World Engineering & Applied Sciences Journal 8 (2): 78-85, 2017
ISSN 2079-2204

DOI: 10.5829/idosi.weasj.2017.78.85

Performance Evaluation of Nine Level Current Sources Multilevel Inverter Using Pi and Fuzzy Controller

[1]Tamilarasi Devaraj and [2]T.S. Sivakumaran

[1]Research Scholar, Department of Electrical and Electronics Engineering, Anna University, Chennai – 600 025, Tamil Nadu, India
[2]Professor & Dean, PG Studies, Department of Electrical and Electronics Engineering, Arunai College of Engineering, Tiruvannamalai – 606 603, Tamil Nadu, India

Abstract: The paper proposes a Current Source Multilevel Inverter (CSMLI) with single rating inductor topology. Multilevel inverters are most familiar with power converter's applications due to reduced dv/dt, di/dt stress and very efficient for reducing harmonic distortion in the output voltage and output current. The proposed nine-level current source inverter has tested under symmetrical and asymmetrical modes of operation and their activities are compared using PI and Fuzzy PI controllers with multicarrier PWM strategy. PV used as a DC source, photovoltaic energy is a renewable energy with high potential, easy installation, simple maintenance, dependability and long life. MATLAB/Simulink simulation has been made for the proposed converter to obtain its performance measures. Some experimental results are given to verify the presented Current Source Multilevel Inverter.

Key words: Current Source Inverter · Multilevel inverter · Multicarrier PWM · Total Harmonic Distortion · Fuzzy PI Controller · PV array

INTRODUCTION

Multilevel inverters can offer substantial benefits for higher power applications, including reduced harmonics and increased power ratings because of reduced switching device voltage and current stresses. Multilevel inverters have been shown more consideration [1-3]. Multilevel inverters comprise of power semiconductors and DC voltage sources, the output of which create voltages with stepped waveforms. The Multilevel inverter configuration can be categorized into the Voltage Source Multilevel Inverter (VSMLI) and Current Source Multilevel Inverter (CSMLI)[4-6]. Multilevel VSI has DC voltage power source and produces an AC output to the load. Whereas Multilevel Current Source Inverter delivers predetermined AC output from a single or more DC sources due to its high impedance DC power supply. The MCSI has the features of short circuit protection, lower voltage and current stress and less THD in the output waveforms [7-10]. The introduction of current source inverters (CSIs) into this field could lead to marketing advantages due to the advantageous characteristics of this currently less used converter topology. These advantages including: (i) a simple structure; (ii) short-circuit protection; (iii) bidirectional operation; (iv) nearly sinusoidal inputs and outputs; (v) the absence of electrolytic capacitors; and (vi) the possibility to connect in series GTO or GCT, make the use of CSI in high-power medium-voltage drives highly desirable [11].Current Source Inverters with pulse width modulation strategies are employed to deliver a minimum distorted input and output waveforms. This inverter circuit is the double cascaded H-bridge multilevel Current Source Inverter.Tragically, the need for isolated DC sources, power devices and their gating circuits are a few issues of this inverter circuit. Reference [12] introduced the multilevel CSI topology utilizing H-bridge and inductor-cell. This topology streamlines the necessity of isolated DC sources in the parallel H-bridge multilevel CSI. An alternate circuit design of multilevel CSI is made by using

Corresponding Author: T.S. Sivakumaran, Professor & Dean, PG Studies, Department of Electrical and Electronics Engineering, Arunai College of Engineering, Tiruvannamalai – 606 603, Tamil Nadu, India.

a multicell arrangement of multilevel CSI [13-15], which is the double flying capacitor multilevel VSI. Various control, strategies have been exhibited to control the voltage at intermediate levels and highlighted in [16- 18]. However, the inverter still requires expensive larger size middle inductors (>100 mH). These inductors will result in more losses in the inverter circuits and the inverter circuits will have lower efficiency.

This paper presents a nine-level single phase single inductor current source inverter using multicarrier PWM strategy controlled with PI and Fuzzy PI Controller. The Fuzzy PI control algorithm that combines the fuzzy logic control results in suitable nonlinear characteristics as well as efficiently reduces the error in power extraction [19].

Current Source Multilevel Inverter (CSMLI): A current source inverter converts the input DC to an AC at its output terminals. In these inverters, the input voltage is kept constant and the amplitude of output voltage does not depend on the load. Nevertheless, the wave form of load current, as well as its magnitude, depends on the nature of the load impedance. In this inverter, the input current is constant, but adjustable. The amplitude of output current from CSI independent of the load. A DC source supplies current Source Inverter. In an adjustable speed drive (ASD), DC source is usually an AC/DC rectifier with a large inductor to provide stable current supply. Usually, a CSI has a boost operation function, its output voltage peak value can be higher than the DC-link voltage [20, 21].A photovoltaic array used as DC source in the proposed Current Source Multilevel Inverter. The PV Array block implements an array of photovoltaic (PV) modules. The array is built of strings of modules connected in parallel, each string consisting of modules connected in series. The PV Array block is a five parameter model using a current source IL (light-generated current), diode, series resistance Rs and shunt resistance Rsh to represent the irradiance and temperature-dependent I-V characteristics of the modules shown in Figs.1 and 2.

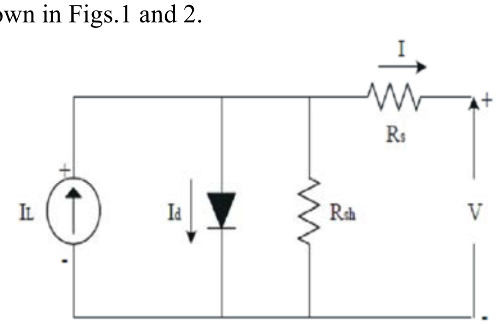

Fig. 1: Equivalent circuit of PV array

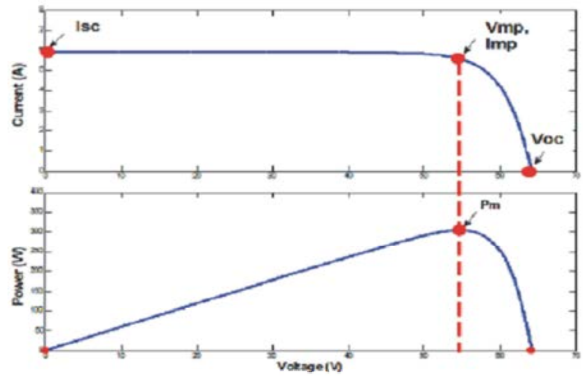

Fig. 2: V-I characteristics of PV

Nine-Level Single Rating Inductor Type Symmetrical Current Source Inverter: Figure 3 shows the power circuit of the proposed nine level single rating inductor type symmetrical current source inverter. From this figure.3, it is observed that the circuit model is obtained by connecting four H-bridge unidirectional controlled power devices and a DC source with equal inductors L. The DC module is working with different intermediate levels for nine-level output waveform generation. All DC sources connected at the common point; due to this the isolated DC sources are no longer necessary in the circuit. The switching sequences for nine level single rating inductor type symmetrical current source inverter shown in Fig.4 and Table.1. The switching sequences show the current level generation of positive, negative and zero level of +I, +2I, +3I, +4I, -I, -2I, -3I, -4I and 0 respectively.

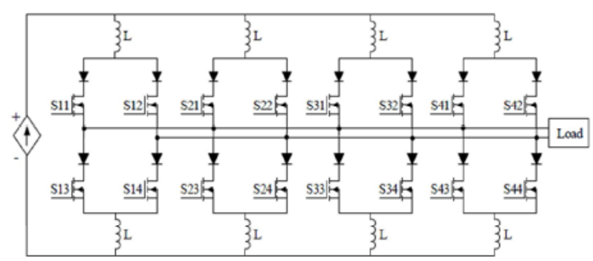

Fig. 3: Proposed nine level single rating inductor type symmetrical current source inverter.

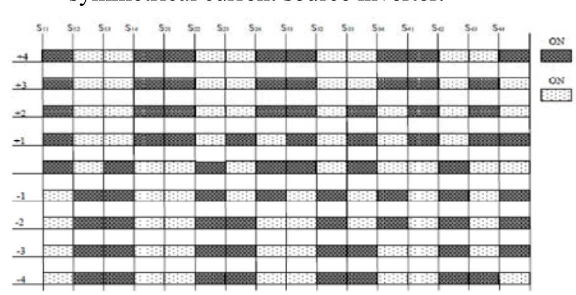

Fig. 4: Switching sequence of nine level symmetrical current source inverter

Table 1: Switching Sequence of proposed symmetrical nine level single rating inductor CSI

Level	S_{11}	S_{12}	S_{13}	S_{14}	S_{21}	S_{22}	S_{23}	S_{24}	S_{31}	S_{32}	S_{33}	S_{34}	S_{41}	S_{42}	S_{43}	S_{44}
+ 4	on	off	off	on	on	off	off	on	on	off	off	on	on	off	off	on
+ 3	on	off	off	on	on	off	off	on	on	off	off	on	on	off	on	off
+ 2	on	off	off	on	on	off	off	on	on	off	on	off	on	off	on	off
+ 1	on	off	off	on	on	off	on	off	on	off	on	off	on	off	on	off
0	on	off	on	off	off	on	off	on	on	off	on	off	off	on	off	on
- 1	off	on	on	off	off	on	off	on	off	on	off	on	off	on	off	on
- 2	off	on	on	off	off	on	on	off	off	on	off	on	off	on	off	on
- 3	off	on	on	off	off	on	on	off	off	on	on	off	off	on	off	on
-4	off	on	on	off	off	on	on	off	off	on	on	off	off	on	on	off

Control Strategy

PI Controller: A Proportional-Integral (PI) control is a particular case of the classic controller family known as Proportional-Integral-Derivative (PID). Till date, these controllers are the most common way of controlling industrial processes in a feedback configuration. More than 95% of all installed controllers are PID [22], for the designed PI controller suited for the multilevel CSI; error signal is as follows,

$$e(t) = I_d(t) - I_{ac}(t) \quad (1)$$

Where Id is the desired current or set point of the proposed current source inverter in amps and Iact is the actual Current drawn by the proposed inverter.

Fuzzy based Proportional Integral controller (Fuzzy PI): The designed Fuzzy Proportional Integral (Fuzzy-PI) controller is a hybrid controller that utilizes two sets of PI gains to achieve a suitable non-linear response. The switching of the controller accomplished with a fuzzy logic section that depends on the input Iin(t). The PI gains utilize e(t) as input that highlighted in equation (1). Fig.5 shows the Fuzzy Proportional and Integral gain response over error and change in error and the fuzzy rule table for proposed converter presented in Table.2.

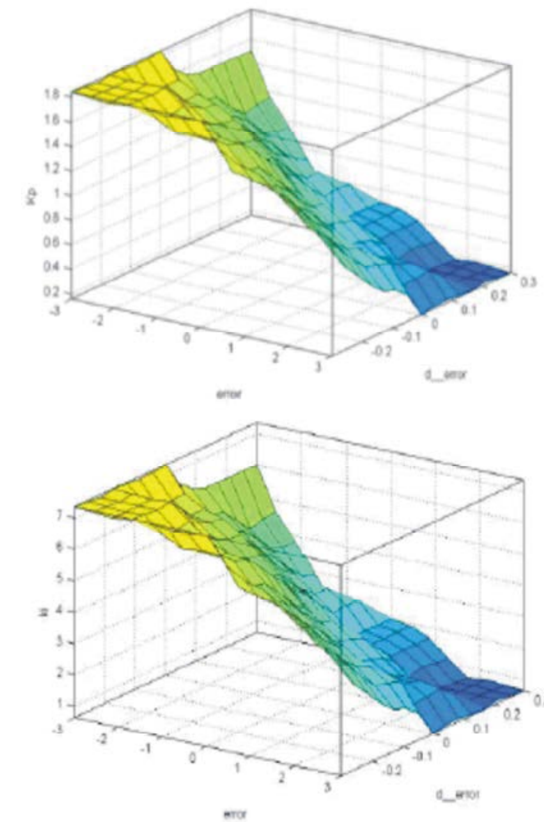

Fig. 5: Fuzzy Proportionality and integral gain response over error and change in error

Table 2: Fuzzy Rule Table for Proposed Converter

e/Δe	NB	NS	Z	PS	PB
NB	PB	PB	NS	PS	Z
NS	PB	NS	PS	Z	NS
Z	NS	PS	Z	NS	PS
PS	PS	Z	NS	PS	NB
PB	Z	NS	PS	NB	NB

Pulse Width Modulation (PWM): In the proposed CSI topology, a level based multicarrier PWM strategy implemented for firing the gate terminals of the MOSFET to obtain the current waveform of nine-level CSI. Multicarrier PWM strategy is a comparison of a reference waveform, with vertically shifted carrier signals. In multicarrier PWM technique, m-1 triangular carriers are used for m-level inverter output voltage or current. In this proposed nine-level topology, eight triangular carriers are preferred. In Phase Opposition Disposition (POD), the carriers above the sinusoidal reference zero points are 180 out of phase with those below the zero point. Fig.6 shows the gate pulse generation of proposed CSI with POD strategy with sine reference of modulation index ma = 0.9 and the carrier frequency of 2 kHz.The carrier waveforms have same amplitude Ac and frequency fc. Similarly, the reference waveforms have frequency fref and an amplitude Aref. At every instant, the response of the comparator is decoded to generate the correct switching sequences with respect to the output of the inverter [23-25].

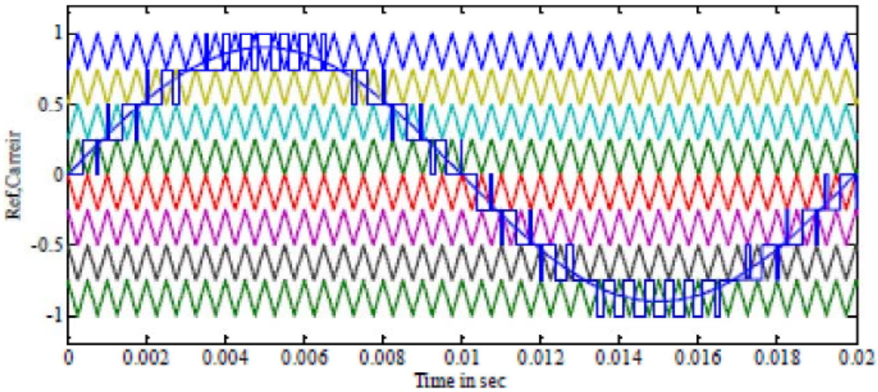

Fig. 6: Gate pulse generation of proposed nine-level CSI

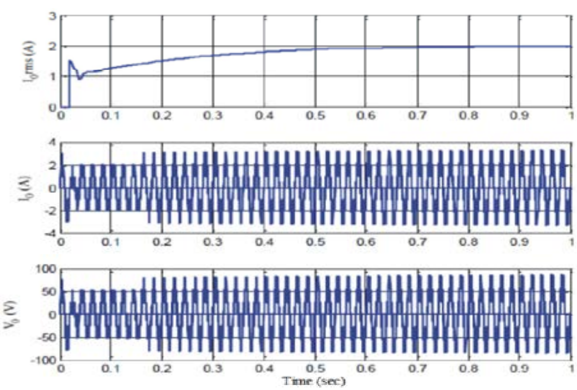

Fig. 7: Closed loop PI controller I0rms, output current and voltage response of symmetrical CSI (set value of Irms=2A)

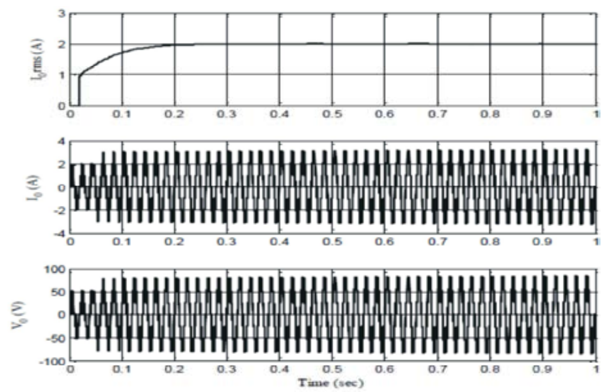

Fig. 8: Closed loop Fuzzy PI Controller I0rms, output current and voltage response of symmetrical CSI (set value of Irms=2A)

Simulation Results

Simulation of Nine Level Single Rating Inductor Type Symmetrical CSI: The current source shared by the four H-bridge inverter with suitable switching sequences generate the nine level output. Multi-carrier pulse width modulation is tuned with proposed PI and Fuzzy PI Controller. Figs.7 and 8 show the individual responses of symmetrical nine-level current source inverter output current, voltage and Irms tuned with PI controller and fuzzy PI controller respectively with a set value of Irms as 2A.

Figure 9 shows the output current responses of PI and fuzzy PI controllers. From this figure, it is observed that the fuzzy PI controller response has been converged very fast compared with conventional PI controller, without any overshoot. Fig.10 shows the current responses comparison of PI and Fuzzy Controller of symmetrical CSI for a step change in load current.

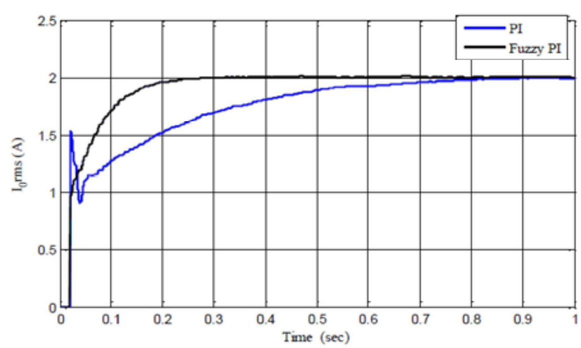

Fig. 9: Current responses comparison of PI and Fuzzy Controller of symmetrical CSI

From figure 10, it is observed that when the load current is suddenly incremented from 2A to 3A at t=1s and decremented from 3A to 2A with respect to time, t=2s. During this instant regulatory responses were obtained and it observed that the fuzzy PI controller response has been settled very fast with its reference current without

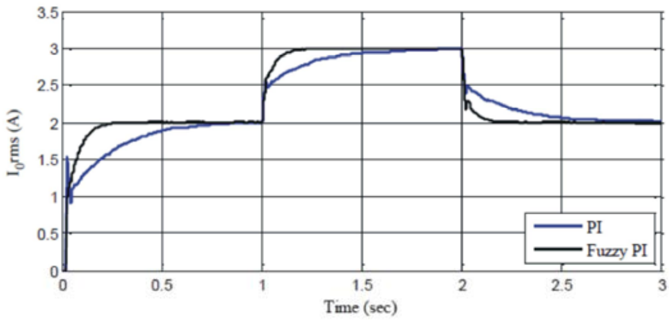

Fig. 10: Current responses comparison of PI and Fuzzy Controller of symmetrical CSI for change in Load resistance (t=0s Iorms = 2A; t=1-2s; Iorms = 3A; t=2s; Iorms = 2A)

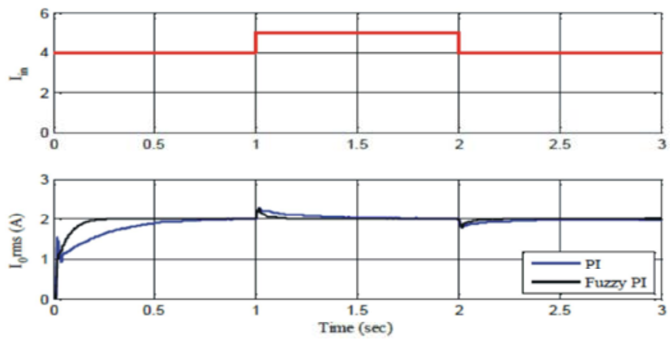

Fig. 11: Current responses comparison of PI and Fuzzy Controller of symmetrical CSI for change in input current (t=0s Iin = 4A; t=1-2s; Iin = 5A; t=2s; Iin = 4A)

Table 3: Performance evaluation of symmetrical CSI with resistive load using MATLAB

Controller	Nominal Case		Servo Response				Regulatory Response			
			Supply Increase 33%		Supply Decrease 33%		Load Increase 33%		Load Decrease 33%	
	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)
PI	0.3027	0.7258	0.352	0.614	0.416	0.690	0.3501	0.7549	0.240	0.468
Fuzzy PI	0.1281	0.2306	0.181	0.119	0.093	0.212	0.1447	0.2658	0.086	0.149

any oscillation compared with PI controller. Similarly, the Fig.11 shows the current responses comparison of PI and Fuzzy Controller of symmetrical CSI for the same change in input. From the figure 11, it is noted that the input current has been suddenly increased from 4A to 5A at t=1s and back to 4A at t=2s. During this servo response, the fuzzy PI controller response has been converged quickly compared with PI controller, which has shown in Table.3.

Simulation of Nine Level Single Rating Inductor Asymmetrical CSI: Figure 12 shows the power circuit of the proposed nine level single rating inductor asymmetrical current source inverter. From this figure, it is observed that the circuit model is obtained by connecting two H-bridge, unidirectional controlled power devices and a DC source with inductors. The switching sequences for nine level single rating inductor asymmetrical current source inverter shown in Table.4.

The switching sequences shows the asymmetrical nine-level current generation with addition and subtraction process of inverter. i.e. active level +I (I+0), +2I (3I-I), +3I (3I+0), +4I (3I+I), negative level -I (-I+0), -2I (-3I+I), -3I (-3I+0), -4I (-3I-I) and 0 respectively. The current source shared by the two H-bridge inverter with suitable switching sequences generate the nine level output. Multicarrier pulse width modulation strategy is implemented for IGBT switching with PI and Fuzzy PI Controller. Figs.13 and 14 show the individual responses of asymmetrical nine-level current source inverter output

Table 4: Switching Sequence of Asymmetrical nine level single rating inductor CSI

Level	S_{11}	S_{12}	S_{13}	S_{14}	S_{21}	S_{22}	S_{23}	S_{24}
+ 4	on	off	off	on	on	off	off	on
+ 3	on	off	on	off	on	off	off	on
+ 2	off	on	on	off	on	off	off	on
+ 1	on	off	off	on	on	off	on	off
0	on	off	on	off	off	on	off	on
- 1	off	on	on	off	off	on	off	on
- 2	on	off	off	on	off	on	on	off
- 3	off	on	off	on	off	on	on	off
-4	off	on	on	off	off	on	on	off

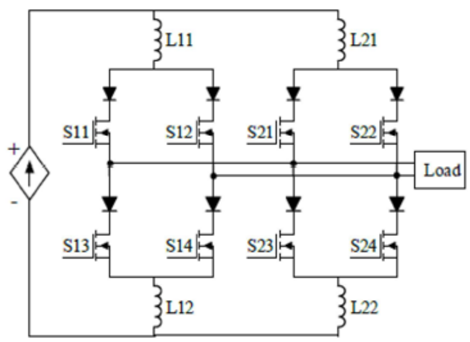

Fig. 12: Proposed nine level single rating inductor asymmetrical CSI.

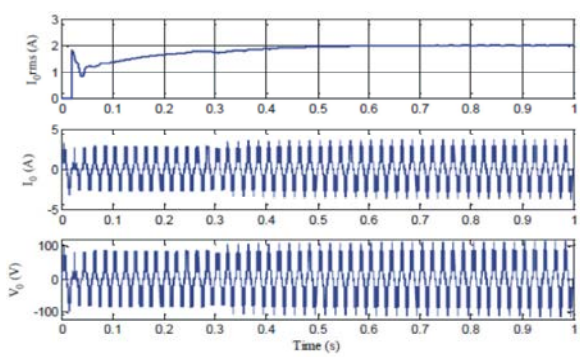

Fig. 13: Closed loop PI controller I0rms, output current and voltage response of Asymmetrical CSI

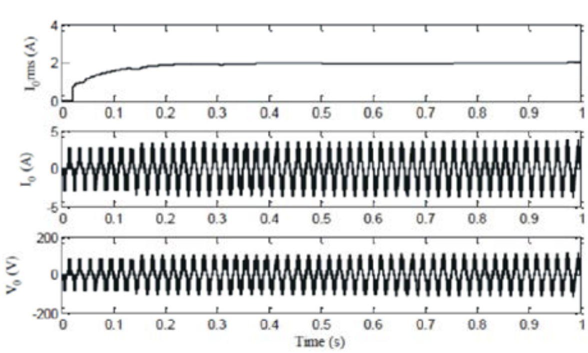

Fig. 14: Closed loop Fuzzy PI Controller I0rms, output current and voltage response of Asymmetrical CSI

current, voltage and Irms tuned with PI controller and fuzzy PI controller respectively with a set value of Irms of 2A. Figs.15 shows the output current responses of PI and fuzzy PI controllers. From this figure, it is observed that the fuzzy PI controller response has been settled at 0.637 sec, whereas the fuzzy PI controller tuned response settled at 0.39 sec, without any disturbances.

Figure 16 shows the current response comparison of PI and Fuzzy Controller of asymmetrical CSI for change in load current. During these regulatory responses, the fuzzy PI controller response has been settled very fast with its reference current without any oscillation compared with

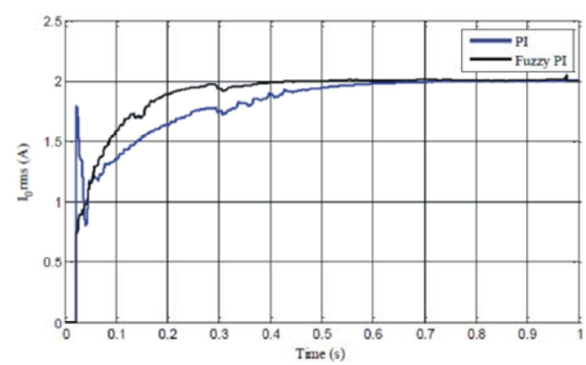

Fig. 15: Current responses comparison of PI and Fuzzy Controller of asymmetrical CSI

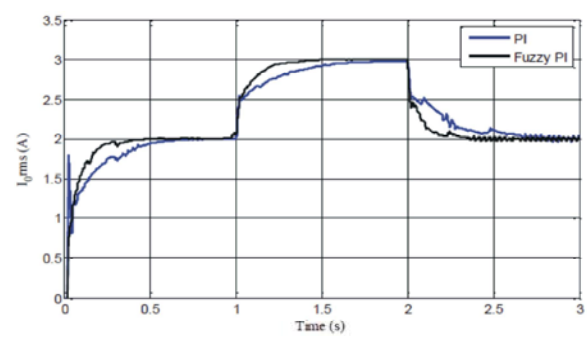

Fig. 16: Current responses comparison of PI and Fuzzy PI Controller of asymmetrical CSI for change in reference (t=0s I0rms = 2A ; t=1-2s I0rms = 3A; t=2s I0rms = 2A)

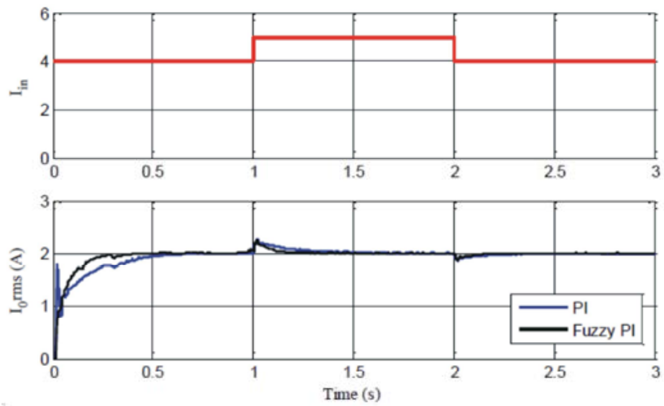

Fig. 17: Current responses comparison of PI and Fuzzy PI Controller of asymmetrical CSI for change in input (t=0s Iin = 4A ; t=1-2s Iin = 5A; t=2s Iin = 4A)

Table 5: Performance evaluation of Asymmetrical CSI with resistive load using MATLAB

Controller	Nominal Case		Servo Response				Regulatory Response			
			Supply Increase 33%		Supply Decrease 33%		Load Increase 33%		Load Decrease 33%	
	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)	Rise Time (sec)	Settling Time (sec)
PI	0.260	0.646	0.251	0.790	0.337	0.935	-	0.540	-	0.320
Fuzzy PI	0.094	0.386	0.158	0.432	0.167	0.361	-	0.193	-	0.105

Table 6: Comparison of Symmetrical and Asymmetrical nine-level single inductor CSI

Description	Symmetrical	Asymmetrical
%THD	14.31	14.26
I_{rms} in Amps	4.015	4.096
No. of switches required	16	8
No. of inductors required	8	4

PI controller. Similarly, the Fig.17 shows the current responses comparison of PI and Fuzzy Controller of asymmetrical CSI for change in input. From the figure 17, it is noted that the input suddenly increased from 4A to 5A at t=1s and back to 4A at t=2s. During this servo response, the fuzzy PI controller response has been converged before PI controller. Table. 5 shows the performance analysis of asymmetrical CSI using PI and Fuzzy Controller. Table 6 shows the comparison of symmetrical and asymmetrical CSI circuit.

CONCLUSION

In this work, an important assessment of Current Source Multilevel Inverter (CSMLI) has been presented. It draws a low-ripple current from the PV cells, therefore maximizing its performance. The inverter is built with state-of the-art power devices that have fast switching times. The overall performance analysis of proposed symmetrical and asymmetrical nine-level single phase single inductor current source inverter tabulated in Table. 3 and 5. From the Table 6, it is observed that the asymmetrical CSI circuit provided a good %THD and steady state analysis controlled by PI and fuzzy PI controllers at different operating conditions. Also in topology wise the asymmetrical inverter is economical with less number of components to achieve the same (nine) level compared with symmetrical CSI. The switching and conduction losses minimized due to the presence of fewer components in the power circuit of asymmetrical CSI. The experimental results are also proved the same.

REFERENCE

1. Li, Z., P. Wang, P. Li and F. Gao, 2012. A novel single-phase five-level inverter with coupled inductors. IEEE Trans. on Power Electronics., 27: 2716-2725.

2. Banaei, M.R., A.R. Dehghanzadeh, E. Salary and H. Khounjahan, 2012. Z-source-based multilevel inverter with reduction of switches. IET Power Electronics, 5: 385-392.
3. Singh, B., N. Mittal, K.S. Verma, D. Singh, S.P. Singh, R. Dixit, M. Singh and A. Baranwal, 2012. Multi-Level Inverter: A Literature Survey on Topologies and Control Strategies, 10: 1-6.
4. Carrara, G., S. Gardella, M. Marchesoni, R. Salutari and G. Sciutto, 1992. A New Multilevel PWM Method: A Theoretical Analysis, IEEE Trans. on Ind. Electron, 7: 497-505.
5. Rodriguez, J., P. Correa and L. Moran, 2002. A vector control technique for medium voltage multilevel inverters, IEEE Trans. Ind. Electron., 49: 882-888.
6. Barbosa, P.G., H.A.C. Braga and E.C. Teixeira, 2006. Boost current multilevel inverter and its application on single phase grid connected photovoltaic system, IEEE Trans. on Power Electron., 21: 1116-1124.
7. Suroso, Noguchi, T., 2014. A single-phase multilevel current source converter using H-bridge and DC current modules, International Journal of Power Electronics and Drive System (IJPEDS), 2: 165-172.
8. Klumpner, C. and F. Blaabjerg, 2006. Using reverse blocking IGBTs in power converters for adjustable-speed drives,IEEE Trans. on Industry Appl., 42: 807-816.
9. Kwak, S. and H.A. Toliyat, 2006. Multilevel converter topology using two types of current-source inverters. IEEE Trans. on Ind. Appl., 42: 1558-1564.
10. Xu, D., N.R. Zargari, B. Wu, J. Wiseman, B. Yuwen and S. Rizzo, 2005. A Medium Voltage AC Drive with Parallel Current Source Inverters for High Power Applications. in Proc. 36th IEEE Power Electronics Specialists Conf., Brazil, pp: 2277-2283.
11. Wiseman, J. and B. Wu, 2004. Active damping control of a high power PWM current source rectifier for line current THD reduction’. Proc. IEEE-PESC04, Aachen, Germany, 1: 552-557.
12. Suroso, S. and T. Noguchi, 2012. Multilevel current waveform generation using inductor cells and H-bridge current source inverter. IEEE Trans. on Power Electron., 27: 1090-1098.
13. Bai, Z.H. and Z.C. Zhang, 2008. Conformation of multilevel current source converter topologies using the duality principle. IEEE Trans. on Power Electron. 23: 2260-2267.
14. Antunes, F.L.M., H.A.C. Braga and I. Barbi, 1999. Application of a generalized current multilevel cell to current source inverters. IEEE Trans. on Power Electron, 46: 31-38.
15. Suroso., Noguchi, T., 2010. New H-Bridge Multilevel Current-Source PWM Inverter with Reduced Switching Device Count, in Proc. IEEE Power Electron. Conf. (IPEC), Sapporo, pp: 1228-1235.
16. Bao. Jianyu, D.G. Holmes, Zhihong Bai., Zhongchao Zhang and Dehong Xu, 2006. PWM control of a 5-level single-phase current-source inverter with controlled intermediate DC link current. Proc. of IEEE PES Conf., Jeju, pp: 1633-1638.
17. McGrath, B.P. and D.G. Holmes, 2008. Natural current balancing of multicell current source inverter, IEEE Trans. On Power Electron, 23: 1239-1246.
18. Vazquez, N., H. Lopez, C. Hernandez, E. Vazquez, R. Osorio and J.Arau, 2010. A different multilevel current source inverter, IEEE Trans. on Industrial Electron, 57: 2623-2632.
19. Torres-Salomao L.A. and H. Gamez-Cuatzin, 2012. Fuzzy Logic Control and PI control Comparison for a 1.5 MW Horizontal Axis Wind Turbine. 2012 16th Int. Conf. on System Theory, Control and Computing, ICSTCC, Control Society, Sinaia, Romania.
20. Bao, J.Y., 2006. A new three-phase 5-level current-source inverter. Journal of Zhejiang University SCIENCE A., 7: 1973-1978.
21. Bao, J.Y., 2010. Generalized multilevel current source inverter topology with self-balancing current. Journal of Zhejiang University-SCIENCE C (Computers & Electronics), 11: 555-561.
22. Åström, K.J. and T.H. Hagglund, 1995. New tuning methods for PID controllers. Proc. of the 3rd European Control Conf., pp: 2456-62.
23. McGrath, B.P. and D.G. Holmes, 2002. Multicarrier PWM strategies for Multilevel Inverters, IEEE trans. On Industrial Electron, 49: 858-867.
24. Jinn-Chang Wu and Chia-Wei Chou, 2013. A Solar Power Generation System With a Seven-Level Inverter. IEEE, Trans. on Power Electronics, 29: 3454-3462.
25. Boost, M.A. and P.D. Ziogas, 1988. State-of-the-Art Carrier PWM Techniques: A Critical Evaluation. IEEE Trans.on Industry Applications, 24: 271-280.