Non-Linear Modulation for High Gain Three-Phase Boost Inverter

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***Abstract*— In this paper a single-stage three-phase boost inverter with non-linear modulation is introduced. This inverter is capable of generating high-voltage AC output from a low-input dc source. In order to prevent voltage drop at the input floor, parallel paths of current are proposed in this converter and a new structure of boost inverter is applied. The performance of this inverter is generally based on charging inductors in parallel and their discharging in series. After analyzing the performance of the proposed converter, the dynamical equations governing the converter are extracted. This converter is simulated in MATLAB/Simulink and results check the validity of the equations. At the end, practical prototype is studied in laboratory and results are extracted, which evaluates the accuracy of the dynamic equations obtained in this new structure.**

Keywords*— *Single-stage DC-AC converter, boost inverter, non-linear modulation.

I. Introduction

Over the past few decades, the growing trend of using renewable energy has led to an increase in utilizing power electronic converters in this field [1, 2]. In the structure of renewable energy, those converters are usually used which generally have two features in common; first, increasing the input voltage range; and second, convert the boosted DC voltage to an alternating voltage of three or single-phase output [3].

Using an all-bridge converter with a boost transformer can be considered as a convenient and reliable solution to convert DC voltage to sinusoidal alternating voltage [4-5]. Due to the fact that all-bridge converter is a BUCK converter, a boost transformer is used to increase its output voltage range. The advantage of this type of converter is output voltage stability in a wide range of load variations (from zero to 100% rated load). One of the strength points of using this converter is to feed asymmetric loads due to the presence of null point in the secondary side. The only drawback of this system is the weight and volume of its iron transformer. However, the utilization of this type of structure is suitable for connecting and exchanging power with the medium-voltage distribution network (20 KV).

Other solution in which DC voltage can be converted to an alternating voltage with larger amplitudes is the use of a two-stage converter, which in the first stage through a DC-DC boost converter, the DC voltage amplitude increases and then in the second stage, it will be converted to an alternating voltage through a Voltage Source Inverter (VSI) [6-8]. Indeed, the DC-DC boost converter acts as a regulator of the input voltage for the main converter. The advantage of this method is that the inverter modulator index can always be considered as the unity and to change the magnitude of the AC output voltage, control the voltage magnitude of DC-DC boost converter. This type of structure has been more encouraging in utilizing solar panels. Disadvantages of a two-stage converter are the size and volume of the inductance associated with the DC-DC converter as well as the number of semiconductor switches in this structure.

In [9], Current Source Inverter (CSI) has been introduced in order to implement DC-AC boost conversion. The important issue in this type of converter is to control and maintain stability at all operating points. Other point is that the designer should always be cautious about the magnitude of the inductor current not to pass through the range of instability and at the same time keep the average value of the inductor current (DC link) at a constant value. As a negative feature, it should be kept in mind that in the case of sudden interruption of load, the output voltage suddenly increases sharply, which can lead to instability or even devastation of switches. Additionally, the high number of switches also causes the CSI not to be considered as a superior choice.

Z-Source inverter may be considered a combination of voltage source and current source inverters, since in practice it exhibits similar behavioral characteristics to both types of converters. Simultaneous activation of both switches in a leg for a short time is the feature that this converter uses to increase the voltage range, known as “shoot through” [10-13]. In Z-Source inverter and CSI, due to existence of inductor in input side, there is no reason to worry about the short circuit in each leg. The ability to increase the voltage range in Z-Source inverter is far less than other methods, but since the structure of the switches and its control method are similar to those of a voltage source, the approach to using it in the field of operation renewable energy is more than the CSI. Compared to the voltage source inverter, the existence of two relatively large inductors and capacitors in input side and low-pass filter in output side of Z-Source inverter, makes the voltage source inverters still more popular.

Other single-stage boost inverters are introduced in [14-18] and each one has its own advantages and disadvantages. Among different structures, in [19] an applicable topology of Boost Inverter is applied which is shown in figure 1.

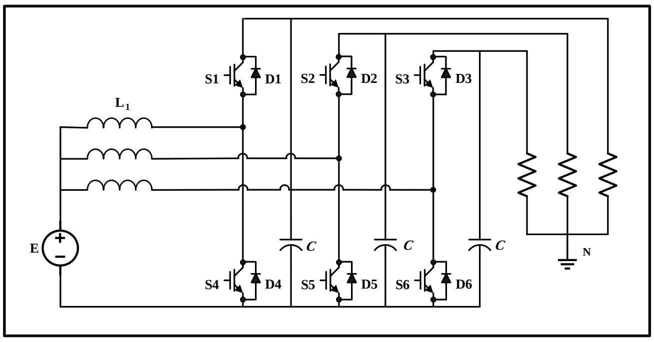

Fig. 1. Single-stage three-phase Boost Inverter.

TABLE I. COMPARISON OF DIFFERENT STRUCTURES OF COMMONLY USED DC-AC CONVERTERS

DC-AC Converters	Number of switches	Weight and volume of filter/transformer	Reliability	Controllability and Stability	The ability to increase the voltage range	Efficiency	Construction Costs
VSI + transformer	6	Overweight	High	Easy and stable	High	High	Medium
DC/DC Boost +VSI	8	Bulky DC inductor, Medium LC filter	Medium	Not so difficult and stable	Medium	Medium	High
CSI	12	Bulky DC inductor, Large capacitive filter	Low	Difficult And unstable	Medium	Low	High
Z-source converter	6	Bulky DC inductor, large capacitors	Medium	Difficult and unstable	Low	Medium	High
Boost-Inverter(Fig.1)	6	Small inductors and capacitors	High	Very difficult and unstable	High	High	Low

This inverter is made up of a differential combination of three boost converters. The point N is the negative pole of the DC voltage source, which is common to all three converters. Pulse width modulation is the same for all three converters with a 120 degrees shift, and thus the voltage V_{dc} is divided between load phases. The output voltage of each boost converter, or related capacitor, is made up of two components; a DC part and an alternating part. The interesting point is that the average value of the output voltage of each of the three phases is equal to each other, and since the converter have been connected differentially, the average load voltage is equal to zero.

This converter has significant characteristics due to its arrangement and the number of switches which is equal to the voltage source converter, also the size of the inductors and the capacitors used in it are not as much as other topologies. The main problem with this type of converter is how to control it in order to generate sinusoidal voltage. Despite offering different solutions, compared to other converters, distortion and low-order harmonics are high on the output side of this converter and since filtering low-order harmonics requires massive filters, it's difficult to use this converter. Regarding significant advantages such as low-frequency, single-stage, minimum number of IGBTs and the possibility of controlling as a voltage source inverter, it is not easy to discard the utilization of this converter. Table I summarizes the advantages and disadvantages of DC-AC converters with the ability to increase the voltage range. The fields that is considered for this comparison include the number and size of structural elements, reliability, efficiency, construction costs, controllability and stability, and the ability to increase the voltage range.

So far, different structures of commonly used DC-AC converters were investigated. Also in the [19] laboratory sample of boost inverter (Fig.1) has been constructed and studied. In the next section, a new structure of this boost inverter is introduced that uses the current dividing technique in input side to reduce the voltage drop across the input side and achieve higher gain. After introducing this inverter, the operational principles are explained and then simulation results in MATLAB software are presented and the accuracy of the results is checked. Finally, in experimental result section a sample prototype which is made in Malayer University is investigated.

II. PROPOSED STRUCTURE

The proposed converter in this paper is a single-stage, three-phase boost inverter capable of generating high-voltage AC output from a low-input dc source. The structure of desired inverter is clearly indicated in figure 2. Fig. 2(a) shows the overall circuit while Fig.2(b) shows the internal circuit for each phase. This inverter has n paths or n layers in each phase. In each path, there is an inductor with the value of L and an internal resistance r. In each phase with n paths, 3n-3 switches are applied. The output of each phase is connected to the midpoint of a leg with two switches. Three capacitors (C) are connected in parallel in each of three leg. In this figure a resistive load which is connected in star form are considered for desired converter.

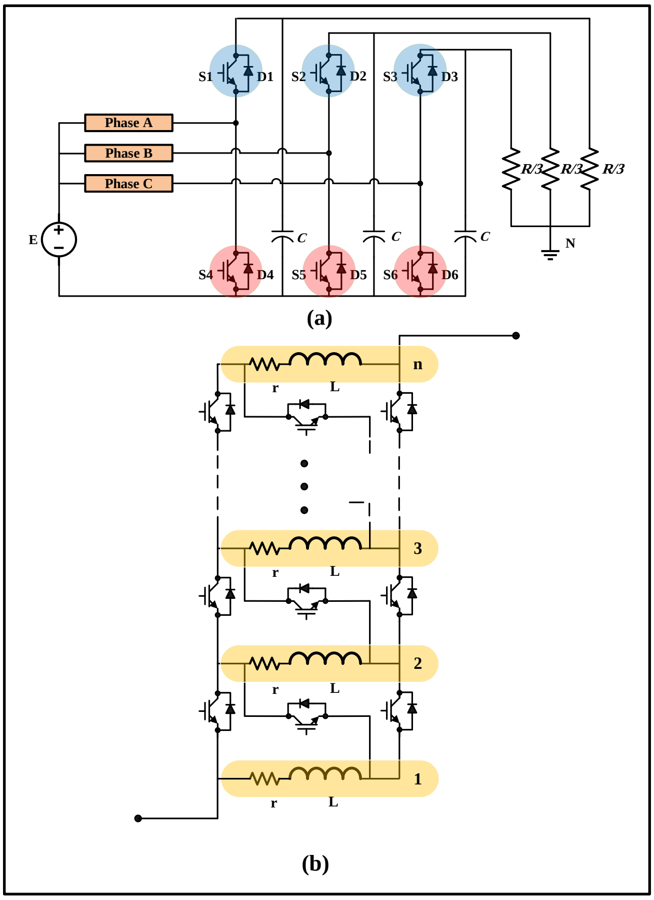

Fig. 2. Proposed Inverter Circuit. a) Overall circuit. b) Internal circuit of each phase (For Phase A,B and C).

As mentioned, this inverter could have n paths in each phase; the number of inductors is equal to the number of paths. Increasing the number of paths from 1 to n has different effects on converter performance. For instance, reducing the pulse width of switches and consequently increasing the efficiency.

III. OPRATIONAL PRINCIPLES

The general equivalent circuit of the proposed structure for phase A has been illustrated in figure 3. As shown in this figure, all switches are marked with two positions of 1 and 2. The performance of this inverter is generally based on the charging inductors in parallel and their discharging in series; which has two main advantages, first reduction of input resistance and second reducing the pulse width of switches. This inverter has two operating conditions, which will be discussed in following section. The proposed inverter is discussed for phase A and extended to other phases. For convenience, the output load is considered to be connected in triangular form.

A. *First state*

In this state, the switches 1 are switched on while switches 2 are off. Figure 4 illustrates this situation. In this state, all inductors in n paths are placed in parallel with the DC source and start charging. The current in each path is the same and the sum of these current is equal to the current drawn from voltage source. Using the voltage and current rules for figure 4, equation (1) is obtained for phase a.

$$\begin{cases} L\dot{I}_a = E - rI_a \\ C\dot{V}_{an} = -\dfrac{V_{an}-V_{bn}}{R} - \dfrac{V_{an}-V_{cn}}{R} \end{cases} \qquad (1)$$

B. *Second state*

In the second state, unlike the first state, the switches 1 are off and the switches 2 are turned on. This situation is shown in figure 5. In this case, all inductors come in series with the source and begin to discharge. In this situation, the current in each path is the same and its value is equal to the current drawn from the source. Equation in this case for phase A are given by,

$$\begin{cases} nL\dot{I}_a = E - nrI_a - V_{an} \\ C\dot{V}_{an} = I_a - \dfrac{V_{an}-V_{bn}}{R} - \dfrac{V_{an}-V_{cn}}{R} \end{cases} \qquad (2)$$

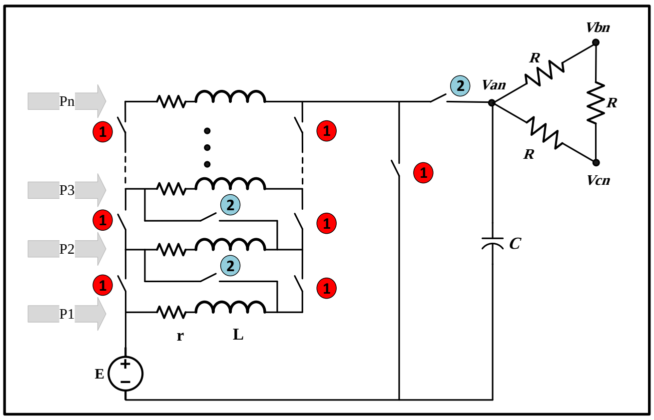

Fig. 3. Proposed inverter circuit for phase A

In this equation n is the number of paths. V_{an}, V_{bn} and V_{cn} are considered as line voltages by default and are defined as followed,

$$\begin{cases} V_{an} = A\sin(wt+0^\circ) + A + E \\ V_{bn} = A\sin(wt+120^\circ) + A + E \\ V_{cn} = A\sin(wt+240^\circ) + A + E \end{cases} \qquad (3)$$

From Equations (1), (2) and (3), the mean values of V_{an} and I_a in a complete period of switching are obtained as follows:

$$\begin{cases} L\dot{I}_a = \dfrac{E[D_a(n-1)+1] + D_a V_{an} - V_{an}}{n} - rI_a \\ C\dot{V}_{an} = D'_a I_a - \dfrac{V_{an} - A - E}{R/3} \\ D_a + D'_a = 1 \end{cases} \qquad (4)$$

Where D_a and D'_a are the switch pulse widths in positions 1 and 2, in the phase A. Equation (4) is a three-dimensional equation with first-order partial derivatives of time. With a little simplification,

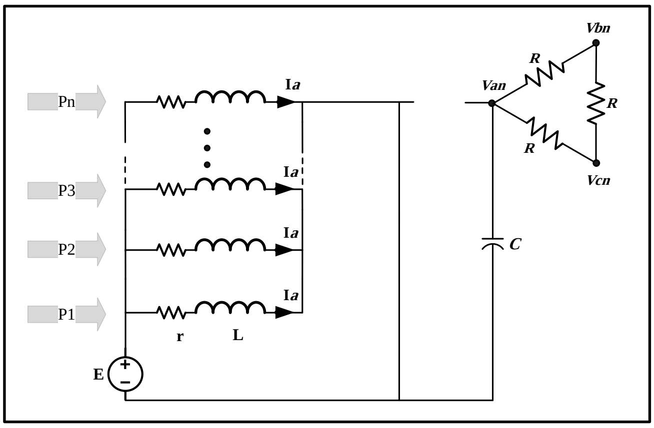

Fig. 4. Inverter circuit in first state for phase A

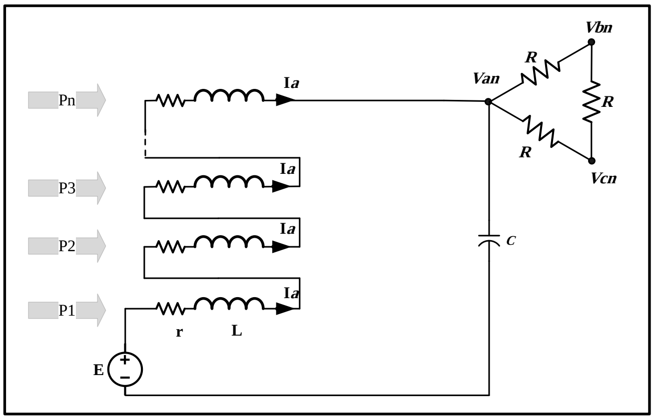

Fig. 5. Inverter circuit in the second state for phase A

$$D'_a = \frac{n(LI'_a + rI_a - E)}{E - nE - V_{an}} \qquad (5)$$

This is a non-linear equation and to obtain pulse width D'_a, this non-linear equation must be solved. Equations (3), (4) and (5) are simulated in the MATLAB software Simulink environment and results are given in following section.

IV. Simulation Result

As previously mentioned, the proposed converter model was based on the Boost Inverter. Therefore, to evaluate the performance of the proposed converter, simulation of this converter was performed in MATLAB Simulink and simulation results were obtained. The values of simulation parameters are given in Table II.

The simulated block diagram model has been used in MATLAB software to solve non-linear equation (5) and obtain D (pulse width) for a period of 20 milliseconds. According to the proposed structure, the number of paths shown in figure 2 can vary and cause different effects on the efficiency of the converter. Increasing the number of paths in each phase leads to a decrease in the maximum duty cycle, which can be clearly seen in figure 6. The output gain and efficiency of the boost inverter are directly dependent on the pulse width of the switches. Increasing the number of induction pathways results in a decrease in the pulse width and consequently a decrease in the losses. Through equations 4 and 5, the non-linear duty cycle was calculated and results for three phase of proposed inverter have been obtained in figure 7. It should be noted that switching frequency is 10 Khz, while the output frequency is 50hz.

Figure 8 shows the three-phase output voltage of the proposed converter. As it is known, the output voltage range is 100 V. According to the input voltage of the converter which is 20 V, the gain value of this converter is around 5. Regarding the obtained waveform, the output voltage is smooth with small fluctuations.

Figure 9 shows the current drawn from the source by each phase and the total current drawn from the source. As it is known, the current drawn from the source is equal to the sum of the currents drawn by each phase.

Figure 10 compares input power and output power of proposed structure. By a simple calculation the desired converter efficiency is roughly 78%.

Table II. Simulation parameters

Description	Variables	Simulation values
DC Source	**E**	20(V)
Load resistance	**R**	30(Ω)
Inductance	**L**	0.3(mH)
Internal resistance	**r**	0.01(Ω)
Capacitors	**C**	0.1(mF)
Switching frequency	**f**	10(Khz)
Output Frequency	f_o	50(Hz)
Number of legs	**n**	3

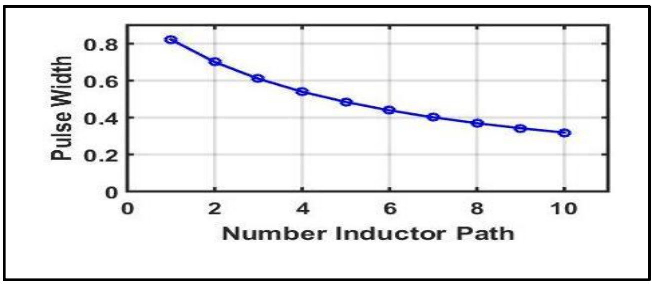

Fig. 6. Increasing the numer of inductor path (pararell path) decrease pulse width

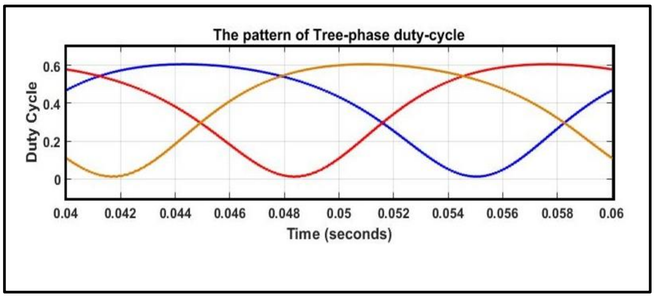

Fig. 7. Duty cycle of three-phases

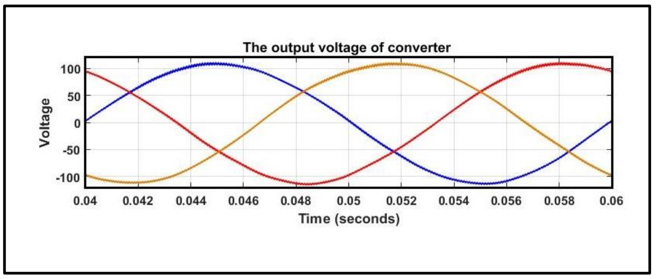

Fig. 8. Three-phase output voltage of the proposed converter

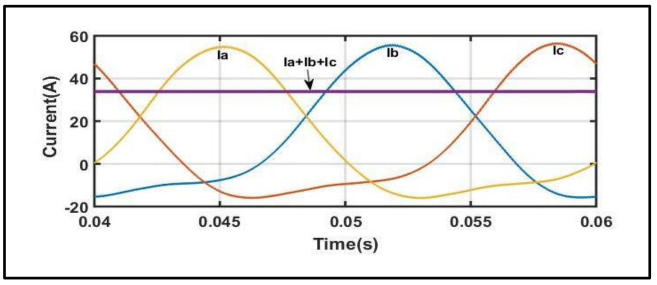

Fig. 9. Three pahse current and total current drawn from the source.

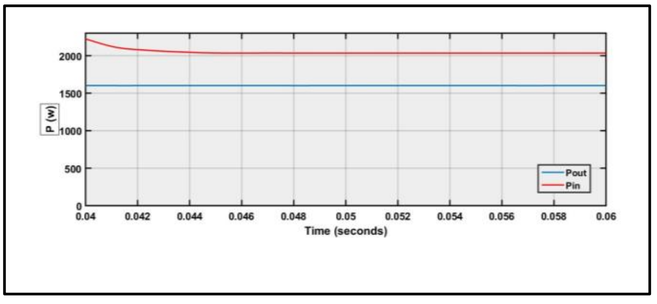

Fig. 10. Input power and output power of proposed structure.

V. Experiment Result

To validate the simulation results and evaluate the performance of the proposed structure, a sample prototype of this converter was built in Malayer University. Figure 11 shows the desired converter along with the different parts used.

The power circuit includes a 12 *V*, 55 *Ah* batteries as the input dc voltage, nine 300 μH, 10A inductors, three 250 μF, 100V capacitors and six IGBT switches (BUP314D). Drivers of the switches are fed through four isolated DC supplies, where the coupler TLP250 interfaces the microprocessor and the power circuit. A three-phase laboratory L-C set as the output filter and a three-phase laboratory R-L were used as the load. The microprocessor is the EZDSP TMS320F28335 that regulates pulse widths for the six switches using code composer.

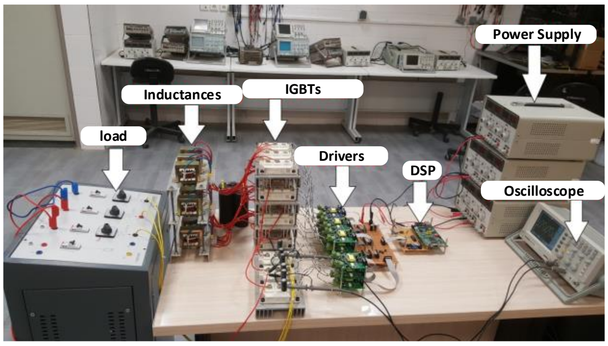

Fig. 11. Proposed Boost Inverter with new structure built in Malayer University laboratory

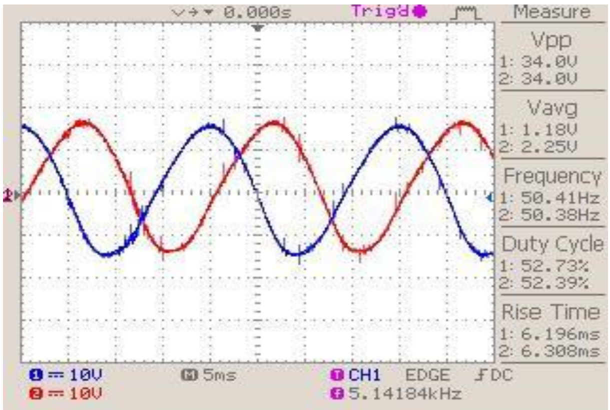

Fig. 12. Results of the implementation . output voltage for the two phase of inverter

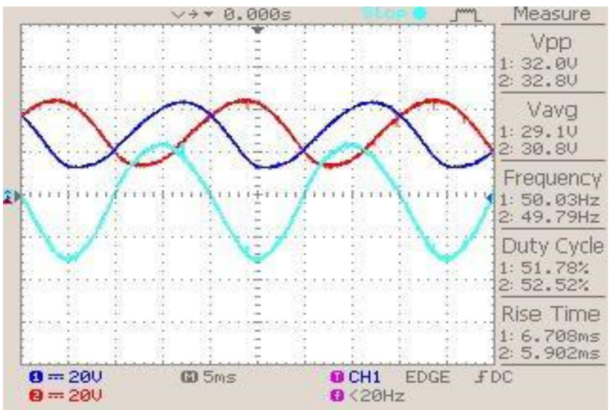

Fig. 13. Output voltage of boost parts of Boost Inverter and their differences which is phase voltage.

The built-in converter has three paths in each phase, so the number of inductors for each phase is 3, which employs a total of 9 inductors. By applying the pulse width discussed in the previous section (Fig. 7), the output results for this inverter are obtained. The output voltage for the two phase of inverter is shown in figure 12. As can be seen, the output is quite sinusoidal, with a higher range than the input value (approximately 50V). Figure 13 shows the output voltage of two boost parts of boost inverter and their differences which is phase voltage. As mentioned earlier, the phase voltage is obtained from the output differences of the boost parts of proposed inverter.

VI. CUNCLUSION

In this paper, an integrated three-phase inverter with improved structure was introduced. The proposed Boost-Inverter presented in this paper had a distinctive structure which reduced the input voltage drop by applying the current-dividing technique. The dynamic equations governing the proposed converter were extracted using a one-cycle averaging technique. By solving the nonlinear equation, the value of the converter duty cycle was obtained. the accuracy of the obtained equations was verified by simulation in MATLAB software. In addition to the simulation results, the results of the practical implementation confirm the obtained equations.

VII. REFERENCES

[1] Debnath, D. and K. Chatterjee, *Solar photovoltaic-based stand-alone scheme incorporating a new boost inverter.* IET Power Electronics, 2016. **9**(4): p. 621-630.

[2] Yaramasu, V., B. Wu, and J. Chen, Model-Predictive Control of Grid-Tied Four-Level Diode-Clamped Inverters for High-Power Wind Energy Conversion Systems. IEEE Transactions on Power Electronics, 2014. **29**(6): p. 2861-2873

[3] Arshadi, S.A., et al., High Step-Up DC–AC Inverter Suitable for AC Module Applications. IEEE Transactions on Industrial Electronics, 2016. 63(2): p. 832-839.

[4] Sayed, M.A., et al., *PWM Switching Technique for Three-Phase Bidirectional Grid-Tie DC–AC–AC Converter With High-Frequency Isolation.* IEEE Transactions on Power Electronics, 2018. **33**(1): p. 845-858.

[5] Esmaeili, S. and A. Sheikholeslami. *Transformer types of extended Z-source inverter with high voltage gain and reduced transformer turns ratio*. in *The 6th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2015)*. 2015.

[6] Steczek, M., P. Chudzik, and A. Szeląg, *Combination of SHE- and SHM-PWM Techniques for VSI DC-Link Current Harmonics Control in Railway Applications.* IEEE Transactions on Industrial Electronics, 2017. **64**(10): p. 7666-7678.

[7] Testa, A., et al. *A buck-boost based DC/AC converter for residential PV applications*. in *International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion*. 2012.

[8] Gandomi, A.A., K. Varesi, and S.H. Hosseini. *DC-AC buck and buck-boost inverters for renewable energy applications*. in *The 6th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2015)*. 2015.

[9] Alzate, R.E. and J. Posada .*Design and implementation of proportional-resonant controller for 3-phase current source inverter in Dspace DS1104*. in *2017 IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA)*. 2017.

[10] Singh, S.A., et al., *Modeling, Design, Control, and Implementation of a Modified Z-Source Integrated PV/Grid/EV DC Charger/Inverter.* IEEE Transactions on Industrial Electronics, 2018. **65**(6): p. 5213-5220.

[11] Soon, J.J. and K. Low, *Sigma-Z-source inverters.* IET Power Electronics, 2015. **8**(5): p. 715-723

[12] Aravindan, M., et al. *Topologies of single phase Z source inverters for photovoltaic systems*. in *2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*. 2016.

[13] Ghosh, S., et al. *A single-phase isolated Z-source inverter*. in *2016 2nd International Conference on Control, Instrumentation, Energy & Communication (CIEC)*. 2016.

[14] Kim, K., H. Cha, and H. Kim, *A New Single-Phase Switched-Coupled-Inductor DC–AC Inverter for Photovoltaic Systems.* IEEE Transactions on Power Electronics, 2017. **32**(7): p.5022-5016

[15] Nahavandi A, Roostaee M, Azizi MR. Single stage DC-AC boost converter. In2016 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC) 2016 Feb 16 (pp. 362-366). IEEE.

[16] Wu, W., J. Ji, and F. Blaabjerg, *Aalborg Inverter - A New Type of "Buck in Buck, Boost in Boost" Grid-Tied Inverter.* IEEE Transactions on Power Electronics, 2015. **30**(9): p. 4784-4793.

[17] Danyali, S., S.H. Hosseini, and G.B .Gharehpetian, *New Extendable Single-Stage Multi-input DC–DC/AC Boost Converter.* IEEE Transactions on Power Electronics, 2014. **29**(2): p. 775-788.

[18] Nguyen, M., G. Cho, and Y. Lim, *Switched-boost network-based single-phase boost DC–AC converter.* IET Power Electronics, 2016. **9**(14): p. 2723-2730.

[19] Eskandari, B. and M.T. Bina, *Support vector regression-based distortion compensator for three-phase dc-ac boost-inverters: analysis and experiments.* IET Power Electronics, 2014. **7**(2): p. 251-258.