \qquad (12)$$

In LV microgrid, where R>>X with small power angle δ and small voltage difference V_1-V_2,the active power P depends mainly on voltage difference V_1-V_2, while the power angle δ and frequency depends mainly on reactive power Q. Thus the traditional frequency droop control through active power and voltage droop control through reactive power, used in HV levels is not functioning very well on LV network based microgrid. As a result, the voltage control would be implemented through active power and frequency control through reactive power production/ consumption in a converter and LV network based microgrid (V_1-V_2=IR).

So, f ≈ Q

V ≈ P

Modelling of Single Phase Full Bridge Inverter and Parallel Connected Inverters

Single Phase Inverter

The single-phase inverter is an electronic circuit that enables a voltage to be applied across a load in either direction. It can be simplified justified with a switching scheme of full-bridge converter. Typically, it consists of a DC power source and a bridge-type inverter with *LCL* filter as shown in Figure 1. The inverter is a device which converts a DC input supply voltage into symmetrical AC voltage based on the modulation signal from the PWM modulation.

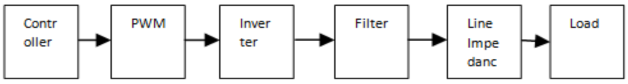

Figure 1.Block diagram of a single-phase Inverter

Parallel Connected Inverters

Two parallel-connected inverters are used to fill in the microgrid configuration as depicted in Figure 2. The model of parallel-connected inverters is a necessary to apply droop method in the system. A PR controller to improve voltage and current loop is used with the voltage/ current feedback loop[29] to regulate the output voltage. In order to ensure in-phase similarity of the output voltage of each inverter, the same voltage reference is used, $V\llcorner 0^0$. The PR controller is used to feedback values of output voltage and current from the inverter, thus, generate a proper controlled signal before transmitted to PWM. Then, PWM used to put through the switching process and pass a practical condition of the microgrid. The active and reactive power of each inverter is obtained based on the voltage and current measurement after filtering, later will be fed to the robust droop controller and then PR controller block to produce new value of reference voltage, V_{ref} and angular frequency, ω_i which will be led to proportional power sharing.

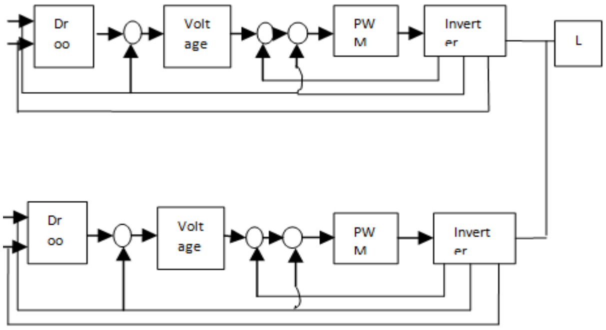

Figure 2.Parallel-connected inverters in microgrid configuration

Robust Droop Controller Modelling

From equation (7),it can be re-written as,

$$\Delta V_i = V_i - V^* = -n_i P_i \qquad (13)$$

And the voltage V_i can be implemented via integrating ΔV_i ,i.e

$$V_i = \int_0^t \Delta V_i dt \qquad (14)$$

This works for the grid connected mode where ΔVi is eventually zero (so that the desired power is sent to the grid without error), as proposed in.[32-34] However, it does not work for the stand alone mode because the actual power Pi is determined by the load and Ei cannot be zero. This is why different controllers had to be used for the standalone mode and the grid-connected mode, respectively. When the operation mode changes, controller also needs to be changed. It would be advantageous if the change of controller could be avoided when the operation mode changes. Also, the load voltage V_0 drops when the load increases. The voltage also drops due to the droop control, according to equation 4. The smaller the coefficient n_i the smaller the voltage drop. However, the coefficient n_i requires drop V* – Vo and needs to be fed back in a certain way to obtain a fast response. In order to make sure that the voltage remains within a certain required range, the load voltage to the basic principles of control theory. It can be added to via an amplifier Ke. This actually results in an improved droop controller shown in Figure. 3. This strategy is able to eliminate (at least considerably reduce) the impact of computational errors, noises and disturbances. As to be explained below, it is also able to maintain accurate proportional load sharing and hence robust with respect to parameter drifts, component mismatches and disturbances.

Proposed Modeling of Robust Droop Controller

In this paper two parallel connected inverters are used for microgrid operation. For applying droop control method, model of parallel connected inverter is necessary. In conventional PI control system, the voltage feedback loop is used to regulate the output voltage. Therefore, it is logical to used PR controller in place of PI controller due to better work in terms of good dynamic response, less steady-state error, and its capability in compressing steady-state deviation of frequency and amplitude PR controller gain the feedback values of output voltage and current from the inverter. Thus, generate a proper controlled signal before transmitted to unipolar pwm generator. Then, unipolar pwm used to put through the switching process and pass a practical condition of the microgrid. The active and reactive power of each inverter is obtained based on the voltage and current measured value after filtering, later will be fed to the robust droop controller in line with PR controller to produce new value of reference voltage, which eventually led to proportional power sharing.

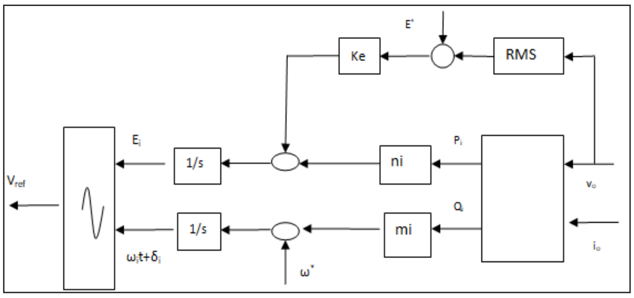

Figure 3.Robust Droop Controller

Result and Discussion

The above strategy has been verified in MATLAB simulink version 2013, which consists of two single-phase inverters powered by separate 400 V dc voltage source. The outer loop controller is actually the robust droop controller for C- Inverter and R-Inverter to achieve 1:1 power sharing. The switching frequency was 10 KHz and the frequency of the system was 50 Hz. The rated voltage is 230V. The filter inductor is L= 4.06 mH with a parasitic resistance of 0.001Ω and the filter capacitance is 6.23 μF, with R load and RL load. In RL load value of resistance and inductor introduce in load in series with R at time t=0.08 sec and removed at time t=0.15 sec. Different parameters values are shown in Table 1.

Table 1.Parameter list

Description	Value
Filter Inductance	4.06e-3 H
Filter Capacitance	6.23e-6 F
Rated frequency	50 Hz
Number of parallel connected Inverter (n)	2
Amplifier (K_e)	10
DC link voltage (V_{DC})	400 V
Value of load Impedance (Z_L)	(R+RL) 20+ 20 +5e-3

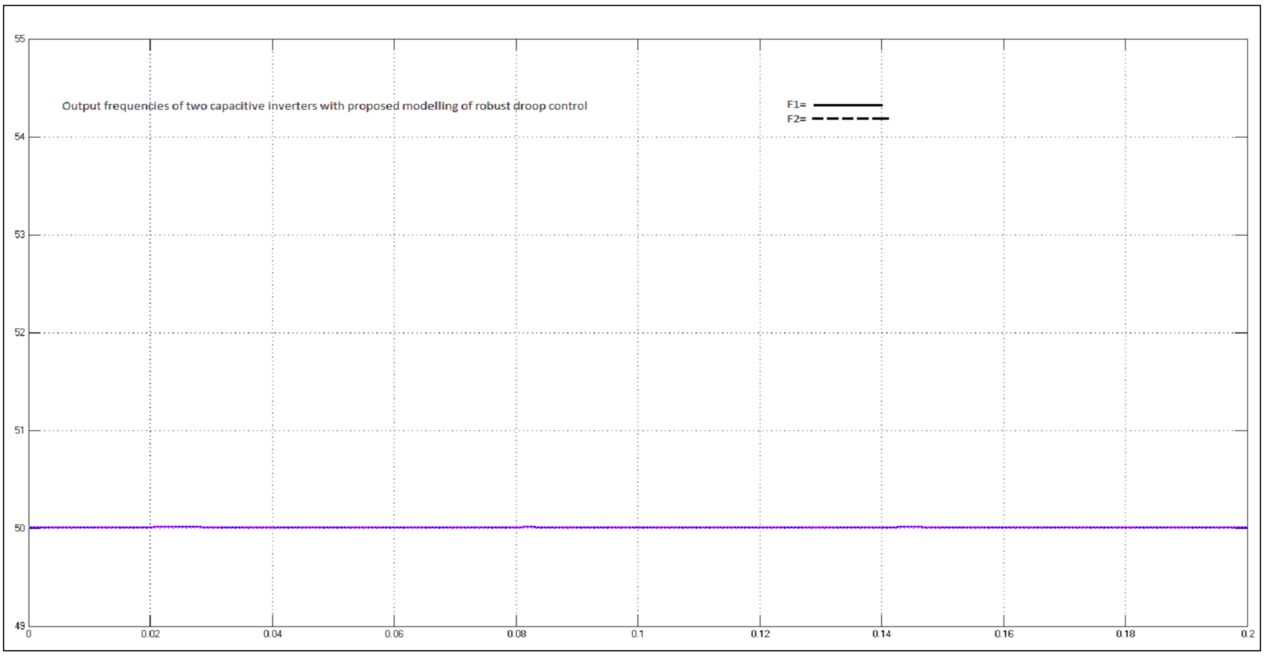

Figure 4(a).Output frequencies of two capacitive inverters with proposed modeling of robust droop control for R load

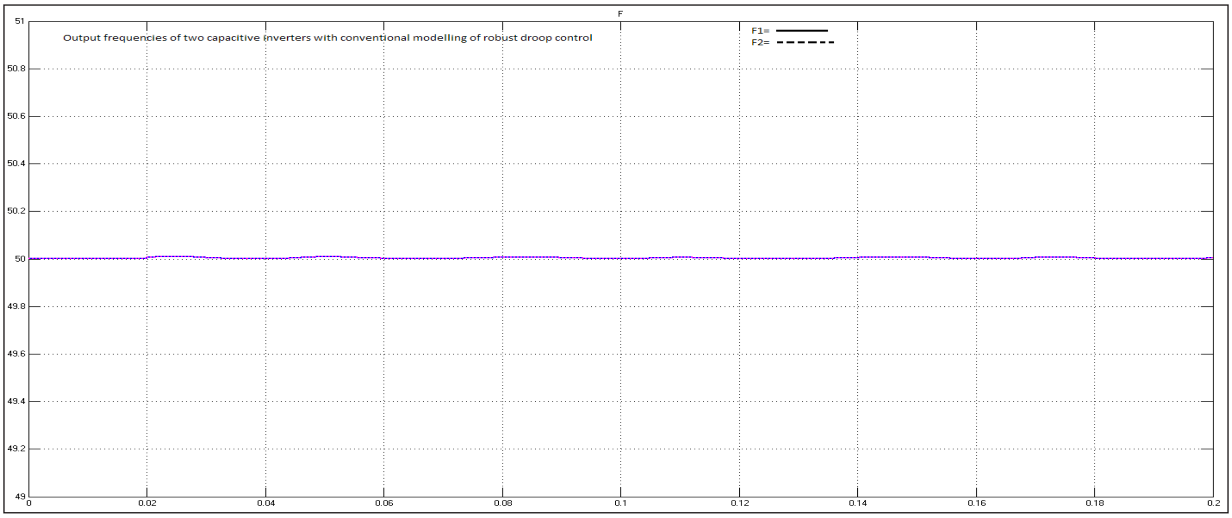

Figure 4(b).Output frequencies of two capacitive inverters with conventional modeling of robust droop control for R load

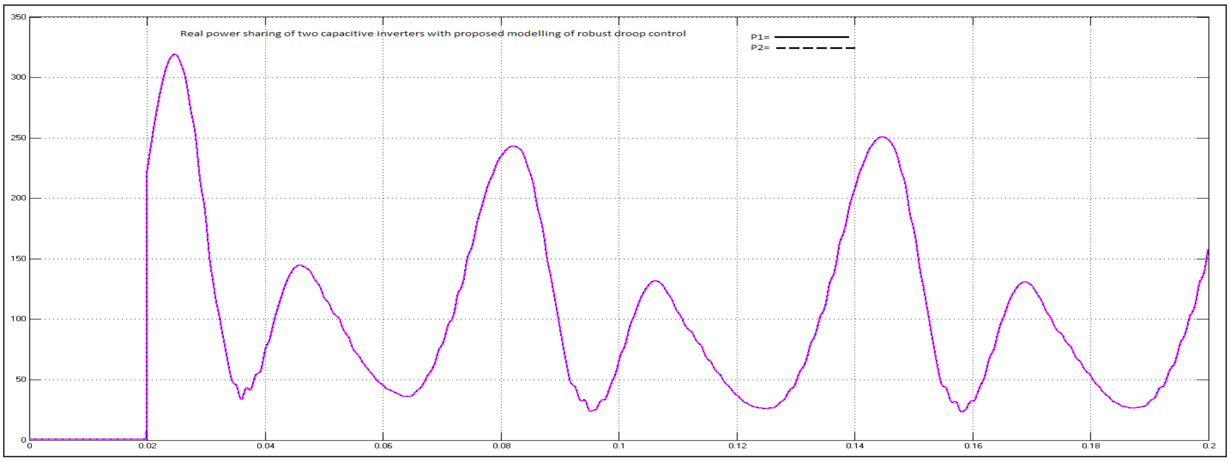

Figure 5(a).Real Power sharing of two capacitive Inverter with proposed modeling of robust droop control for R load

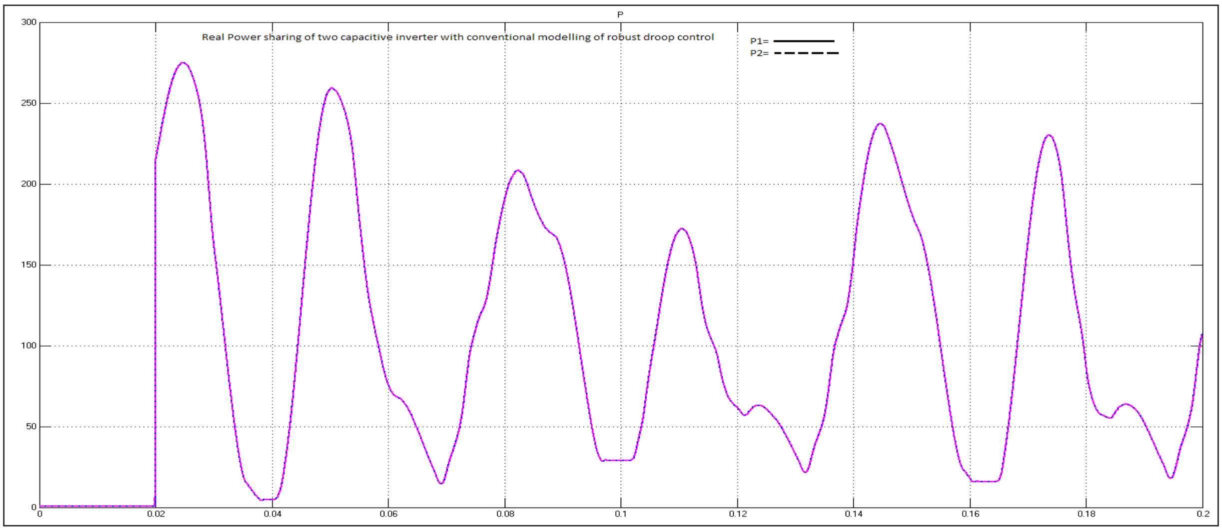

Figure 5(b).Real Power sharing of two capacitive Inverter with conventional modeling of robust droop control for R load

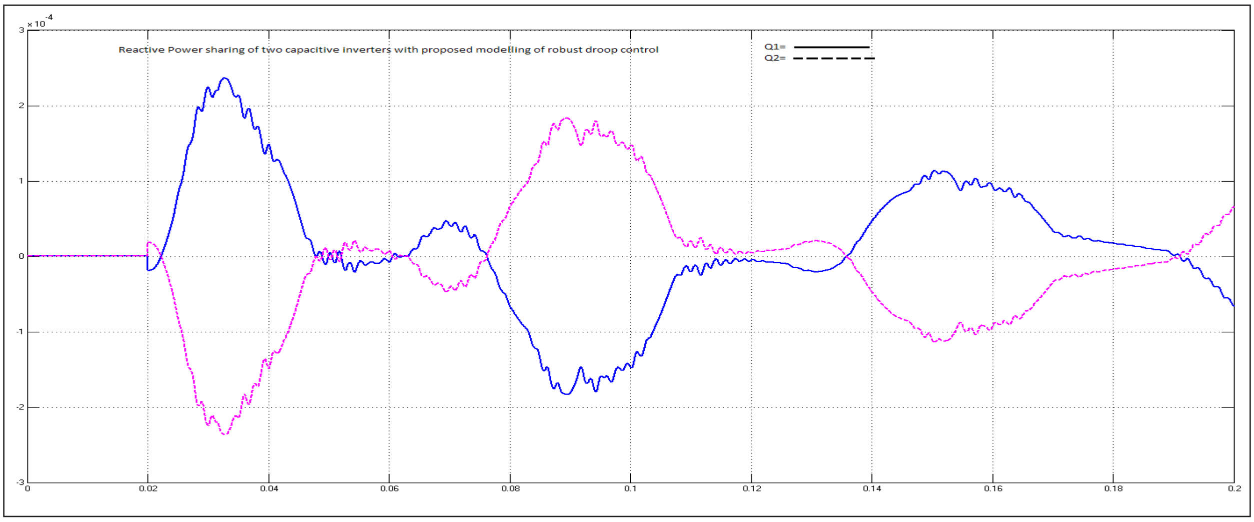

Figure 6(a).Reactive Power sharing of two capacitive Inverter with proposed modeling of robust droop control for R load

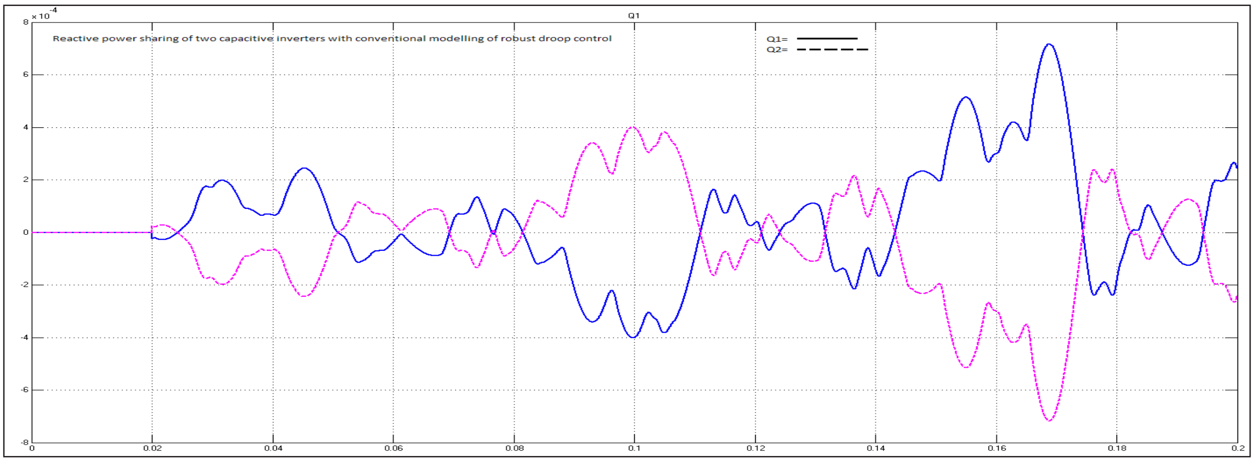

Figure 6(b).Reactive Power sharing of two capacitive Inverter with conventional modeling of robust droop control for R load

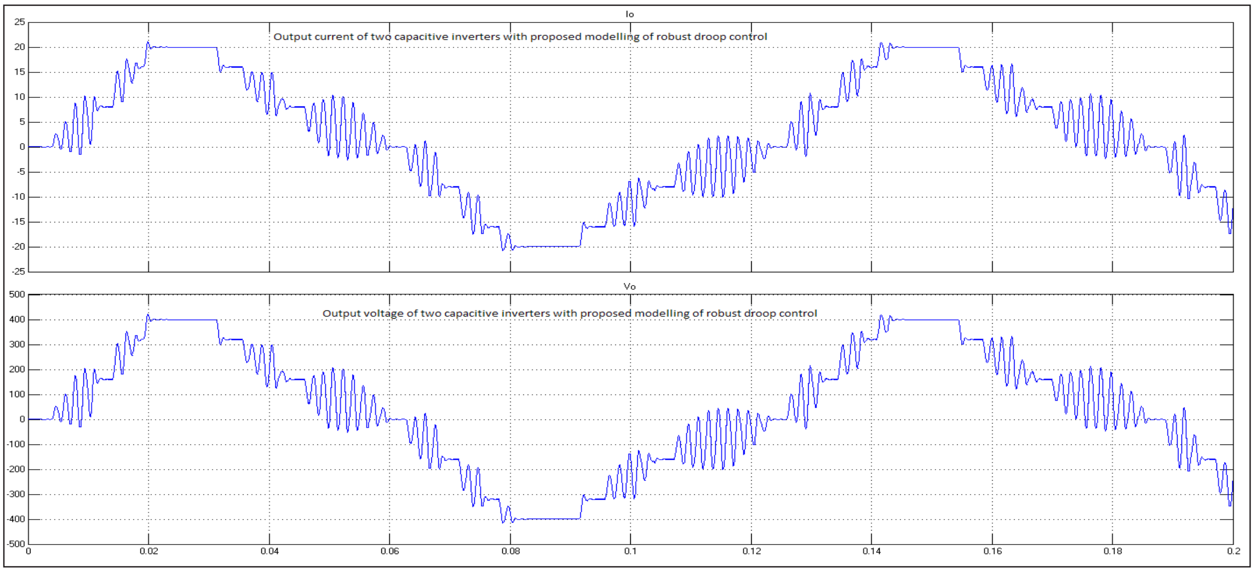

Figure 7(a).Output current and voltage of two capacitive Inverter with proposed modeling of robust droop control for R load

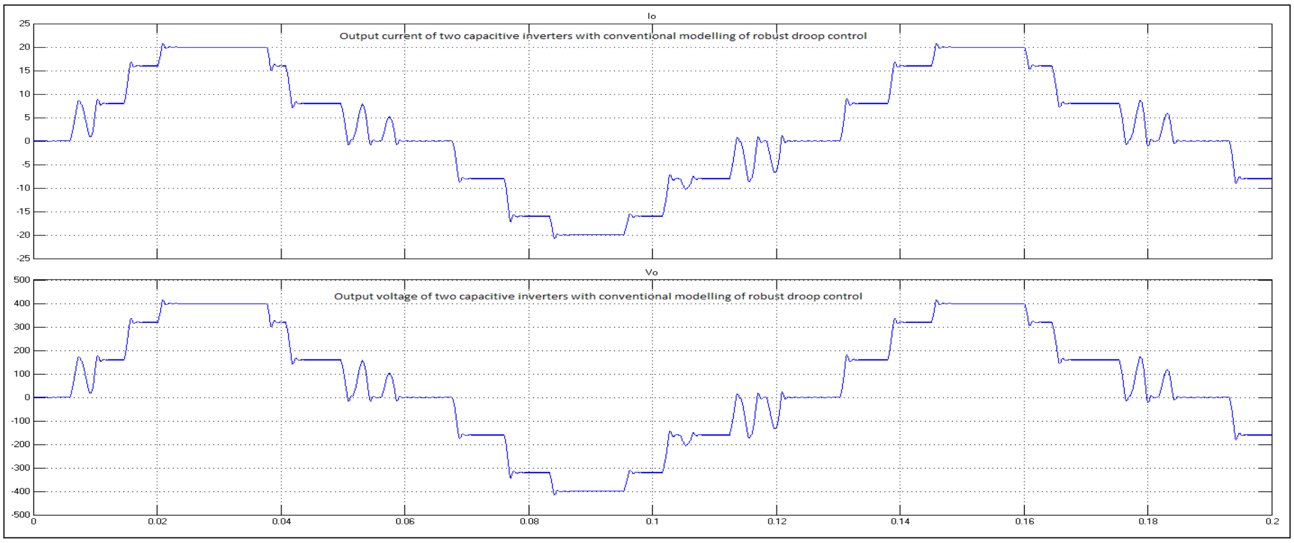

Figure 7(b).Output current and voltage of two capacitive Inverter with conventional modeling ofrobust droop control for R load

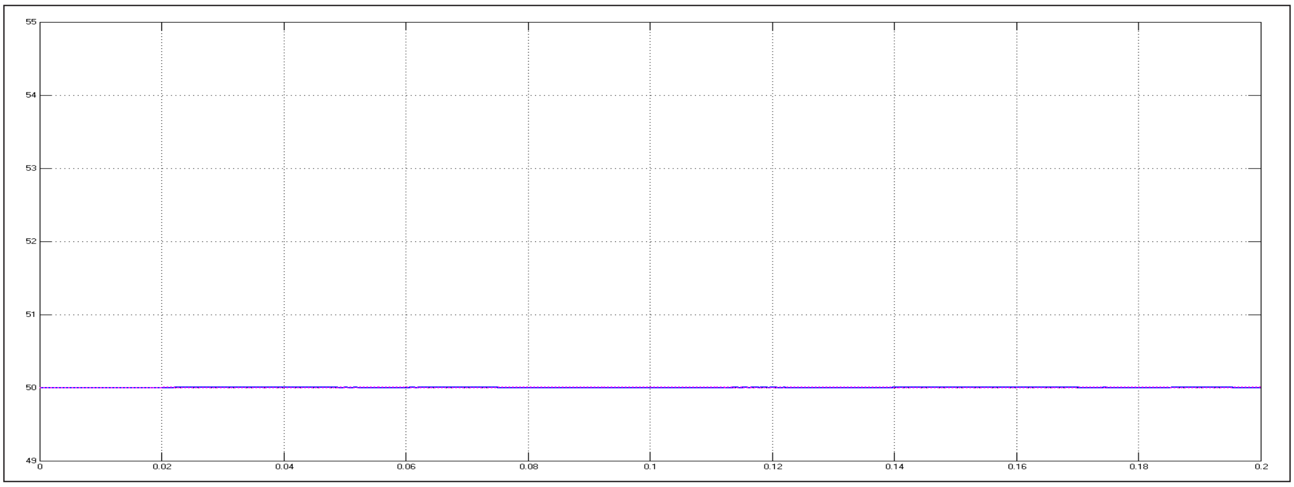

Figure 8(a).Output frequencies of two resistive inverters with proposed modeling of robust droop control for R load

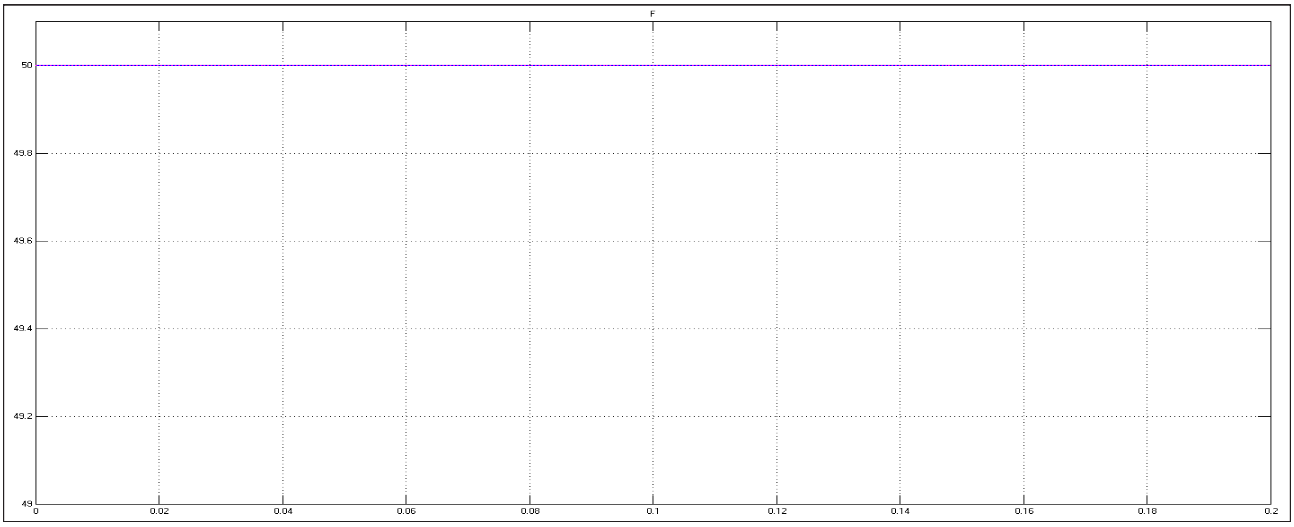

Figure 8(b).Output frequencies of two resistive inverters with conventional modeling of robust droop control for R load

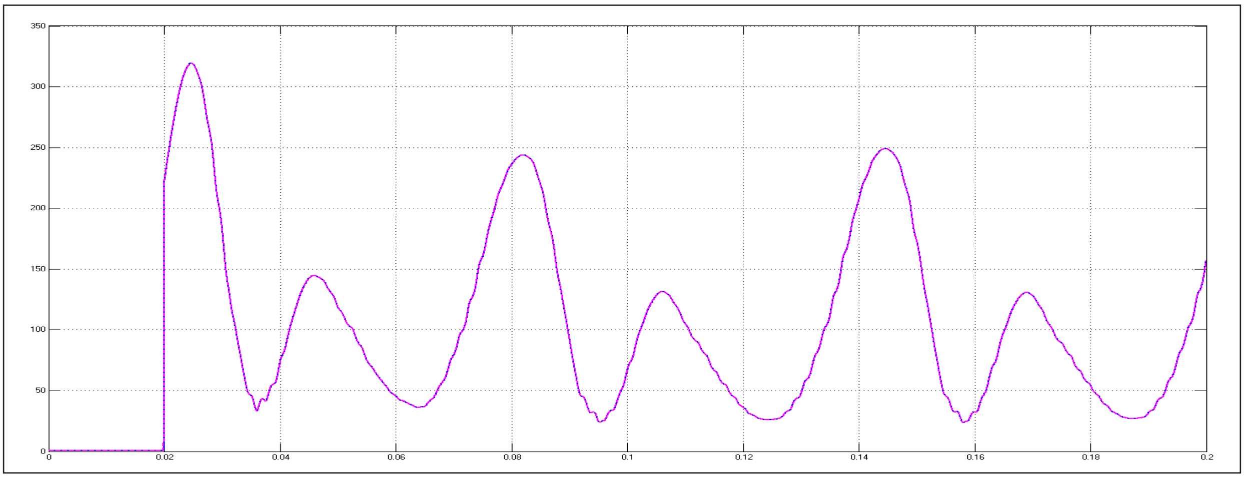

Figure 9(a).Real Power sharing of two resistive Inverter with proposed modeling of robust droop control for R load

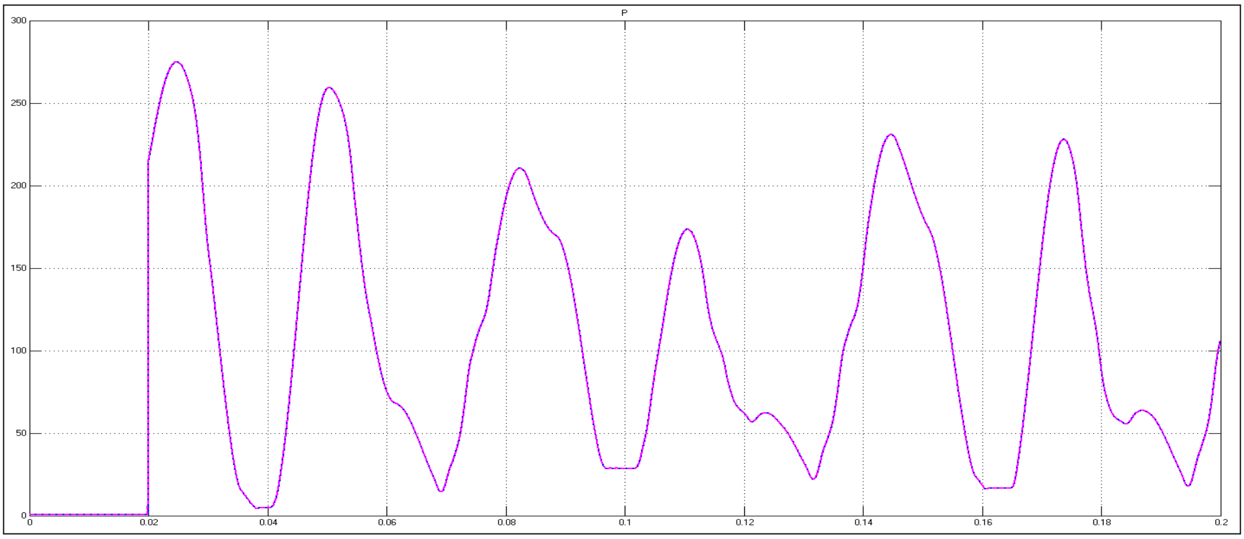

Figure 9(b).Real Power sharing of two resistive Inverter with conventional modeling of robust droop control for R load

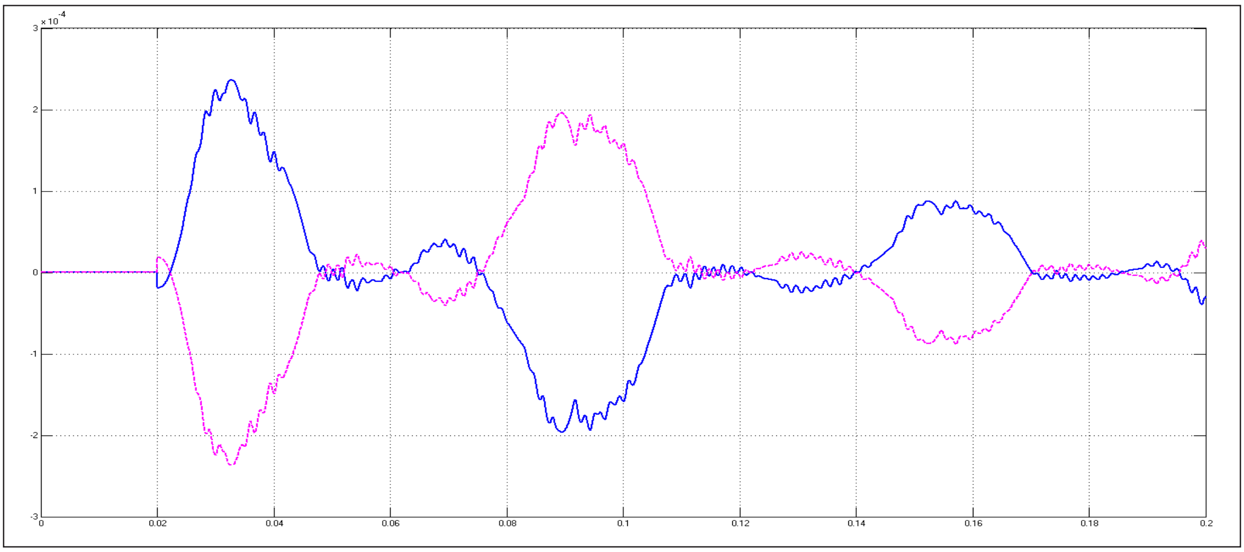

Figure 10(a).Reactive Power sharing of two resistiveinverter with proposed modeling of robust droop control for R load

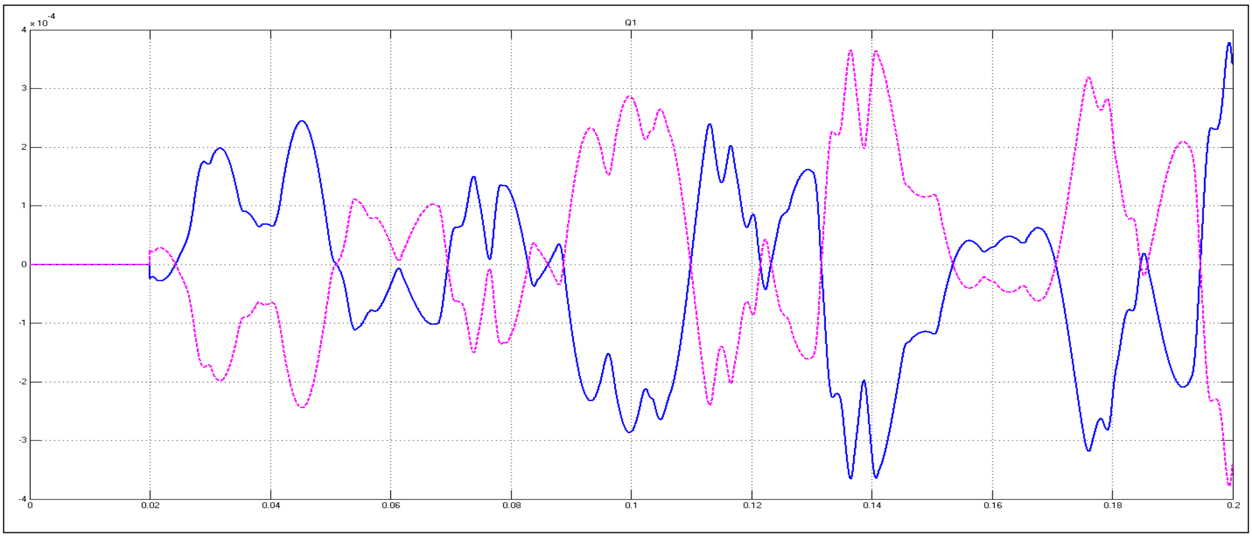

Figure 10(b).Reactive Power sharing of two resistive Inverter with conventional modeling of robust droop control for R load

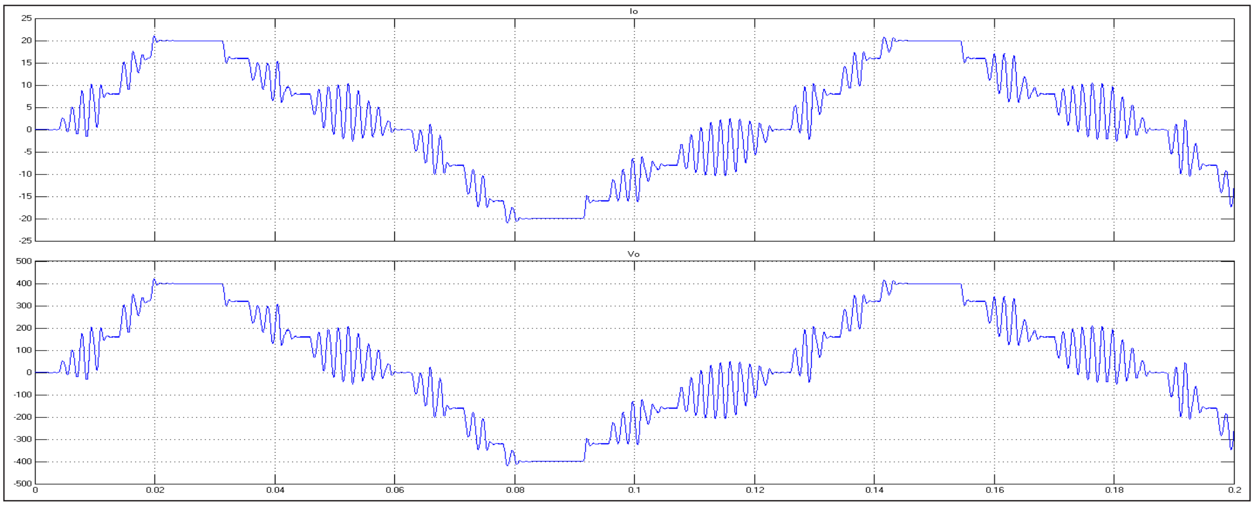

Figure 11(a).Output current and voltage of two resistive Inverter with proposed modeling of robust droop control for R load

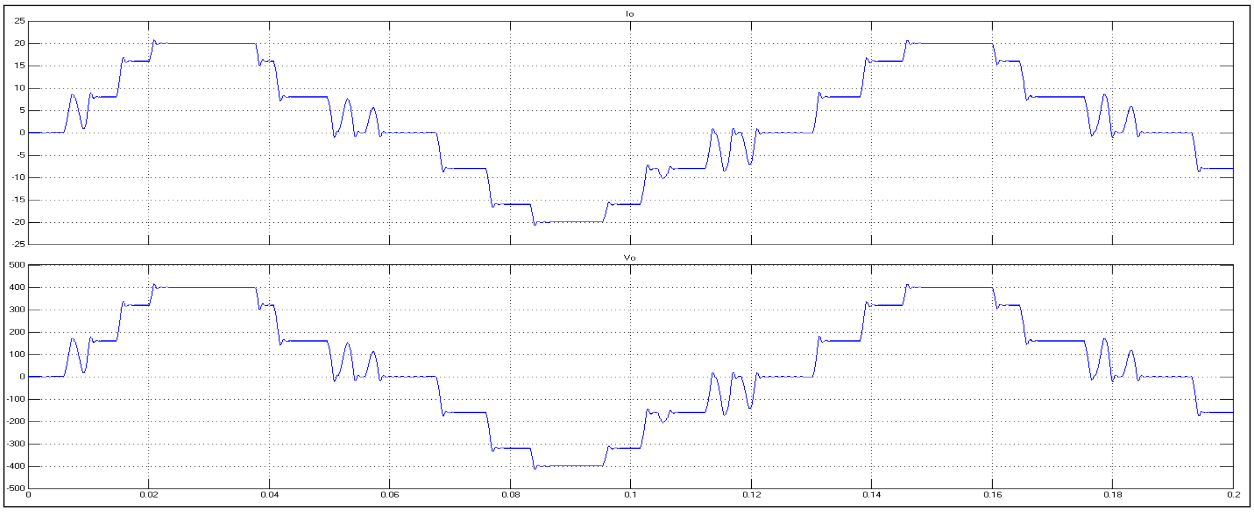

Figure 11(b).Output current and voltage of two resistiveinverter with conventional modeling of robust droop control for R load

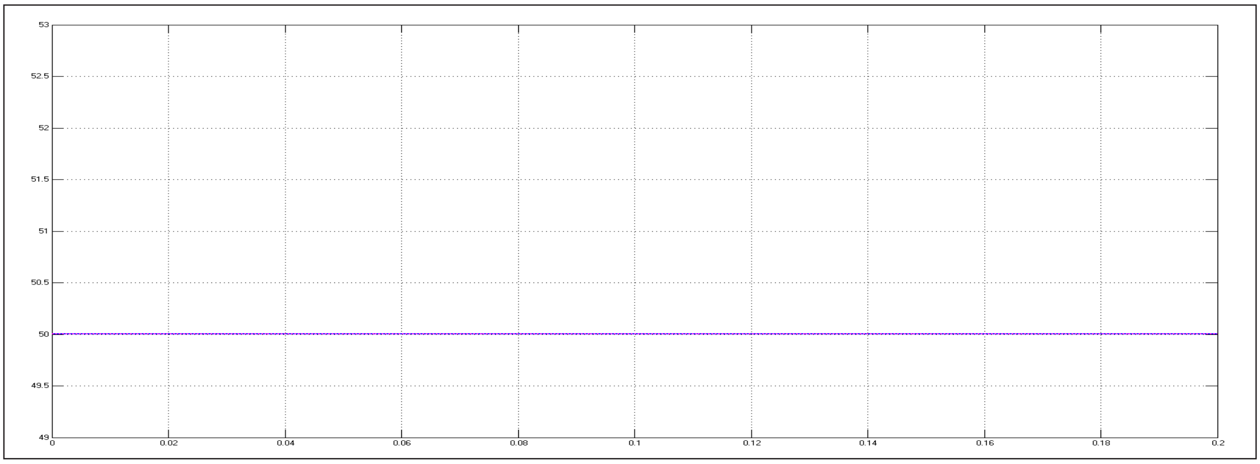

Figure 12(a). Output frequencies of two capacitive inverters with proposed modeling of robust droop control for RL load

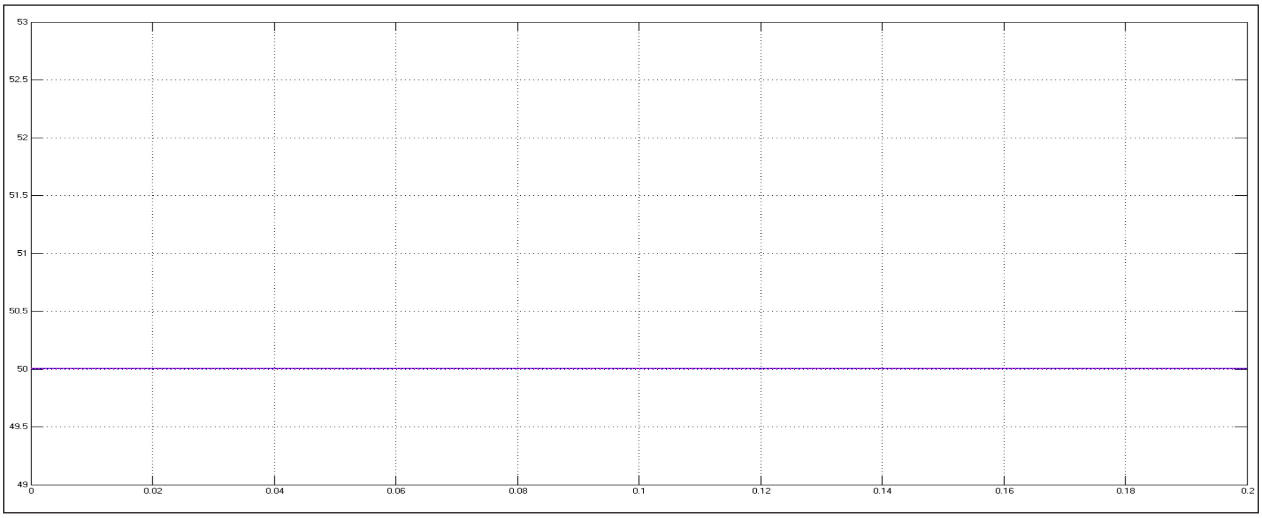

Figure 12(b). Output frequencies of two capacitive inverters with conventional modeling of robust droop control for RL load

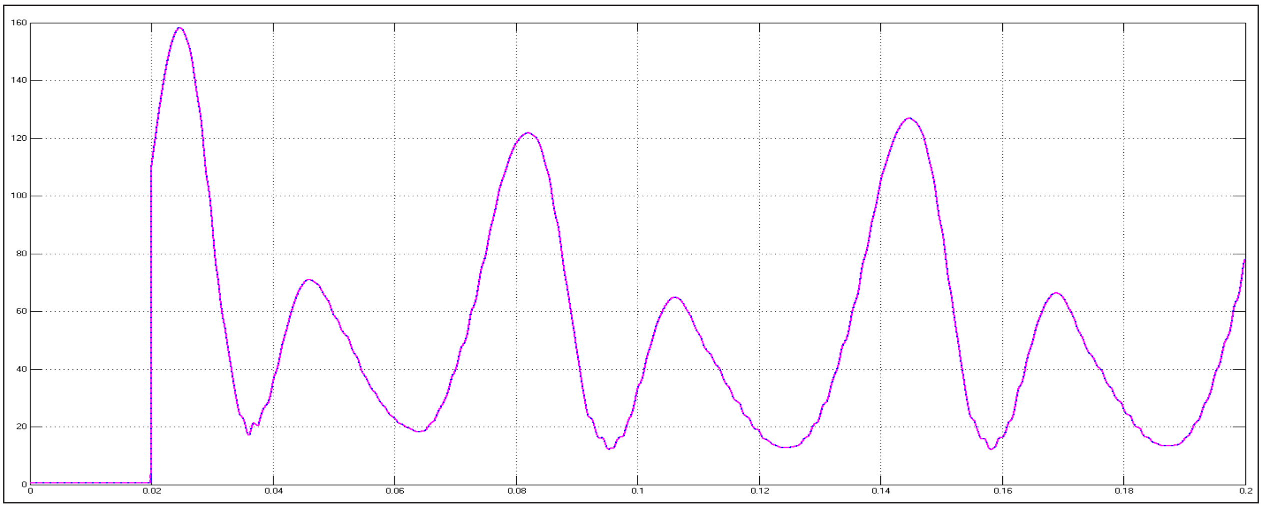

Figure 13(a). Real Power sharing of two capacitive Inverter with proposed modeling of robust droop control for RL load

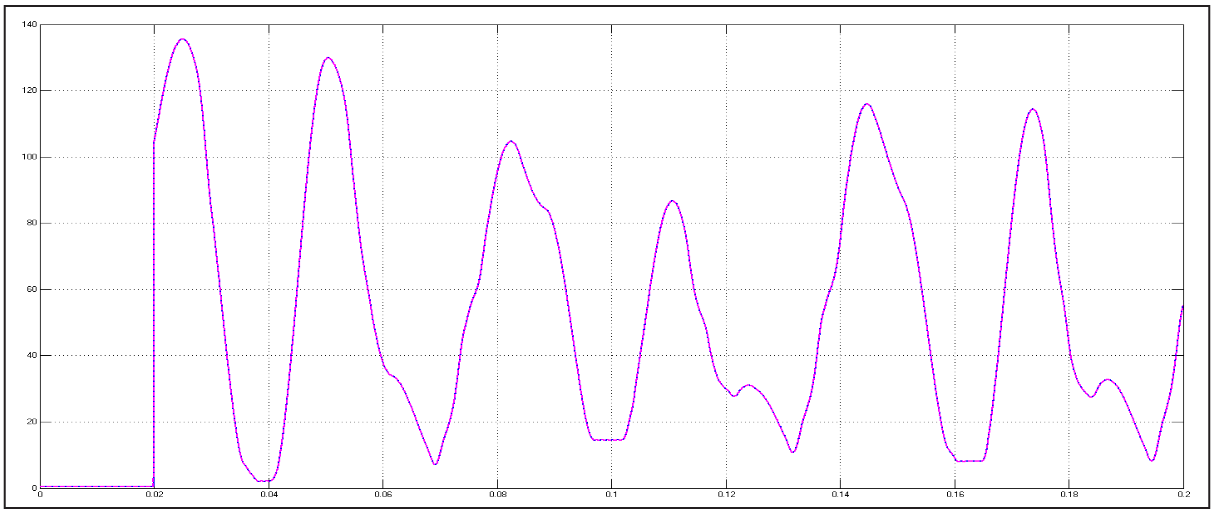

Figure 13(b).Real Power sharing of two capacitive Inverter with conventional modeling of robust droop control for RL load

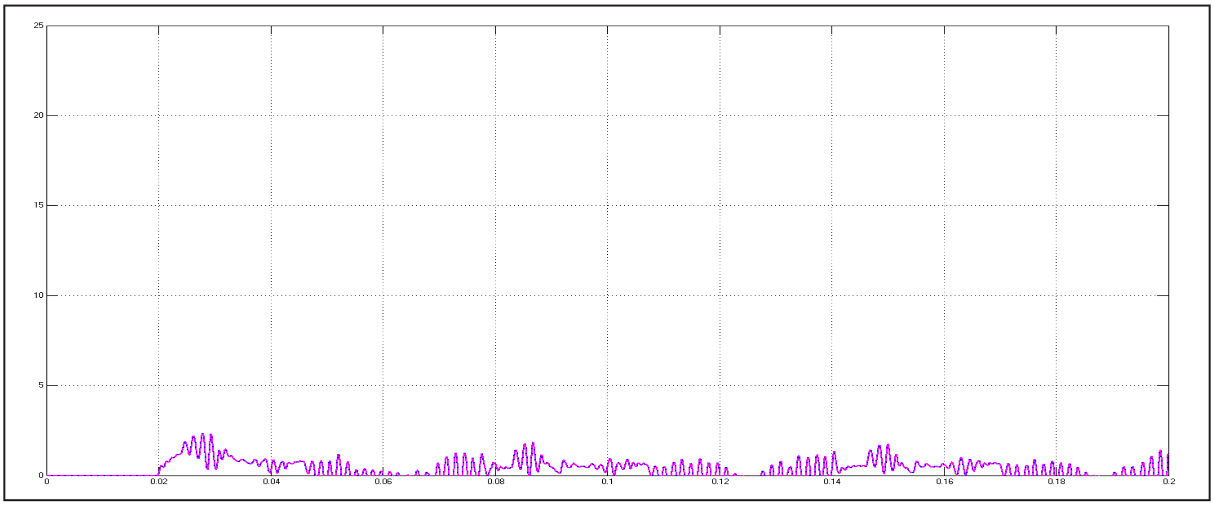

Figure 14(a).Reactive Power sharing of two capacitive inverter with proposed modeling of robust droop control for RL load

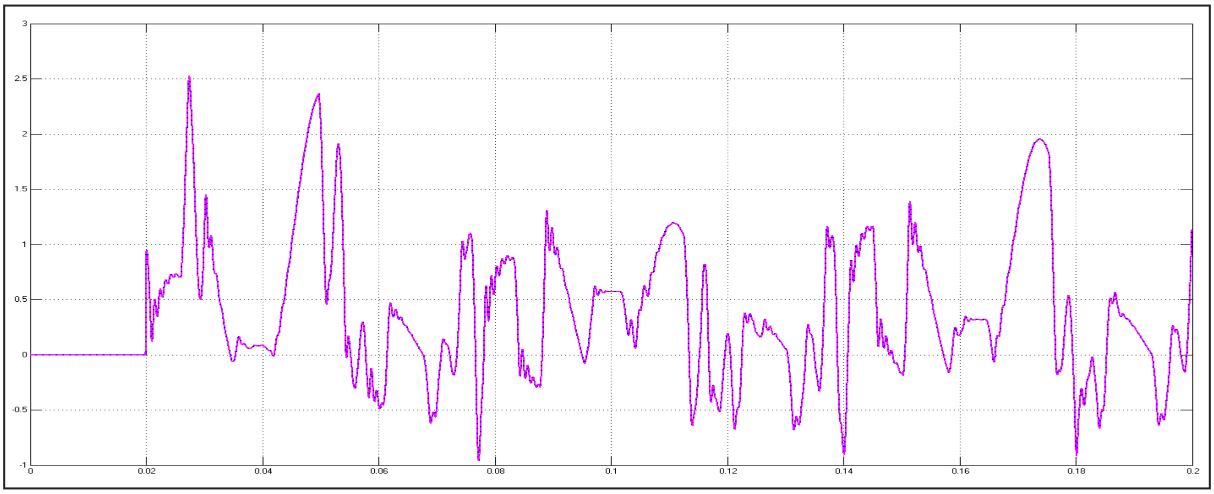

Figure 14(b).Reactive Power sharing of two capacitive Inverter with conventional modeling of robust droop control for RL load

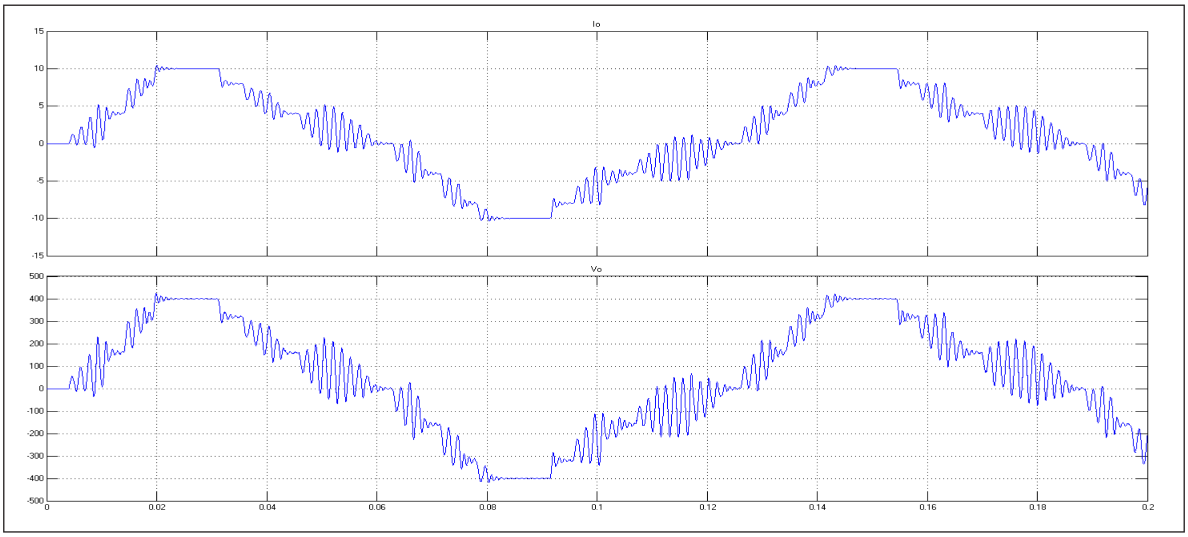

Figure 15(a).Output current and voltage of two capacitive Inverter with proposed modeling of robust droop control for RL load

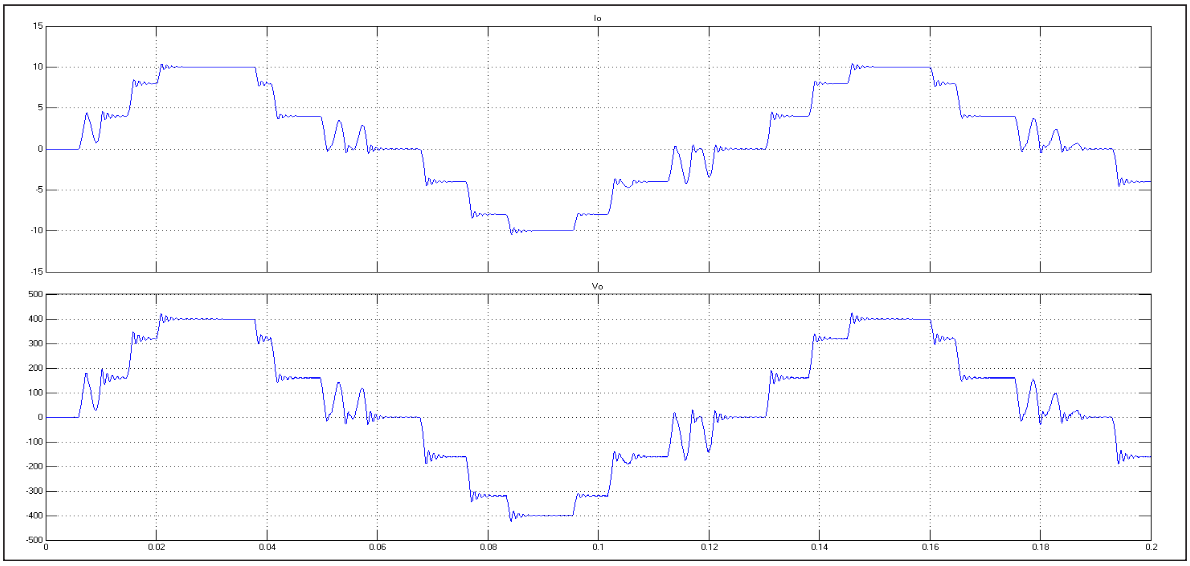

Figure 15(b).Output current and voltage of two capacitiveinverter with conventional modeling of robust droop control for RL load

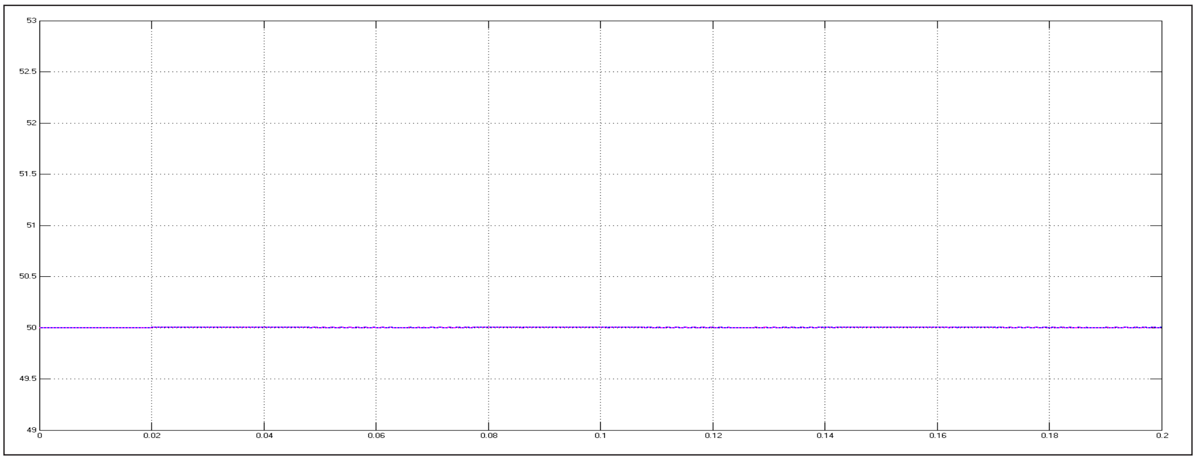

Figure 16(a).Output frequencies of two resistive inverters with proposed modeling of robust droop control for RL load

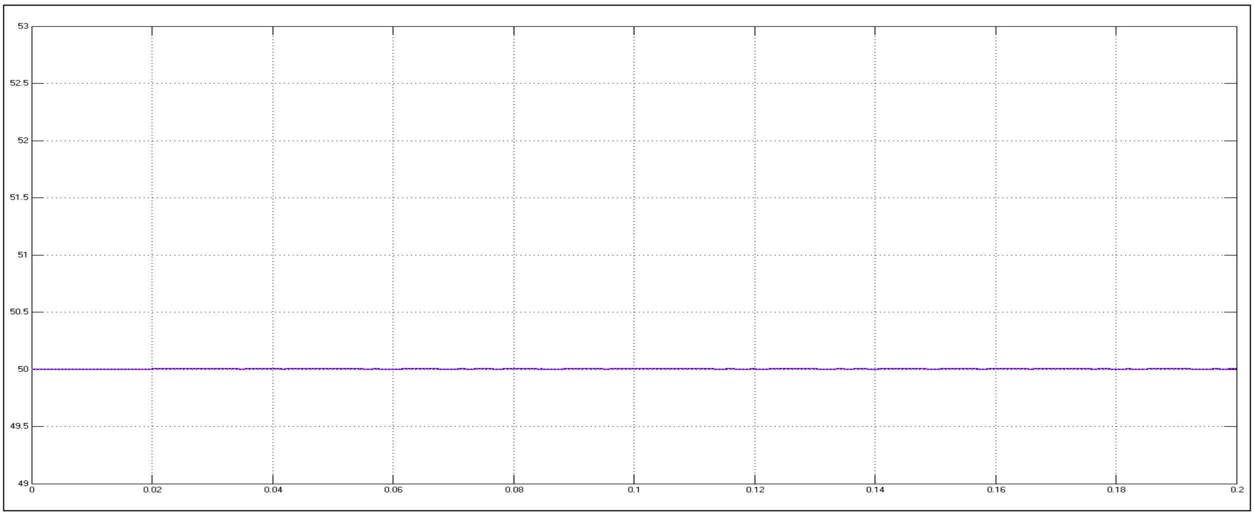

Figure 16(b).Output frequencies of two resistive inverters with conventional modeling of robust droop control for RL load

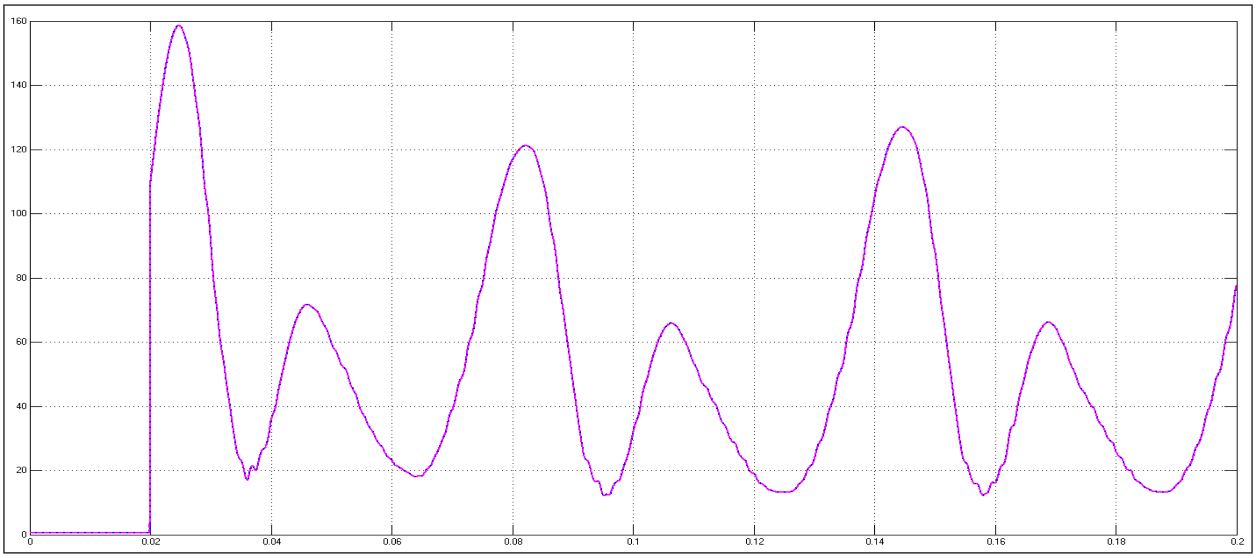

Figure 17(a).Real Power sharing of two resistive Inverter with proposed modeling of robust droop control for RL load

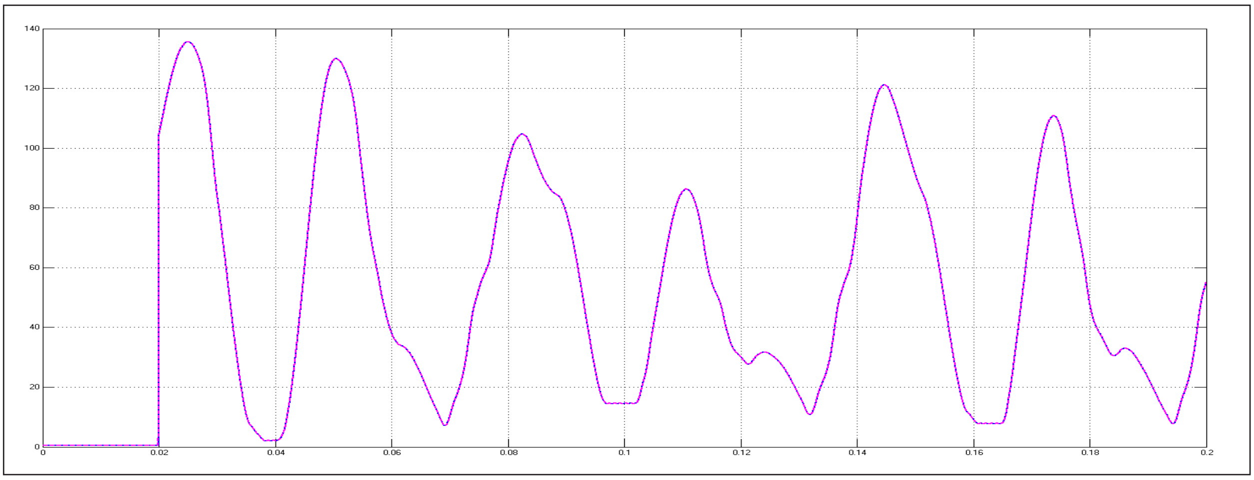

Figure 17(b).Real Power sharing of two resistive Inverter with conventional modeling of robust droop control for RL load

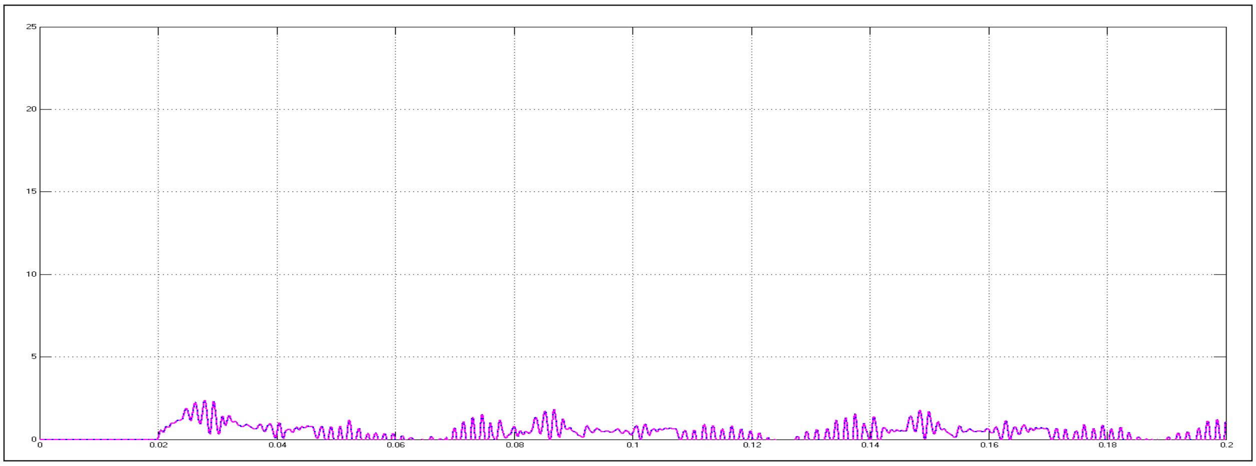

Figure 19(a).Reactive Power sharing of two resistiveinverter with proposed modeling of robust droop control for RL load

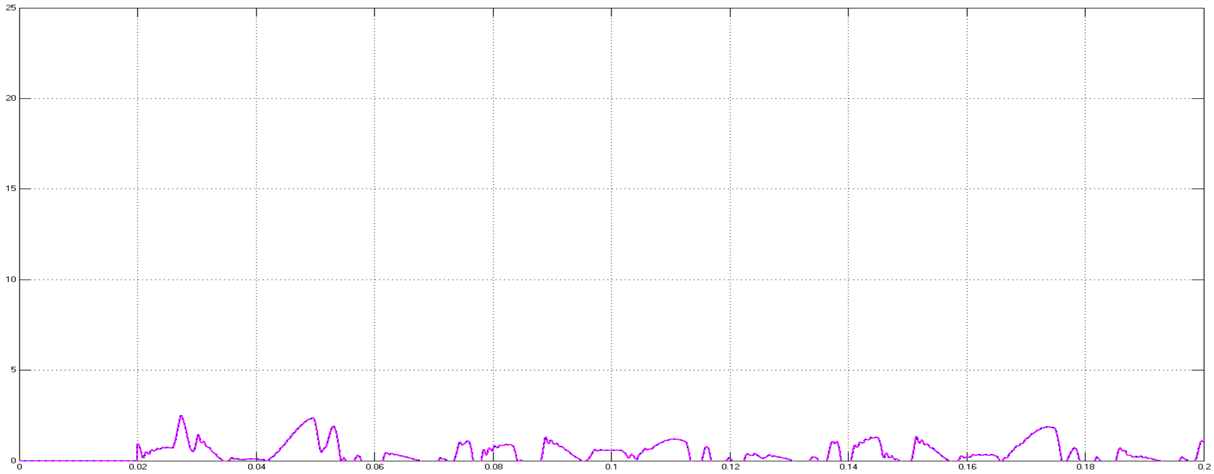

Figure 18(a).Reactive Power sharing of two resistiveinverter with proposed modeling of robust droop control for RL load

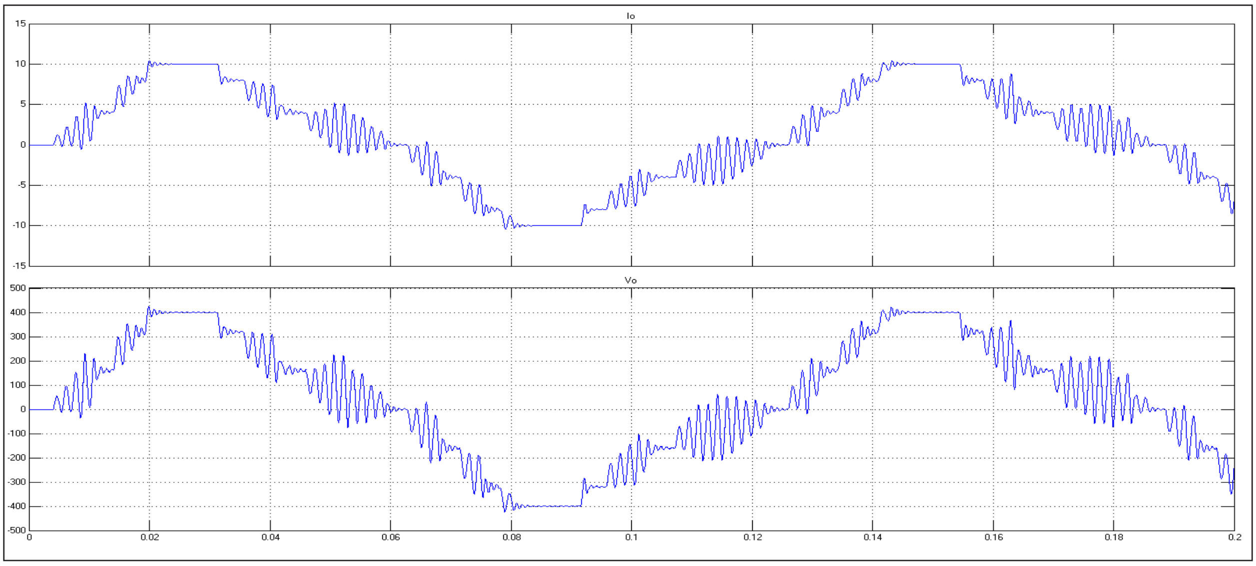

Figure 19(a).Output current and voltage of two resistive Inverter with proposed modeling of robust droop control for RL load

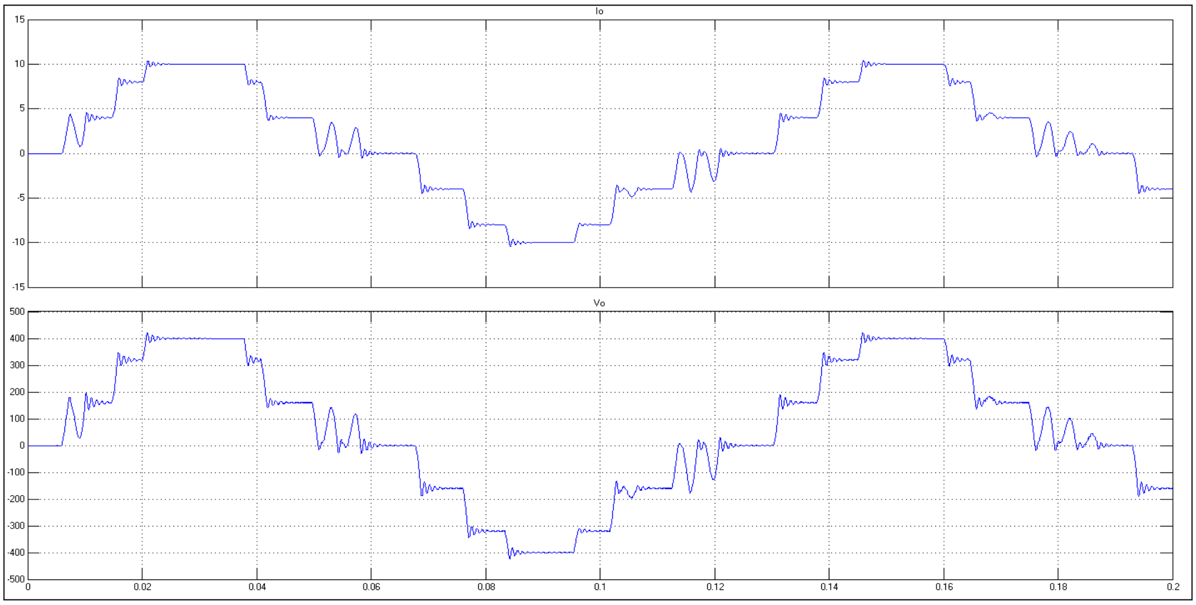

Figure 19(b).Output current and voltage of two resistiveinverter with conventional modeling of robust droop control for RL load

The results from the proposed modeling of robust droop controller with Ke = 10 are shown within the first individual graph of Figure's 5-20 and therefore the results from the conventional modeling of robust droop control are shown within the second individual graph of Figure's 5-20. From Figures 8(a), 12(a), 16(a) and 20(a) in capacitive inverter and resistive inverter with R and RL load, better amplitude of output voltage and currents are getting in proposed modeling of robust droop control compare to respective conventional modeling. The value of RMS output voltage and output current is 133.8V and 6.69A respectively for capacitive inverter with R load with proposed droop control and 132.6V and 3.239A respectively with RL load as compare to 93.31V and 4.666A respectively with conventional modeling with R load and 93.43V and 2.306A respectively with conventional modeling with RL load. Also good dynamic response of equal real power sharing is obtained. With the help of proposed modeling in capacitive inverter, value of real powers are 157.7W and 78.06W for R and RL load respectively, which shows good response as compare to conventional modeling in which values are 107W and 55.01W for R and RL load. Also considerable values of reactive power sharing are obtained for proposed modeling of robust droop control as compare to conventional modeling for R and RL load. So, the proposed modeling of robust droop control outperformed the conventional modeling of robust droop controller in terms of output voltage, output current and real and reactive power. Scrutiny of output frequency graphs of all inverters shown in Figures.5,9,13 and 17 there have been no noticeable changes within the performance for the proposed modeling. Comparative output is shown in Table 2, 3, 4, 5.

Table 2.Results of two capacitive inverters with R load

Result with proposed modeling of robust droop control	Result with conventional modeling of robust droop control
Frequency of Inverter 1 = 50.01Hz	Frequency of Inverter 1 = 50Hz
Frequency of Inverter 2 = 50.01 Hz	Frequency of Inverter 2 = 50 Hz
Output voltage (rms) = 133.8V	Output voltage (rms)= 93.31V
Output current (rms) = 6.69A	Output current (rms)= 4.666A
P of Inverter 1 = 157.7 w	P of Inverter 1 = 107 w
P of Inverter 2 = 157.7 w	P of Inverter 2 = 107 w
Q of Inverter 1 = -6.583e-05 var	Q of Inverter 1 = 0.0002429 var
Q of Inverter 2 = 6.583e-05 var	Q of Inverter 2 = -0.0002429 var

Table 3.Results of two resistive inverters with R load

Result with proposed modeling of robust droop control	Result with conventional modeling of robust droop control
Frequency of Inverter 1= 50Hz	Frequency of Inverter 1 = 50Hz
Frequency of Inverter 2= 50 Hz	Frequency of Inverter 2 = 50Hz

Output voltage (rms)= 133.6V	Output voltage (rms) = 93.07V
Output current (rms)= 6.68 A	Output current (rms) = 4.653A
P of Inverter 1=156.8 w	P of Inverter 1 = 105 w
P of Inverter 2=156.8 w	P of Inverter 2 = 105 w
Q of Inverter 1=-3.017e-05 var	Q of Inverter 1 = 0.0003419 var
Q of Inverter 2=3.017e-05 var	Q of Inverter 2 = -0.0003419 var

Table 4.Results of two capacitive inverters with RL load

Result with proposed modeling of robust droop control	**Result with conventional modeling of robust droop control**
Frequency of Inverter 1 = 50Hz	Frequency of Inverter 1 = 50Hz
Frequency of Inverter 2 = 50Hz	Frequency of Inverter 2 = 50Hz
Output voltage (rms) = 132.6V	Output voltage (rms) = 93.43V
Output current (rms) = 3.239A	Output current (rms) = 2.306A
P of Inverter 1 = 78.06 w	P of Inverter 1 = 55.01 w
P of Inverter 2 = 78.06 w	P of Inverter 2 = 55.01 w
Q of Inverter 1 = 1.197 var	Q of Inverter 1 = 1.132 var
Q of Inverter 2 = 1.197var	Q of Inverter 2 = 1.132 var

Table 5.Results of two resistive inverters with RL load

Result with proposed modeling of robust droop control	**Result with conventional modeling of robust droop control**
Frequency of Inverter 1= 50Hz	Frequency of Inverter 1 = 50Hz
Frequency of Inverter 2= 50Hz	Frequency of Inverter 2= 50Hz
Output voltage (rms)= 132.7V	Output voltage (rms) = 94.39V
Output current (rms)= 3.231A	Output current (rms)= 2.331A
P of Inverter 1=77.4 w	P of Inverter 1 = 54.99 w
P of Inverter 2=77.4 w	P of Inverter 2 = 54.99 w
Q of Inverter 1=1.069 var	Q of Inverter 1 = 1.03 var
Q of Inverter 2=1.069 var	Q of Inverter 2=1.029 var

Conclusion

This paper has given a new approach for modeling of robust droop control in parallel connected inverters. It centered on management action taken in the voltage reference by applying the controller to improve output voltage, output current and output power. A simplified model of single-phase inverter is employed to research system stability in terms of output current and voltage. The proposed controller supply a stable angular frequency voltage, current and power for microgrids operating within the islanded mode. The proposed modeling has tested with two types inverters, and result shows that proposed modeling improve the output voltage, current and power and provide a stable response.

So in conclusion, capacitive inverter and resistive inverter for R and RL load, better performance is obtained in capacitive inverter with R and RL load, in terms of output voltage, output current, output real and reactive power compare to resistive inverter with R and RL load.

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