Performance Evaluation of CCC Inverter Topology Employing Average Current-mode Control Technique

Dr.S.EDWARD RAJAN,[1] **A.ALLWYN CLARENCE ASIS,**[2] **T.RAKESH** [3]

[1]Professor, [2, 3]Assistant Professor, Dept.of Electrical and Electronics Engineering,
Mepco Schlenk Engineering College, Sivakasi-626005, TamilNadu, India.
Email: sedraj@yahoo.com, iamallwyn@rediffmail.com, rakeshtme@gmail.com

Abstract— **Controlled-Capacitor-Charging (CCC) is a technique to synthesize a desired voltage profile at the output from the unregulated DC at the input. This research paper deals with the dynamic performance of Controlled-capacitor-charging type inverter. A novel method to design the L-C elements of such an inverter is proposed. The output voltage is forced to follow the corresponding reference waveform by a tracking Average Current-mode controller. The switching devices are made to operate in the discontinuous conduction mode to reduce the size of the inductor and also for producing the better dynamic performance. The Zero current switching (ZCS) at all turn-ON of the devices could be achieved automatically. The current through the inductor is used in the controller to operate the inverter always in Discontinuous conduction mode (DCM). The CCC inverter can supply all types of load, including lagging, leading, and unity power factor. The proposed inverter is extremely suitable for UPS applications, Dynamic voltage restorers, Induction heating, Low-power drives etc which require pure sine wave for its efficient operation. The proposed inverter simulations have been performed using MATLAB-Simulink environment and results obtained are reported.**

Keywords: **Controlled-capacitor-charging, Discontinuous conduction mode, Zero-current switching (ZCS), Average Current-mode control, Controlled-capacitor-charging type inverter, embedded controller.**

1. Introduction

Simple topology, reliable operation, and low cost are some of the reasons that make the Hard-switched inverters very popular. This inverter is tested with time, and the technology has reached a level of maturity. However, the hard switching emits Electromagnetic interference (EMI) and increases loss. Therefore, the switching frequency of the inverter may not be increased beyond a few kilohertz [1]–[4]. A paradigm shift was necessary to look for new inverters that operate well at higher frequency with definite advantages like low filtering requirement, higher efficiency, lower size and cost, reduced EMI, etc. This welcomes the further investigation on inverters unearthing various Soft-switched versions of the network. However, this is at the cost of high voltage or current stress for the switching devices or increased device count. In addition the soft-switched inverters prefer a pulse density modulation that makes the effective frequency far less than the switching frequency [5, 6]. Different Soft-switched topologies and Zero-voltage-switching (ZVS) / Zero-current-switching (ZCS) based Pulse-width modulation (PWM) controllers are regularly reported to take care of these limitations [7]–[9].

On the other hand, multilevel inverters have better band-width, reduced EMI, and THD. Efforts are put toward applying space vector PWM to optimize the switching frequency for a desired performance [10]–[13]. However, such inverters require more number of devices and are not suitable for low-power applications.

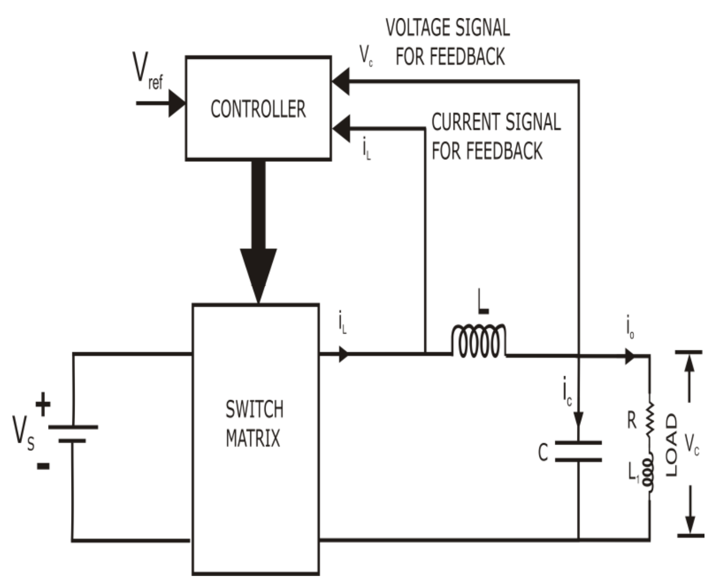

Fig.1: Schematic diagram of the CCC inverter.

This research paper looks the standard PWM inverters from a different perspective. Understanding that, in most of the inverters, a PWM signal is actually fed to an L–C filter, the performance of the filter is extremely important. A higher inductance in the filter not only increases size and cost but also makes the dynamic performance of the inverter poor. Therefore, in this paper, a different algorithm to realize the inverter operation is proposed by a Controlled-capacitor-charging (CCC) technique. For such strategy, a capacitor is charged /discharged in a controlled manner to synthesize a desired waveform at the output. To enhance the performance and to have better controllability, the inverter is deliberately operated in a Discontinuous conduction mode (DCM). The ZCS at all turn-ON of the devices is thus automatically achieved. It is important to note that the capacitor-charging power supplies are well investigated in the literature [14]–[16]. However, they were used for pulse-power applications, where a capacitor of sufficiently high magnitude is charged for a longer duration and the energy (in the capacitor) is discharged quickly to a load when required. Such a mechanism is not suitable to realize sinusoidal power supply.In earlier publications, authors have reported the performance of the single-phase inverter based on Controlled charging of the capacitor [17], [18] but the dynamic performance was not available. This paper presents the dynamic performance of the CCC inverter.

This research paper is organized into six sections. The following section presents the single-phase inverter topology followed by controllers in Section 3. Designs are discussed in Section 4. Simulation and results appear in Sections 5. Section 6 concludes this paper.

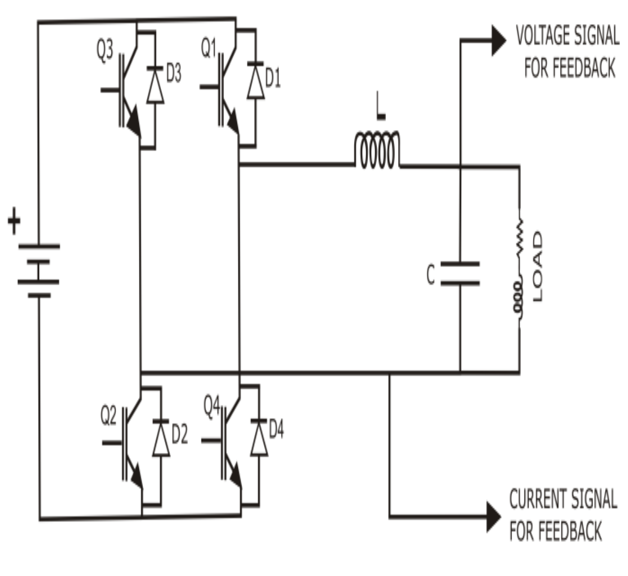

Fig. 2: Single phase CCC-based inverter topology.

2. Single Phase Inverter Topology

Capacitive-charging type inverters require a current source and a switching mechanism to apply positive or negative current pulses to charge the capacitor (C) in a controlled manner. The load is connected across the capacitor. This makes the load voltage same as the capacitor voltage, and these two terms (i.e., load voltage and capacitor voltage) are used interchangeably. For a Voltage-fed inverter, an inductor (L) may be used to limit the charging current. Therefore, for a Voltage-fed Converter, the CCC Inverter may be interpreted as shown in Fig. 1, where the Switch Matrix is a combination of switching devices that applies either a positive, negative, or null voltage to the L–C load network. The Fig.2 shows a configuration of single-phase CCC Inverter. The choice of L and C values is dependent on several factors, such as switching frequency, peak value of output voltage and load to be delivered, etc. The Inductor-Current and the Capacitor-Voltage signals are used for feedback in the single-phase topology.

3. Controller

The Capacitor-Charging controllers form a tracking mechanism to synthesize any smoothly varying reference waveform by operating the inverter in different modes as per the requirement. Hence, for successful operation of the controller, a reference sinusoidal wave at power frequency (i.e., 50 or 60 Hz) is required. By using this signal as reference, the controller forms the PWM signals and appropriate switches are to be activated. The inverter may be operated in the DCM to achieve better dynamic performance and reduce the size of the inductor. To ensure operation in the DCM, the controller continuously monitors the inductor current. It turns on a switch only when the inductor current is zero. The Voltage-mode control senses the output voltage and compares it with a reference. The result, suitably compensated to avoid instability, forms the control signal input to the PWM modulator. A slightly more advanced method of control technique, known as Average Current-mode control uses a pair of Nested-loops. The inner loop derives an error signal from the difference of the inductor current and the output of the outer loop, in which the error signal is derived as a Voltage-mode control. The Current-mode control carries a number of advantages over Voltage-mode control where selection of component values to optimize loop speed is concerned, and it is primarily with this form of control, the proposed investigation is concerned. A block diagram of the complete embedded controller is shown in the Fig.3 in which the Voltage signal and the Current signal is given as feedback to the controller and it makes the PWM modulator to control the switches Q_1,Q_2,Q_3 and Q_4 correspondingly such that the output voltage is always maintained close to the given reference.

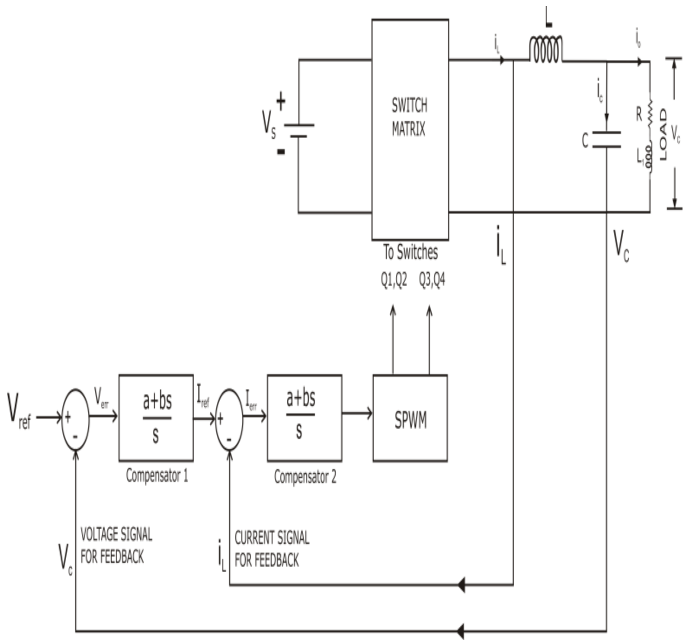

Fig.3:Complete Embedded Controller.

4. Design paramerters

The proposed technique needs a controlled-current source to charge a capacitor to synthesize a desired voltage at the output. For a voltage-fed converter, the capacitor C may be charged/discharged through an inductor L.

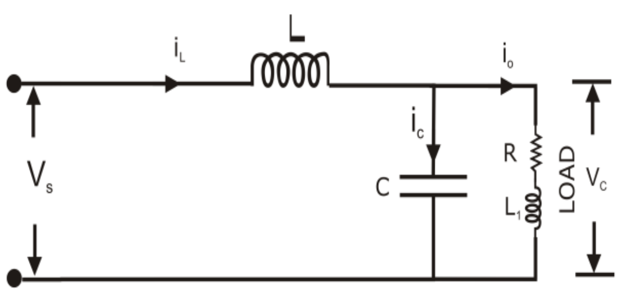

Fig.4: CCC from a voltage source.

The inductor L helps to limit the charging/discharging current. The load is connected across the capacitor, and the capacitor voltage is fed back to compare with a corresponding reference waveform. Assuming ideal components, the following may be derived for the network in Fig. 4.

$$v_c(n) = v_c(n-1) + \frac{1}{C}\int_{t_{n-1}}^{t_n} i_c(t)dt \tag{1}$$

$$i_c(t) = C\frac{dv_c(t)}{dt} = i_L(t) - i_O(t) \tag{2}$$

$$Ri_O(t) + L_1\frac{di_O(t)}{dt} = v_c(t) \tag{3}$$

$$L\frac{di_L(t)}{dt} = V_s - v_c(t) \tag{4}$$

The idea is to keep the voltage across the capacitor close to the reference voltage by suitably charging/discharging the capacitor by operating the switches Q_1 to Q_4. An important aspect of this scheme is that the switching pattern of the devices is adaptive and decided by the nature of the input voltage, LC components, and the load.

Based on the profile to be achieved and the value of L and C, the inverter must switch from one mode to the other. How long will the inverter stay in any mode is decided by the Average Current-mode controller. Using Eq. (1) to Eq. (4) and applying the proper sign for Vs during the powering and regenerative modes, the general equation, describing the dynamics of the capacitor voltage, is found as:

$$v_c(n) = v_c(n-1) + \frac{1}{C}\int_{t_{n-1}}^{t_n} i_L(t)dt - \left(\frac{V_s}{RC}\right)(t_{on} - t_{off}) + \frac{L_1}{RC}\left[I_O(n) - I_O(n-1)\right] \tag{5}$$

5. Simulation Results

In this section, the computer simulation of the controlled-capacitor-charging type inverter has been carried out to evaluate their performances using a MATLAB-Simulink software package for Single phase. The Fig. 5 and Fig. 6 show the simulink model of CCC type single-phase inverter without controller and with controller as open-loop and closed-loop circuit.

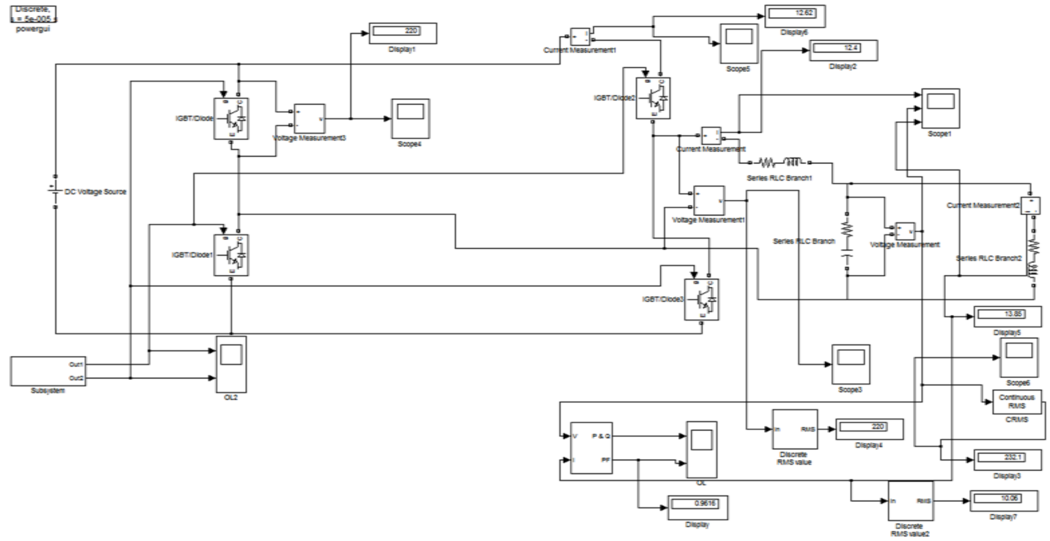

Fig.5: Simulink model of CCC type single-phase inverter without controller (Open-loop).

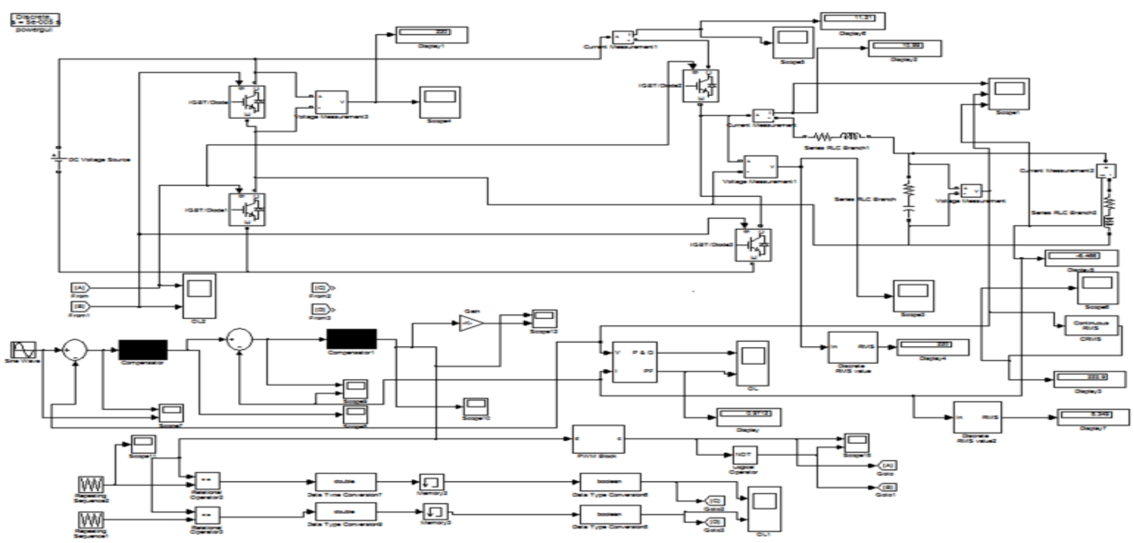

Fig. 6: Simulink model of CCC type single-phase inverter with controller (Closed-loop).

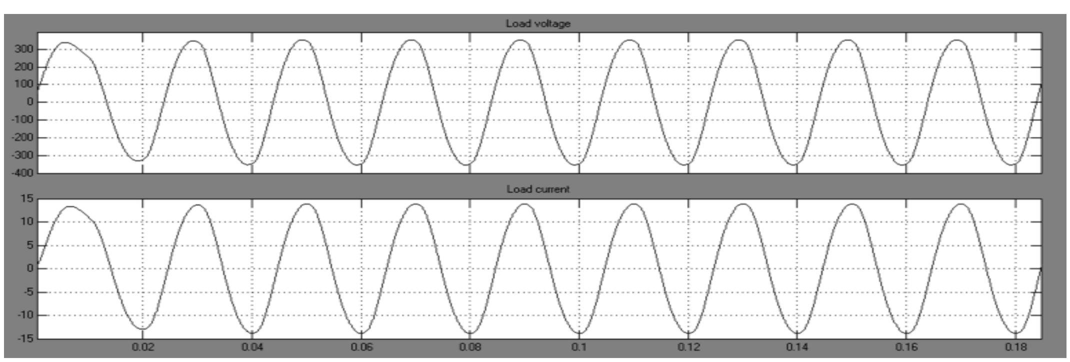

Fig.7: Output voltage and output current for R-L load ($R = 25\ \Omega$, $L = 20$ mH) (Open-loop).

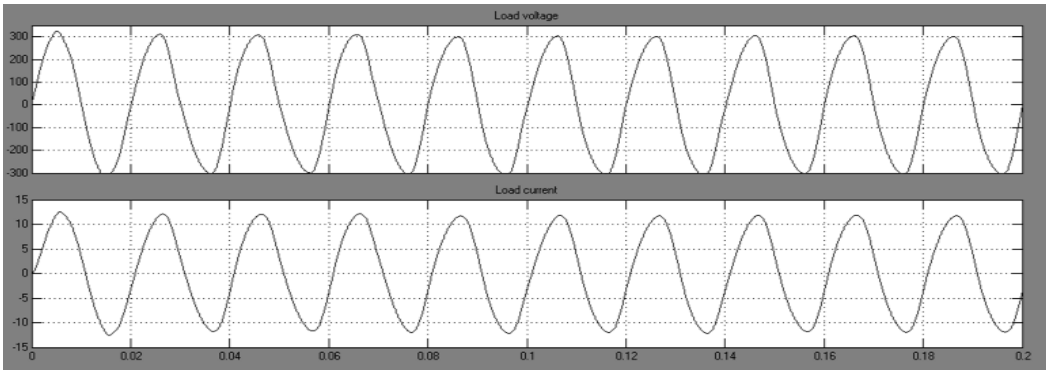

Fig. 8: Output voltage and output current for R-L load ($R = 25\ \Omega$, $L = 20$ mH) (Closed-loop).

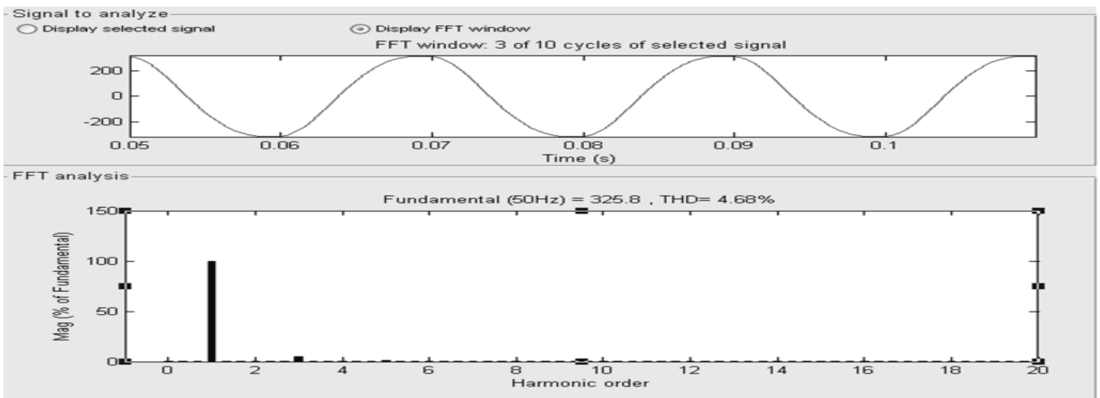

Fig.9: THD value in % for R-L load ($R = 25\ \Omega$, $L = 20$ mH) (Open-loop).

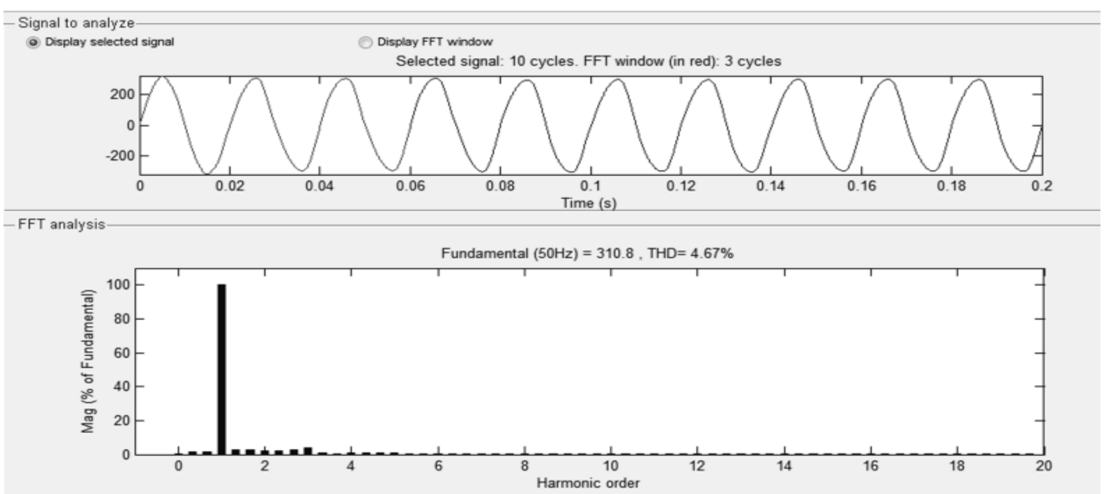

Fig.10: THD value in % for R-L load ($R = 25\ \Omega$, $L = 20$ mH) (Closed-loop).

The Fig.7 and Fig. 8 shows the simulation results obtained from Single-phase CCC type inverters both without and with controller (open-loop and closed-loop operation) explaining that the output voltage gets maintained close to the reference in closed-loop and drastically varying with change of loads for resistive and resistive-inductive loads in open-loop. Moreover, results shown in the Fig. 9 and Fig. 10 are concerned with the various THD values obtained, explaining that the THD value is reduced with the controller showing the improved performance of the proposed CCC inverter. The experimental results for various load conditions have been tabulated from Table-1 to Table-4.

Table-1: Open-Loop Performance for Various R-Loads

R-Load in Ω	V_{rms} in Volts	I_{rms} in Amps	THD in %
25	257	10.2	3.45
30	296	9.8	2.72
35	333	9.5	2.44
40	366	9.12	3.50

Table-2: Closed-Loop Performance for Various R-Loads

R-Load in Ω	V_{rms} in Volts	I_{rms} in Amps	THD in %
25	229	9.19	3.24
30	230.5	7.68	1.62
35	229.8	6.5	1.53
40	230.5	5.76	2.55

Table-3: Open-Loop Performance for Various R-L Loads

RL-Load in Ω	V_{rms} in Volts	I_{rms} in Amps	THD in %
25Ω, 20mH	245.7	9.40	4.68
25Ω, 30mH	248	8.6	4.02
30Ω, 20mH	282.8	9.19	3.08
30Ω, 30mH	286	7.07	3.33

Table-4: Closed-Loop Performance for Various R-L Loads

R L-Load in Ω	V_{rms} in Volts	I_{rms} in Amps	THD in %
25Ω, 20mH	230.5	8.83	4.67
25Ω, 30mH	228.3	8.13	3.07
30Ω, 20mH	229.8	7.21	2.29
30Ω, 30mH	229.8	6.56	2.27

6. Conclusion

The proposed CCC inverter and their control scheme have been demonstrated by the simulated results obtained using MATLAB-Simulink. Unlike a standard PWM inverter, the proposed inverter can operate in a closed-loop mode, and it generates a desired sinusoidal waveform. The proposed converter achieves ZCS at turn-ON and soft turn-OFF. However, the switching frequency varies, depending on several system parameters such as load demand, LC components, magnitude of the DC voltage at the input side etc. The CCC inverter can supply all types of load, including lagging, leading, and unity power factor. The results obtained from Single-phase CCC type inverter both without and with controller is explaining that the output voltage gets maintained close to the reference in closed-loop and significantly varying with change of loads for resistive and resistive-inductive loads in open-loop. The various THD values obtained are proved that the THD value is reduced with the controller showing the improved performance of the proposed CCC inverter. Also the proposed inverter is suitable for UPS applications, Dynamic voltage restorers, Low-power drives,Satellite antennas and other House-hold appliances like DVD players, Vacuum cleaners, Emergency lighting etc which require pure sine wave for its efficient operation.

References

[1] N. Mohan, T. M. Undeland, and W.P. Robbins, Power Electronics: Converters, Applications and Design, 2nd ed. New York: Wiley, 1995.

[2] B. K. Bose, Power Electronics and Motor Drives: Advances and Trends. Amsterdam, The Netherlands: Elsevier, 2006.

[3] M. H. Rashid, Power Electronics: Circuits, Devices and Applications, 3rd ed. New Delhi, India: Prentice-Hall, 2006.

[4] J.Holtz, “Pulsewidth modulation-A survey,” IEEE Trans. Ind. Electron, vol. 39, no. 5, pp. 410–420, Dec. 1992.

[5] M.D.Bellar, T.S.Wu, A.Tchamdjou, J.Mahdavi, and M.Ehsani, “A review of softswitched DC AC converters,”IEEE Trans .Ind. Appl., vol.34, no.4, pp.847860, Jul./Aug. 1998.

[6] Y. Xue, L. Chang, S. B. Kjaer, J. Bordonau, and T. Shimizu, “Topologies of single-phase inverters for small distributed power generators: An Overview,” IEEE Trans. Power Electron., vol. 19, no. 5, pp. 1305–1314, Sep. 2004.

[7] M. Mezaroba, D. C. Martins, and I. Barbi, "A ZVS PWM half-bridge voltage source inverter with active clamping," IEEE Trans. Ind. Electron, vol. 54, no. 5, pp. 2665–2672, Oct. 2007.
[8] C-M. Wang, C-H. Su, M-C. Jiang and Y.-C. Lin, "A ZVS-PWM single- phase inverter using a simple ZVS-PWM commutation cell," IEEE Trans. Ind. Electron., vol. 55, no. 2, pp. 758–766, Feb. 2008.
[9] S. V. Mollov and M. P. Theodoridis, "A frequency multiplication resonant inverter with constant frequency phase control," IEEE Trans. Ind. Electron., vol. 55, no. 3, pp. 1206–1212, Mar. 2008.
[10] A. K. Gupta and A. M. Khambadkone, "A space vector PWM scheme for multilevel inverters based on two-level space vector PWM," IEEE Trans. Ind. Electron, vol. 53, no. 5, pp. 1631–1639, Oct. 2006.
[11] K. Jin, X. Ruan, and F. Liu, "An improved ZVS PWM three-level converter," IEEE Trans. Ind. Electron, vol.54, no.1, pp. 319–329, Feb. 2007.
[12] A. R. Beig, G. Narayanan, and V. T. Ranganathan, "Modified SVPWM algorithm for three levels VSI with synchronized and symmetrical wave- forms," IEEE Trans. Ind. Electron, vol. 54, no.1, pp.486–494, Feb. 2007.
[13] L. G. Franquelo, J. Napoles, R. C. P. Guisado, J. I. Leon, and M. A. Aguirre, "A flexible selective harmonic mitigation technique to meet grid codes in three-level PWM converters," IEEE Trans. Ind. Electron, vol. 54, no. 6, pp. 3022–3029, Dec. 2007.
[14] A. C. Lippincott and R. M. Nelms, "A capacitor-charging power supply using a series-resonant topology, constant on-time/variable frequency control, and zero current switching," IEEE Trans. Ind. Electron., vol. 38, no. 6, pp. 438–447, Dec. 1991.
[15] R.M. Nelms and J. E. Schatz, "A capacitor charging power supply utilizing a ward converter," IEEE Trans. Ind. Electron, vol.39, no. 5, pp. 421–428, Oct. 1992.
[16] R. L. Newsom, W. C. Dillard, and R. M. Nelms, "Digital power factor correction for a capacitor-charging power supply," IEEE Trans. Ind. Electron, vol. 49, no. 5, pp. 1146–1153, Oct. 2002.
[17] S.Dalapati, C. Chakraborty, and S. Bhattacharya, "Single phase, full bridge, controlled capacitor charging (CCC) type inverter," in Proc. IEEE ICIT, Mumbai, India, Dec. 15–17, 2006, pp. 265–270.
[18] S.Dalapati and C. Chakraborty, "A direct PWM technique for a single-phase full-bridge inverter through controlled capacitor charging," IEEE Trans. Ind. Electron., vol. 55, no. 8, pp. 2912–2922, Aug. 2008.