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Design and Simulation of Fuzzybased DC-DC Interleaved Zeta Converter for Photovoltaic Applications

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Abstract— **This paper presents the design and simulation of Fuzzy based DC-DC Interleaved Zeta converter for photovoltaic and renewable energy applications. The conventional converter doesn't meet the basic requirements like high efficiency, less losses and fewer ripples. In order to achieve the better performance the Interleaved DC-DC Zeta converter has been operated in discontinuous conduction mode (DCM) and also can be able to do step-up or step down DC output voltage with high efficiency. This Fuzzy based DC-DC Interleaved Zeta converter is best suitable for the renewable energy resources like solar photovoltaic applications and wind power. The operating principle of the Interleaved Zeta converter and analysis based on steady-state and dynamic has been done in this work. A 100W, 48V load has been designed and simulated to ensure the feasibility and performance of this converter.**

Keywords— Interleaved Zeta converter(ILZ), pulse width modulation (PWM), Continuous conduction mode (CCM), Discontinuous conduction mode (DCM), Single Ended Primary Inductor Converter (SEPIC), Light Emitting Diode (LED), Switched Reluctance Motor (SRM), Brushless DC Motor (BLDC).

I. INTRODUCTION

Traditionally lot of single stage converters has been used including Buck[1], Boost [2], Buck-Boost, SEPIC and LUO [3] converters as DC-DC converter, for converting fixed DC supply to variable DC supply because of their reliability, costless and simple structure. But the above said converters have less efficiency, very high ripples, pulsating source and load current. In order to resolve these problems, multiple DC-DC converters with different topology have been proposed to improve the efficiency and reduce the ripples. Based on the type of applications following DC-DC converters can be employed viz., Buck converter [4], Boost converter [5], and Buck-Boost converter. Advanced soft computing techniques also used to achieve the faster settling time and high efficiency [6] [7]. The continuous conduction mode (CCM) of operation of those converters causes complicated design and increased cost. In order to reduce size, cost and weight some converters have been operated in discontinuous conduction mode (DCM) [8]. But, to reduce the switching losses and voltage stress across the switches these converters has been used for the low power applications. The Buck converters can be operated in the DCM mode of operation to step down the voltage but results in more ripples and inefficient. When the conventional buck-boost converter operated in the DCM mode of operation in order to boost-up or step-down the voltage, but results in narrow output power range and the converter is not suitable for the renewable energy applications which have low input line voltage (12 V).

This paper presents Fuzzy based interleaved DC-DC step – up or step-down Zeta converter. This interleaved zeta converter can be operated in wide voltage regulation and wide range of duty-cycle compared with the conventional converters. The Interleaved Zeta have the special features includes wide range of voltage regulation for low input voltage range, wide output-power range, less ripples in the voltage and current, high efficient, and adjustable step-up or step- down the DC output voltage. Fig. 1 shows the electrical circuit configuration of the conventional Zeta converter [9]. From this conventional converter different new topologies have been developed. Fuzzy based [10] DC-DC Interleaved Zeta converter has been developed by including two identical conventional Zeta converters connected in parallel circuit [11]. Except the Zeta converter, all the other converters have been widely used and studied for different applications like LED drivers [12], BLDC motor and SRM motor with different operating modes such as continuous, discontinuous and boundary conduction modes [13].

The buck converter is the basic converter with simple configuration and the cheapest converter [14]. But, the Buck converter can be used only when the output DC voltage requirement is smaller than the input DC supply. Also the Buck converter causes high ripples and distortion in the supply and output current. Therefore, the buck converter is not suitable for all the voltage regulation applications. On the other hand, the boost converter has a simple construction, cheap in price, higher efficiency and the overall performance is better and widely used in industries. However, this converter can be used such applications like the output voltage requirement is higher than the input voltage. Applications like solar, fuel cell and renewable resources which output voltage need to be boosted up, hence it requires Boost converter [15]. But some applications like LEDs are generally required low-voltage. Hence multiple LEDs need to be connected in series which leads to complexity. Hence, the Boost converter not suitable for the low-power loads and not appropriate.

In order to overcome the limitations of Buck converter and Boost converter, the Buck–Boost converter comes in to the picture [16]. The Buck–Boost converter plays a vital role in industries, to step-up or step-down the DC voltages. Based on the operating modes and conditions the converter attains maximum efficiency. But this converter doesn't attain the high efficiency over the wide DC input voltage range and also produce ripples in the input current. LUO converter is a new DC-DC conversion topology, which using the voltage lift technique prototype [17]. CUK converter on the other hand, is a cascade combination of Buck and Boost converters with the collective advantages of Buck and Boost converters [18]. The advantages of using the CUK converter are the input and output current is continuous and less ripples. The SEPIC converter is one more new topology derived from the CUK and Boost converters [19]. However, these converters were totally different from the Zeta converter. Zeta converter is a fourth order DC to DC converter and the output of the Zeta converter is non-inverting DC output voltage. SEPIC, LUO and CUK converters [20] are developed from Boost converter, but the Zeta converter [21] is developed from a buck–boost converter.

II. CONVENTIONAL ZETA CONVERTER

Zeta converter is a fourth order single stage non isolated DC to DC converter, developed from a buck–boost converter. The Zeta converter provides non-inverting output voltage at its output. The purpose of using the single-stage dc–dc power converter is to attain the high efficiency as well as good voltage regulation to its load. Among the different dc–dc converter topologies, six basic converters are widely used in industries, viz., Buck, Boost Buck–boost, SEPIC, CUK and Zeta converter. Most of the research works comes out with the various applications with different modes of operation such as CCM and DCM except the Zeta converter. The research on the Zeta converter has been explored the advantages and applications of Zeta converter. Fuzzy based Zeta converter have the attractive advantages includes high efficiency, less ripples, less settling time and applicable for the low-power renewable energy applications. The preference of the Zeta converter has also emerged due to the different problems observed in other converters.

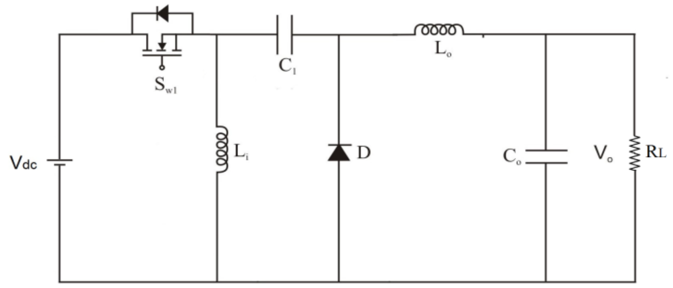

Fig. 1.Circuit diagram of conventinal Zeta converter

The Zeta converter has a less ripples in the output voltage but discontinuous input current compared with SEPIC and CUK converters. Most of the loads are highly sensitive to the voltage variation, hence ripple is one of the important requirements for the converter. Since the output current is discontinuous, the SEPIC converter requires large capacitor at the DC link, causing the component cost is more compare to Zeta converter. The Fuzzy based non-isolated interleaved DC-DC Zeta converter efficiently serves the purpose to improve the performance and the efficiency for the primary-side regulation (PSR) technique.

III. INTERLEAVED ZETA CONVERTER

The conventional Buck-Boost converter is employed with DCM operation is widely used for step up or step down the DC supply with moderate efficiency. But for wide voltage range and output power range, the conventional Zeta converter is not suitable due to less efficiency. This paper presents Fuzzy based interleaved not isolated DC-DC step-up/down Zeta converter. This converter can be operated with wide duty-ratio range and wide supply voltage variation range than the conventional Zeta converter. The Interleaved Zeta converter contains operational features includes high efficiency, less output voltage ripple, low input current distortion, adjustable step-up/down output voltage and wide output-power range. At the same time, the electromagnetic interference (EMI) will be reduced with the continuous input current and size of the filter components have been reduced. Fig. 2 shows the circuit configuration of the Interleaved Zeta converter, which consists of two identical Zeta converters connected in parallel connection.

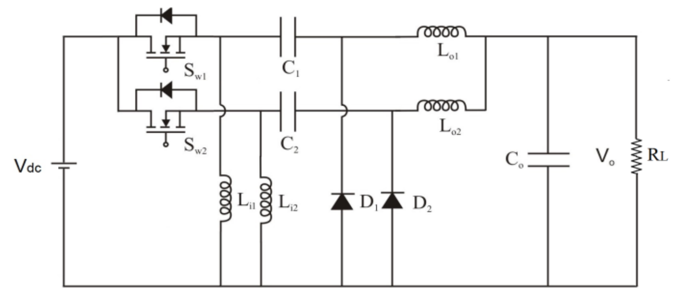

Fig. 2.Circuit diagram of Interleaved Zeta converter

IV. MODES OF OPERATION

To simplify the analysis of the circuit, all the components used in the circuit are assumed to be ideal. The input inductor L_{i1} is operated in CCM mode and the output inductor L_{o1} is operated in DCM mode. The inductors specifications are chosen to operated in such a way. Fig. 3 illustrated four modes of operation for different switching period for one complete cycle.

Mode 1 $[t_0 \leq t \leq t_1]$:

During Mode 1, switch S_1 is turned on and at the same time S_2 is in off condition. The inductor L_{i1} & capacitor C_1 is storing energy from the DC supply V_{dc}. The inductor L_{o1} is releasing its stored energy to the load through the output DC link capacitor C_o. The inductor L_{o1} and C_o are resonating during this mode.

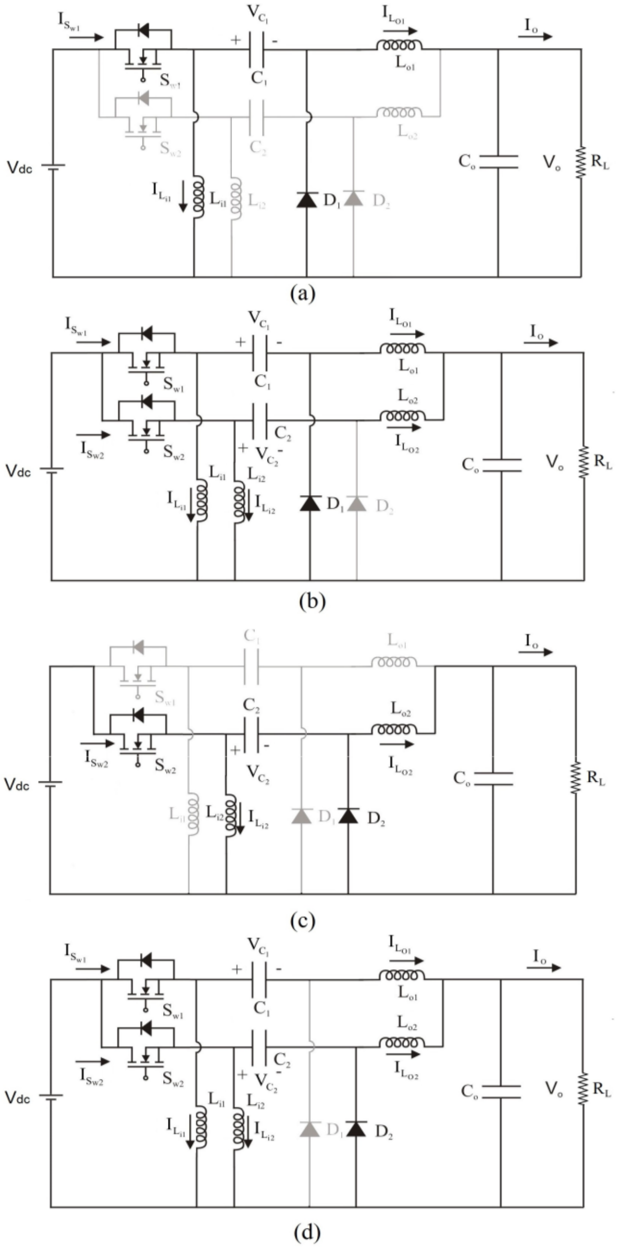

Fig. 3.Different Modes of Operation (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Mode 2 [$t_1 \leq t \leq t_2$]:

During Mode 2, switches S_1 and S_2 both are turned ON. The inductor L_{o1} is dissipating energy to the load through output capacitor C_o. The inductor L_{i2} & C_2 starts charging from the DC supply through the switch S_2. End of this mode the inductors L_{i1} completely charged L_{o1} starts discharging.

Mode 3 [$t_2 \leq t \leq t_3$]:

In Mode 3 the switch S_2 is kept on condition, and S_1 turned off. The inductor L_{i2} & C_2 is continuously charging until the switch is on. The inductors L_{i1}, L_{o1} starts discharging to the load through DC link capacitor. End of this mode, L_{o1} completely discharged charging in reverse direction and there is minimum current circulating through the output capacitor and load.

Mode 4 [$t_3 \leq t \leq t_4$]:

Switches S_1 and S_2 both are turned ON. The inductors L_{i2}, L_{o2} starts discharging to the load through the DC link capacitor. The inductors L_{i1}, L_{o1} & capacitor C_1 is storing energy from the DC supply V_{dc} through the sweitch S_1. End of this mode the L_{i2}, L_{o2} inductors completely discharged and the cycle repeats.

V. PULSE WIDTH MODULATION SCHEME

Since the output DC bus voltage need to be maintain constant, the MOSFET switches have to be controlled by varing the magnitude and frequency of PWM signals. This could be accomplished by generating proper PWM signals using FPGA which controls the converter output [22-24].

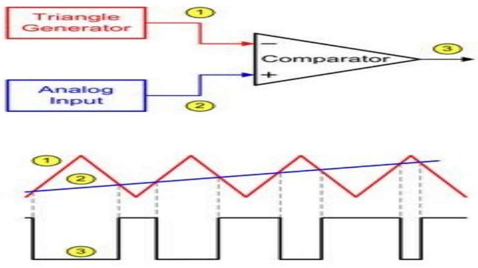

Fig. 4.Generation of PWM pulses

Among various methods of pulse generation, the square PWM technique is very popular in industrial applications. Eventhugh the PWM generations is easy, there are two major concerns for generating square PWM. The first objective is to minimize the ripples in the output voltage and another concern is to reduce the creation of distortion. The general principle of generating square PWM technique is the comparison of two different waveforms, one is a high frequency triangular wave, which is also called as the carrier signal and another one is control signal. The triangular carrier waveform has fixed amplitude and frequency. Fig.4 shows the simulink model of PWM generation. In a square PWM waveform the current distortion is still very significant. If square PWM is implemented in a converter with a large number of pulses per half cycle, such as motor speed control, no separate filter may be needed on the output side. Square PWM offers greater functionality includes minimization of output voltage ripples, reductions in size and price and in additional improves inverter functional capabilities such as active filtering and reactive power support.

VI. SIMULATION RESULTS

The interleaved Zeta converter helps to improve the efficiency and reduce ripples in the output voltage. In practical conventional Zeta converter circuit, the ripple current is high in the DC load. Due to this effect more complicated switching function and current waveforms are produced. Waveform analysis for Interleaved Zeta converters have been done, the constant DC Bridge current has been assumed for the derivation of the currents. In conventional and proposed circuits are simulated and compared. Fig.5 shows the simulation diagram of open loop simulation of Interleaved Zeta converter. Fig.6 shows the switching pulses generated for the switches S_1 and S_2 for open loop simulation with the help of the triangular signal generator.

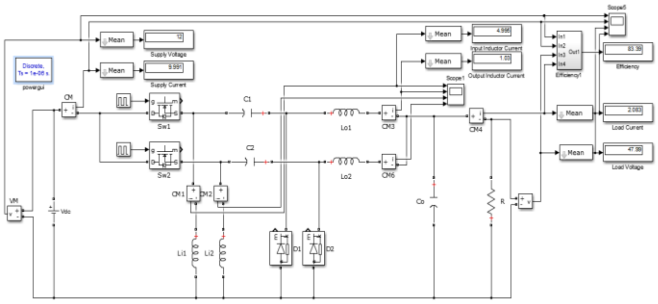

Fig. 5.Open loop simulation of Interleaved Zeta converter

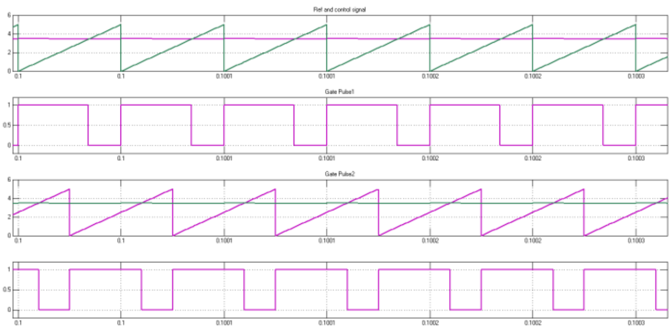

Fig. 6.Switching pulses for S_1 & S_2

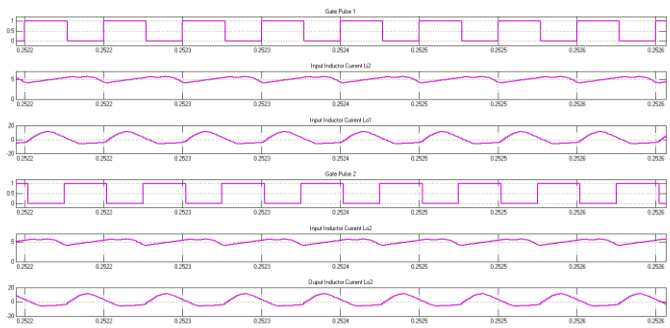

Fig. 7.Input and Output Inductor current waveforms

The inductor current wave forms have captured for the further analysis as per the fig. 7. This picture shows that the output inductor currents are in discontinuous current mode and the input inductor is in the continuous current mode. Fig.8 shows the output voltage and current waveforms of interleaved Zeta converter for the desired output voltage of 48V DC. Further analysis have been done to make sure the better performance of the Interleaved Zeta converter and the values are tabulated.

Table 1 shows the open loop readings with the supply voltage variation. It gives the maximum efficiency of 88.35% at the supply voltage of 48V. Table 2 shows the open loop readings with the duty cycle variation. The desired voltage achieved when the duty cycle is 0.81.

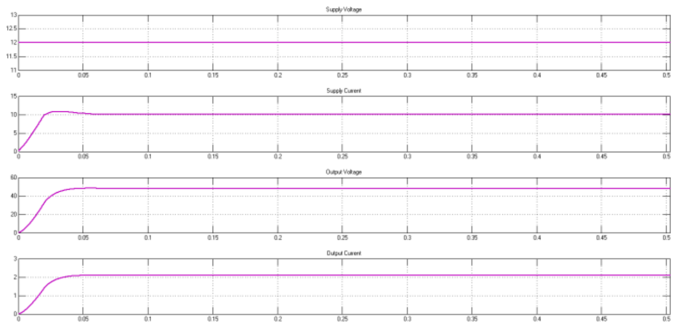

Fig. 8.Output voltage and Current

TABLE 1. OPENLOOP READINGS WITH SUPPLY VOLTAGE VARIATION

S.No	Vin (V)	Iin (A)	ILi1 (A)	ILo1 (A)	Vo (V)	Io (A)	η %
1	8	6.87	0.53	0.56	33.0	1.43	86.07
2	12	9.64	0.96	0.99	48.0	2.08	86.43
3	16	13.89	1.07	1.12	66.7	2.90	86.97
4	20	17.40	1.34	1.45	83.6	3.63	87.16
5	24	17.95	1.60	1.71	87.3	4.36	88.35

TABLE 2. OPENLOOP READINGS WITH DUTY CYCLE VARIATION

S.No	D	Vin (V)	Iin (A)	ILi1 (A)	ILo1 (A)	Vo (V)	Io (A)	η %
1	0.1	12	0.03	0.01	0.05	2.1	0.09	56.83
2	0.2	12	0.10	0.05	0.10	4.5	0.20	73.51
3	0.3	12	0.22	0.11	0.15	7.0	0.30	80.14
4	0.4	12	0.39	0.19	0.21	9.5	0.41	83.59
5	0.5	12	0.62	0.31	0.26	12.0	0.52	85.03
6	0.6	12	1.22	0.61	0.98	17.3	0.75	88.70
7	0.7	12	3.00	1.50	1.63	27.5	1.19	91.22
8	0.8	12	7.60	4.30	3.95	48.0	1.73	91.16
9	0.9	12	9.24	9.58	9.64	48.0	2.08	90.17

In order to achive the constant output voltage the closed loop simulation has been done as shown in fig.9 for the Interleaved Zeta converter to ensure to achieve the desired output voltage. PI controller has been used to accomplish the closed loop simulation of the Interleaved Zeta converter. Fig.10 shows the switching waveforms and the inductor waveforms. The input inductor waveform is continuous and the output inductor waveform is discontinuous conduction mode.

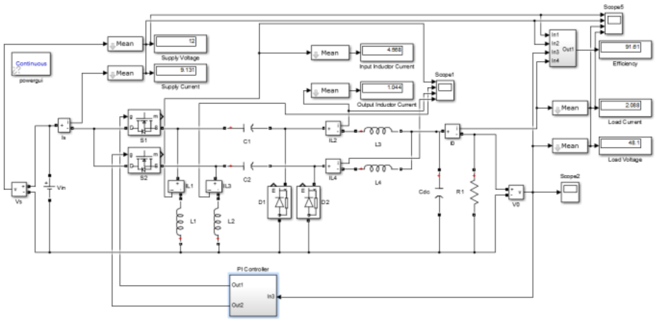

Fig. 9.Closed loop simulation of Interleaved Zeta converter with PI controller

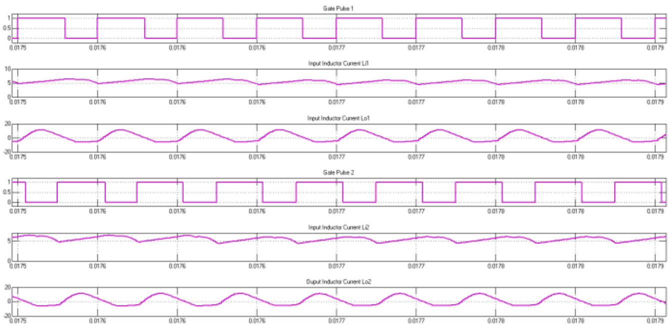

Fig. 10. Switching and Inductor waveforms of Interleaved Zeta converter

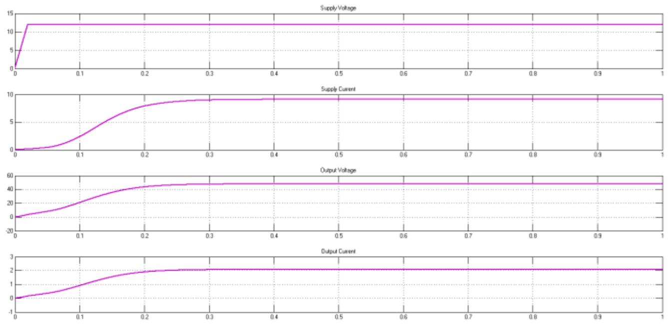

Fig. 11. Supply voltage, output voltage and output current waveforms

TABLE 3. CLOSEDLOOP READINGS WITH SUPPLY VOLTAGE VARIATION

S.No	Vin (V)	Iin (A)	ILi1 (A)	ILo1 (A)	Vo (V)	Io (A)	η %
1	8	13.70	7.25	1.04	48	2.083	91.23
2	12	9.12	4.56	1.04	48	2.083	91.41
3	16	6.90	3.42	1.07	48	2.083	90.57
4	20	5.50	2.60	1.01	48	2.083	90.89
5	24	4.60	1.92	0.88	48	2.083	90.57

Fig.11 shows the supply voltage, output voltage and output current waveforms of the Interleaved Zeta converter.Table 3 shows the closed loop readings with supply voltage variation. The maximum efficiency is 91.41% at the supply voltage of 12V DC. Table 4 shows the closed loop readings with the load variation. The efficiencyc at full load is 91.41%. Table 5 shows the setpoint variation.

TABLE 4. CLOSED LOOP READINGS WITH LOAD VARIATION

S. No	Load (W)	Vin (V)	Iin (A)	ILi1 (A)	ILo1 (A)	Vo (V)	Io (A)	η %
1	100	12	9.12	4.56	1.04	48	2.083	91.41
2	75	12	6.85	3.388	0.7773	48	1.562	91.21
3	50	12	4.61	2.262	0.5223	48	1.041	90.29
4	25	12	2.29	1.172	0.2597	48	0.521	90.91

TABLE 5. CLOSED LOOP READINGS WITH SET POINT VARIATION

S. No	Set point	Vin (V)	Iin (A)	ILi1 (A)	ILo1 (A)	Vo (V)	Io (A)	η %
1	30	12	3.515	1.761	0.6494	30	1.299	92.39
2	40	12	6.277	3.141	0.8677	40	1.735	92.14
3	48	12	9.115	4.564	1.043	48	2.083	91.41
4	60	12	14.325	7.319	1.332	60	2.602	90.82

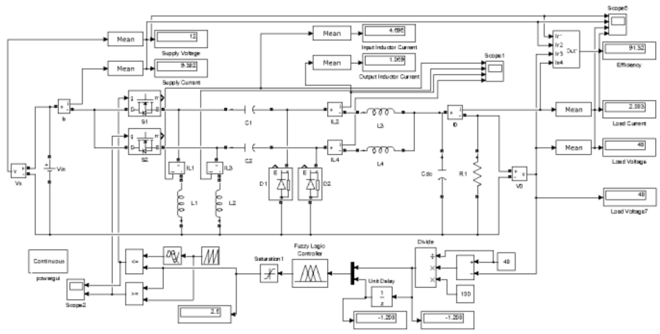

Fig. 12.Closed loop simulation of Interleaved Zeta converter with Fuzzy controller

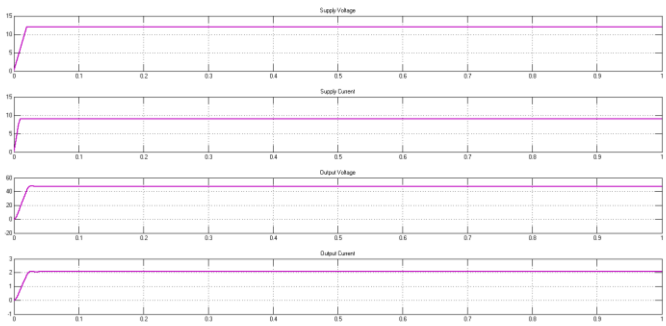

Fig. 13.Supply and output voltage and current waveforms

The closed loop implementation using the PI controller tooks some time to settle in the specific voltage. The settling time can be reduced by using a soft computing technique, which is Fuzzy controller. Fig.12 shows the simulation of Fuzzy based Interleaved DC-DC Zeta converter. Fig.13 shows the supply voltage, supply current, output voltage and output current waveforms. The Fuzzy controller ensures the much more faster settling time of 0.02s compared to the PI controller 0.32s.

VII. CONCLUSION

The Fuzzy based non-isolated interleaved dc-dc Zeta converter with a low voltage ripples with high efficiency has been designed and analyzed. This new topology concentrates on the improvement from the conventional Zeta converter through the development of a new Fuzzy based Interleaved topology. The non-isolated interleaved dc-dc Zeta converter has been tested and analyzed in MATLAB with various performance parameters and ensure the operating conditions with various modes which provides significant performance. Various performance analysis has been evaluated on Interleaved dc-dc Zeta converter with open loop simulation, closed loop simulation with PI controller and closed loop simulation with Fuzzy controller. The performance of the converter has been evaluated based on the steady state performance and the dynamic performance, and also performance indices obtained. The maximum efficiency of 91.32% obtained using Fuzzy based non-isolated Interleaved dc-dc Zeta converter for wide range of input voltages.

REFERENCES

[1] Zhang, Chuanlin, Junxiao Wang, Shihua Li, Bin Wu, and Chunjiang Qian. "Robust control for PWM-based DC–DC buck power converters with uncertainty via sampled-data output feedback." *IEEE Transactions on Power Electronics* 30, no. 1 (2015): 504-515.

[2] Zaions, Deividi F., Anderson J. Balbino, Cássio L. Baratieri, and Adilson L. Stankiewicz. "Comparative analysis of buck and boost converters applied to different maximum power point tracking techniques for photovoltaic systems." In *Power Electronics Conference (COBEP), 2017 Brazilian*, pp. 1-6. IEEE, 2017.

[3] Gnanavadivel J, Senthil Kumar N, C. N. Priya, S. T. Christa, and K. S.Krishna Veni. "Single phase positive output super-lift luo converter fed high power LED lamp with unity power factor and reduced source current harmonics." *Journal of Optoelectronics And Advanced Materials* 18, no. 11-12 (2016): 1007-1017.

[4] Qi, Wenlong, Sinan Li, Siew-Chong Tan, and SY Ron Hui. "Parabolic-Modulated Sliding-Mode Voltage Control of a Buck Converter." *IEEE Transactions on Industrial Electronics* 65, no. 1 (2018): 844-854.

[5] Shobana, P, N. Geetha, and Gnanavadivel J. "Enhancement of power quality of AC-DC Boost converter with HCC and FLC-A comparative study." In *Computing, Electronics and Electrical Technologies (ICCEET), 2012 International Conference on*, pp. 254-258. IEEE, 2012.

[6] Gnanavadivel J, Senthil Kumar, and P. Yogalakshmi. "Comparative Study of PI, Fuzzy and Fuzzy tuned PI Controllers for Single-Phase AC-DC Three-Level Converter." *Journal of Electrical Engineering & Technology* 12, no. 1 (2017): 78-90.

[7] Smiline E Therese Reena, Gnanavadivel J, ST Jaya Christa, and N. Senthil Kumar. "Performance evaluation of PI and fuzzy tuned PI controllers for single phase bridgeless modified SEPIC converter." In *Circuit, Power and Computing Technologies (ICCPCT), 2016 International Conference on*, pp. 1-6. IEEE, 2016.

[8] Liang, Tsorng-Juu Peter, Kai-Hui Chen, and Jiann-Fuh Chen. "Primary Side Control For Flyback Converter Operating in DCM and CCM." *IEEE Transactions on Power Electronics* 33, no. 4 (2018): 3604-3612.

[9] Ramaprabha N, Gnanavadivel J, N. Senthil Kumar, and ST Jaya Christa. "Power quality improvement in single phase AC to DC zeta converter." In *Sustainable Energy and Intelligent Systems (SEISCON 2013), IET Chennai Fourth International Conference on*, pp. 533-537. IET, 2013.

[10] Thenmozhi, R., C. Sharmeela, P. Natarajan, and R. Velraj. "Fuzzy logic controller based bridgeless isolated interleaved zeta converter for LED lamp driver application." *International Journal of Power Electronics and Drive Systems* 7, no. 2 (2016): 509.

[11] Jothimani, Gnanavadivel J, Senthil Kumar Natarajan, and Yogalakshmi Palanichamy. "Fuzzy controller based power quality improvement in three level converter with multiloop interleaved control for marine AC/DC applications." (2017) Indian journal of Geo Marine Sciences, Vol. 46(09), Sep2017, pp. 1908-1919.

[12] Shrivastava, Ashish, Bhim Singh, and Somnath Pal. "A novel wall-switched step-dimming concept in LED lighting systems using PFC zeta converter." *IEEE Transactions on Industrial Electronics* 62, no. 10 (2015): 6272-6283.

[13] Gnanavadivel J, N. Senthil Kumar, and P. Yogalakshmi. "Implementation of FPGA based three-level converter for LIED drive applications." *Journal of Optoelectronics and Advanced Materials* 18, no. 5-6 (2016): 459-467.

[14] Zhang, Chuanlin, Junxiao Wang, Shihua Li, Bin Wu, and Chunjiang Qian. "Robust control for PWM-based DC–DC buck power converters with uncertainty via sampled-data output feedback." *IEEE Transactions on Power Electronics* 30, no. 1 (2015): 504-515.

[15] Kim, Jae-Kuk, Jae-Bum Lee, and Gun-Woo Moon. "Isolated switch-mode current regulator with integrated two boost LED drivers." *IEEE Transactions on Industrial Electronics* 61, no. 9 (2014): 4649-4653.

[16] Saharia, Barnam Jyoti, Munish Manas, and Subir Sen. "Comparative Study on Buck and Buck-Boost DC-DC Converters for MPP Tracking for Photovoltaic Power Systems." In *Computational Intelligence & Communication Technology (CICT), 2016 Second International Conference on*, pp. 382-387. IEEE, 2016.

[17] Gnanavadivel J, N. Senthil Kumai, CN Naga Priya, and KS Krishna Veni. "Investigation of Power Quality Improvement in Super Lift Luo Converter." *International Journal of Power Electronics and Drive Systems* 8, no. 3 (2017): 1240.

[18] Wu, Hongfei, Junjun Zhang, and Yan Xing. "A family of multiport buck–boost converters based on DC-link-inductors (DLIs)." *IEEE Transactions on power electronics* 30, no. 2 (2015): 735-746.

[19] Gnanavadivel J, Vidhya Chellappa, and N. Senthil Kumar. "Comparison of power quality improvement techniques in ac-dc Cuk converter." In *Computer, Communication and Electrical Technology (ICCCET), 2011 International Conference on*, pp. 400-404. IEEE, 2011.

[20] Simonetti, Domingos Savio Lyrio, Javier Sebastian, and Javier Uceda. "The discontinuous conduction mode Sepic and Cuk power factor preregulators: analysis and design." *IEEE Transactions on Industrial Electronics* 44, no. 5 (1997): 630-637.

[21] Kumar, Rajan, and Bhim Singh. "BLDC motor-driven solar PV array-fed water pumping system employing zeta converter." *IEEE Transactions on Industry Applications* 52, no. 3 (2016): 2315-2322.

[22] Gnanavadivel J, N. Senthil Kumar, and S. T. Christa. "Implementation of FPGA based fuzzy and hysteresis controllers for power quality improvement in single phase three-level rectifier." *Optoelectronics and Advanced Materials-Rapid Communications* 9, no. 9-10 (2015): 1264-1272.

[23] Zhang, Zhenbin, Fengxiang Wang, Tongjing Sun, José Rodríguez, and Ralph Kennel. "FPGA-based experimental investigation of a quasi-centralized model predictive control for back-to-back converters." *IEEE Transactions on Power Electronics* 31, no. 1 (2016): 662-674.

[24] Divya, E., and Gnanavadivel J. "Harmonic elimination in three phase PWM rectifier using FPGA control." In *Emerging Trends in Electrical and Computer Technology (ICETECT), 2011 International Conference on*, pp. 436-441. IEEE, 2011.