A FUZZY LOGIC CONTROLLER-BASED APPROACH FOR LOW-HARMONIC CONTROL OF BI-DIRECTIONAL THREE-PHASE Z-SOURCE CONVERTERS IN VEHICLE-TO-GRID APPLICATIONS

A.Vishnu Chakravarthy[1], P.Poorna Prathap[2], B.L. Vardhan Reddy[3], J. Satya Priyanka[4], B. Rajesh[5], E. Nihar BhavaniShankar[6]
[1]Assistant Professor, Department of ELECTRICAL & ELECTRONICS ENGINEERING, SANKETIKA VIDYA PARISHAD ENGINEERING COLLEGE
Email id: vishnu.chakravarti@gmail.com
[2], Student of B-TECH, SANKETIKA VIDYA PARISHAD ENGINEERING COLLEGE
(Approved by AICTE, Ministry of HRD, New Delhi & Affiliated to Andhra University, Visakhapatnam), Behind Y.S.R A. C. A-V.D.C.A Stadium, P.M .Palem, Visakhapatnam-530 041.
Email id: poornaprathappotnuru52530@gmail.com
[3], Student of B-TECH, SANKETIKA VIDYA PARISHAD ENGINEERING COLLEGE
(Approved by AICTE, Ministry of HRD, New Delhi & Affiliated to Andhra University, Visakhapatnam), Behind Y.S.R A. C. A-V.D.C.A Stadium, P.M .Palem, Visakhapatnam-530 041.
Email id: vardhanreddy805@gmail.com
[4], Student of B-TECH, SANKETIKA VIDYA PARISHAD ENGINEERING COLLEGE
(Approved by AICTE, Ministry of HRD, New Delhi & Affiliated to Andhra University, Visakhapatnam), Behind Y.S.R A. C. A-V.D.C.A Stadium, P.M. Palem, Visakhapatnam-530 041.
Email id: satyapriyankajannarapu143@gmail.com
[5], Student of B-TECH, SANKETIKA VIDYA PARISHAD ENGINEERING COLLEGE
(Approved by AICTE, Ministry of HRD, New Delhi & Affiliated to Andhra University, Visakhapatnam), Behind Y.S.R A. C. A-V.D.C.A Stadium, P.M .Palem, Visakhapatnam-530 041.
Email id: rajeshkumar938383@gmail.com
[6], Student of B-TECH, SANKETIKA VIDYA PARISHAD ENGINEERING COLLEGE
(Approved by AICTE, Ministry of HRD, New Delhi & Affiliated to Andhra University, Visakhapatnam), Behind Y.S.R A. C. A-V.D.C.A Stadium, P.M .Palem, Visakhapatnam-530 041.
Email id: nihar9797@gmail.com

ABSTRACT

Three new modulation schemes for three-phase Z-source converters are proposed and analyzed in this paper, aiming to enhance voltage boosting and bi-directional operation capabilities, particularly for applications like Vehicle-to-Grid (V2G) chargers in transportation electrification. The best-performing scheme is further refined into a closed-loop PI control method, offering flexible voltage conversion ratios and maintaining output voltage Total Harmonics Distortion (THD) below 3% across a wide range of voltage ratios from 0.5 to 2.5. Validation through MATLAB/Simulink simulations and RT-LAB Hardware-In-Loop (HIL) experiments using the OPAL-RT OP4510 real-time simulator demonstrates the effectiveness of the proposed method, showcasing improved performance with reduced harmonics, adaptable voltage gain, and simplified control algorithm compared to existing methods.

Keywords: MATLAB/Simulink simulations and RT-LAB Hardware-In-Loop (HIL)

1. INTRODUCTION

There is a growing demand for advanced power converters and control algorithms in transportation electrification, particularly in railway electrification. Traditional full-bridge three-phase inverters face challenges like dead time requirements leading to waveform distortions and reduced efficiency due to the addition of DC-DC converters. Z-source and quasi-Z-source inverters have been proposed to address these issues, offering single-stage topology with shoot-through states for voltage boosting and bi-directional operation, beneficial for applications like Vehicle-to-Grid (V2G) chargers. These inverters have been extensively studied in various applications, including EV charging, motor drives, PV systems, and microgrid integration, owing to their advantages in voltage gain capability and modulation indexes. However, existing Z-source converters may suffer from complexity, instability, and voltage stress issues. Hence, this paper focuses on improving the performance of basic three-phase Z-source converters through optimized control methods rather than adding complexity. Several modulation schemes, particularly the sine variable modulation, are proposed to enhance performance, off. A Z-source converter incorporates an innovative x-shaped impedance network known as the Z-source impedance network, linking the converter's main circuit to the power source. This converter, adaptable to various conversion types, earns the designation of a Z-source inverter when operating from AC to DC. Since its emergence in 2003, this conversion concept has effectively addressed numerous conversion challenges.

Power electronic converters have undergone extensive research and development in recent decades, with a continual demand for new solutions and topologies aimed at enhancing system reliability and efficiency while reducing costs, size, and weight. The impedance source converter (ZSC), introduced by Peng in 2002, represents a significant advancement in this regard. Derived from a three-phase, two-level voltage source inverter topology, the ZSC featured six power transistors, one diode, two inductors, and two capacitors. The inclusion of the impedance circuit facilitated single-stage conversion with buck and boost capabilities, eliminating the need for dead-time protection and enhancing system reliability by offering short-circuit tolerance. The intentional utilization of shoot-through, or short-circuiting of the leg switches, enabled voltage boosting. Subsequently, numerous modifications, enhancements, and applications of this solution have emerged, extending its utility to various types of power converters (DC-AC, DC-DC, AC-DC, AC-AC) and diverse applications, including PV systems, wind energy conversion, fuel cells, motor drives, and power factor correction. The evolution of ZSC-based solutions continues unabated, with new applications continually emerging.

2. RELATED COMPONENTS DESCRPTION

2.1 Introduction for Inverter

The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static var compensators, active filters, flexible ac transmission systems (FACTS), and voltage compensators, which are only a few applications. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable. According to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform.

These structures are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as adjustable speed drives (ASDs), which are the most popular application of inverters; see Fig. 14.1a. Similarly, these topologies can be found as current source inverters (CSIs), where the independently controlled ac output is a current waveform. These structures are still widely used in medium-voltage industrial applications, where high-quality voltage waveforms are required.

Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones. For instance, the ac output voltage produced by the VSI of a standard ASD is a three-level

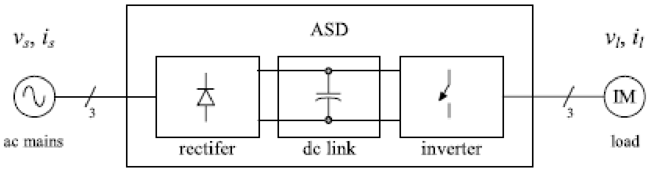

FIG 1:- Static power converters

2.2 Basic designs for Inverters:

In one simple inverter circuit, DC power is connected to a transformer through the center tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a vibrator or buzzer, was once used in vacuum tube automobile radios. A similar mechanism has been used in door bells, buzzers and tattoo. As they became available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.

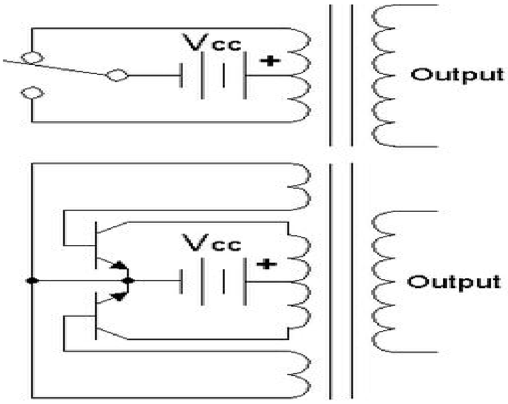

FIG 2:- Basic designs for Inverters

2.3 Output waveforms:

The switch in the simple inverter described above, when not coupled to an output transformer, produces a square voltage waveform due to its simple off and on nature as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called harmonics, that are included in the series have frequencies that are integral multiples of the fundamental frequency.

3. IMPLMENTATION STUDY

The power topology of a full-bridge VSI. This inverter is like the half-bridge inverter; however, a second leg provides the neutral point to the load. As expected, both switches S1. and S1ÿ (or S2. and S2ÿ) cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are four defined and one undefined

The undefined condition should be avoided to be always capable of defining the ac output voltage. To avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. It can be observed that the ac output voltage can take values up to the dc link value vi, which is twice that obtained with half-bridge VSI topologies. Several modulating techniques have been developed that are applicable to full-bridge VSIs. Among them are the PWM (bipolar and unipolar) techniques.

3.1 PROPOSED MODEL

A study of inverters connected to resistive loads is presented here. Control methods of three-phase Z-source inverters could be classified into two categories: shoot-through of three-phase-leg modulation schemes and shoot-through of single-phase-leg modulation schemes. Each subcategory could be further divided by continuous modulation methods and discontinuous modulation methods. If only one bridge is inserted with shoot-through states, then the high current during shoot-through states would all flow into the two switches of this bridge. Switches of the other two bridges do not share the same current stress, which leads to the asymmetry of the topology and the operation. Therefore, the three-phase-leg modulation scheme is selected for the proposed methods. In non-shoot-through states, its operation is divided by zero states and non-zero states. Based on this, there are three primary subcategories of inserting shoot-through states: (1) Simple boost control: part of zero states is converted into shoot-through states; (2) Maximum boost control: all zero states areas are converted into shoot-through states; (3) Constant boost control: most of zero states areas are converted into shoot-through states. The proposed methods of inserting shoot-through states are based on conventional SPWM scheme of three-phase full-bridge inverters and belong to constant boost control.

Three sinusoidal modulating signals at the frequency of the desired output but displaced from each other by $2\pi/3$ phase are generated. The triangular carrier wave is compared with the modulation waves to generate six gate signals. The concept is modifying the magnitude of three modulation waves to create overlaps. In Fig. 2(a), the sine modulation waves of generating signals for switch T1 and T2 in phase A bridge are presented. The black solid curve represents a standard sine wave whose magnitude ranges from $-M$ to M, where $0 < M < 1$. Two more modulation waveforms are derived by adding a variable b(t) which varies with time respectively. The red dashed modulation wave is used for generating gate signals for upper switch T1, which is marked as wT1..

4. METHODOLOGIES

Basic Principle of Three-phase Z-source inverters

The Z-source topology is composed of two inductors LZ1, LZ2 and two capacitors CZ1, CZ2. To achieve the symmetrical characteristic, the two inductors usually would have the same inductance, i.e. LZ1=LZ2=LZ, while the two capacitors also would have the same capacitance, i.e. CZ1=CZ2=CZ. Otherwise, an asymmetric topology would lead to unbalanced operation as well as difference in voltage and current stress of devices. The output side of the Z-source topology is connected to a classical three-phase full-bridge inverter with six switches. The diode Dr is placed in series with the DC voltage source to block any reverse current from the Z-source topology to achieve voltage boosting.

When circuit breaker S1 is turned on, the converter operates bi-directionally as a rectifier and power transfers from the grid to the DC side of the converter. The Z-source network acts as a special LC filter of the three-phase rectifier. Traditional SPWM control method of three-phase full bridge rectifiers is applicable.

When circuit breaker S1 is turned off, the converter operates as an inverter and power transfers from the DC side to the three-phase loads or the grid. Circuit breaker S2 determines whether the converter operates in grid-connected mode or resistive load mode.

The voltage-boosting principle of three-phase Z-source inverters is like the one of single-phase ones as described in, and therefore the detailed analysis and equivalent circuits in each state are not repeated here. In short, the voltage VZ is boosted higher than the input voltage Vdc because of shoot-through states. In steady state, the operation of Z-source inverter is divided into two periods: shoot-through states and non-shoot-through states. It is assumed that the total time of shoot-through states in one switching cycle is Ts, and the period of one cycle is T, then the shoot-through duty ratio D of shoot-through states is:

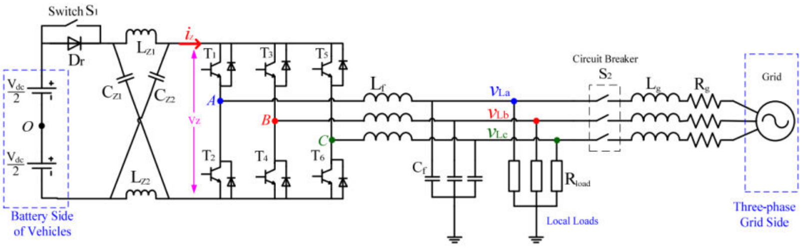

FIG 3:- Three-phase Z-source inverters

$D = \frac{T_s}{T}$ Equation shows the state space equation:

$$\frac{d}{dt}\begin{bmatrix} i_{LZ1}(t) \\ i_{LZ2}(t) \\ v_{CZ1}(t) \\ v_{CZ2}(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{2D-1}{L_Z} & 0 \\ 0 & 0 & 0 & \frac{2D-1}{L_Z} \\ \frac{-D}{C_Z} & \frac{1-D}{C_Z} & 0 & 0 \\ \frac{1-D}{C_Z} & \frac{-D}{C_Z} & 0 & 0 \end{bmatrix}$$

$$\cdot \begin{bmatrix} i_{LZ1}(t) \\ i_{LZ2}(t) \\ v_{CZ1}(t) \\ v_{CZ2}(t) \end{bmatrix} + \begin{bmatrix} \frac{1-D}{L_Z} \\ \frac{1-D}{L_Z} \\ 0 \\ 0 \end{bmatrix} \cdot V_{dc} + \begin{bmatrix} 0 \\ 0 \\ \frac{D-1}{C_Z} \\ \frac{D-1}{C_Z} \end{bmatrix} \cdot i_Z$$

The steady-state parameters could be obtained by setting to zero, as shown in:

$$\begin{cases} \overline{i_{LZ_1}} = \overline{i_{LZ_2}} = \frac{1-D}{1-2D} \cdot \overline{i_Z} \\ \overline{v_{CZ_1}} = \overline{v_{CZ_2}} = \frac{1-D}{1-2D} \cdot V_{dc} = \overline{V_Z} \\ v_{Z-peak} = \frac{1}{1-2D} \cdot V_{dc} \end{cases}$$

Since D must be greater than 0 and smaller than 1, the average magnitude of the output voltage across the Z-source topology VZ is boosted higher than input DC voltage Vdc as shown. When more shoot-through states are inserted, the output voltage gain will become higher. The voltage gain of Z-source inverters could be infinite theoretically, whereas the effect of parasitic components and harmonics requirement limit the maximum practical gain.

The core concept of Z-source converter's control is to boost voltage by inserting shoot-through states while reducing output harmonics and power loss. Three shoot-through states inserting methods are proposed below for three-phase Z-source converters.

5 RESULTS AND DISCUSSION SCREEN SHOTS

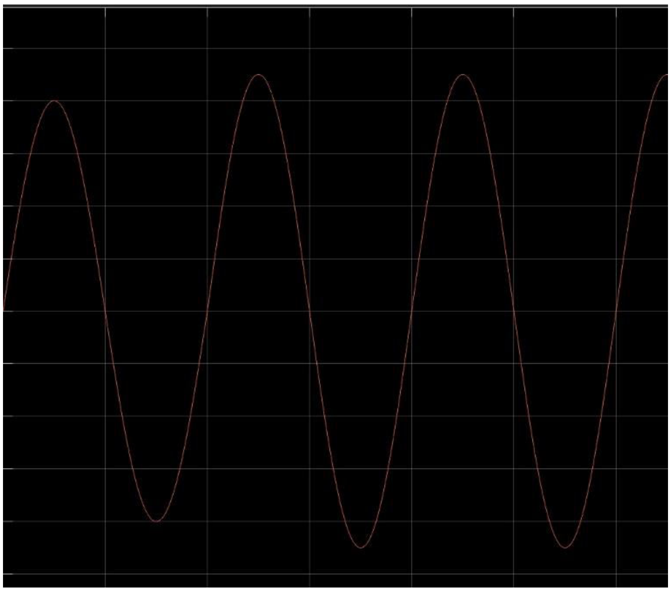

Figure 4: OUTPUT WAVE FORM1

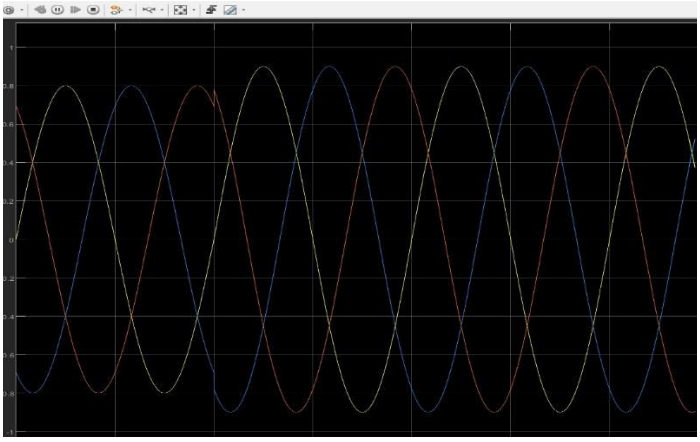

Figure 5: OUTPUT WAVE FORM2

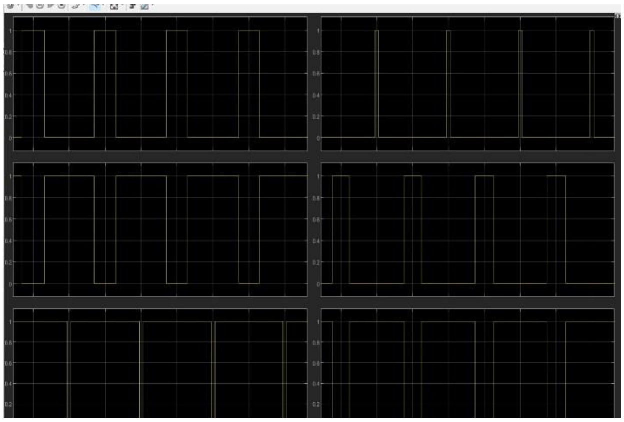

Figure 6:-0 UTPUT WAVE FORM3

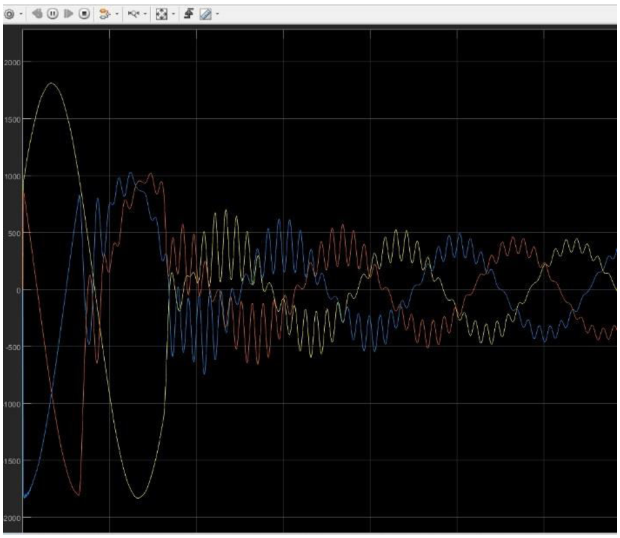

Figure 7: OUTPUT WAVE FORM 4

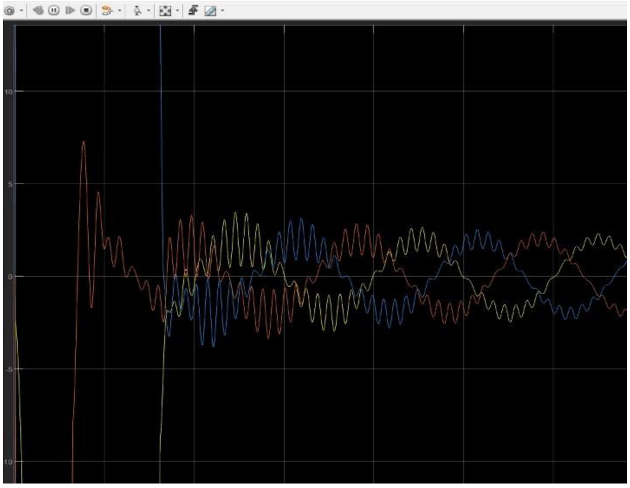

Figure 8: OUTPUT WAVE FORM 5

6. CONCLUSION

The theoretical analysis, simulation and experimental results in the paper proved the good performance of the proposed methods for bi-directional three-phase Z-source converters. Shoot-through states are inserted sinusoidally, and the output three-phase voltages could be boosted while the harmonics are maintained within a low level. Constant variable method, sine variable method and cosine variable method are introduced and compared. Sine variable method produces least harmonics, and hence is further developed into a closed-loop PI control method. Steady-state waveforms in experiment results proved the capability of voltage boosting with all circuitry waveforms matched the theoretical analysis. Transient waveforms showed the dynamic response with the disturbance of input voltage and load resistance. The output phase voltages could catch the reference quickly and smoothly. Compared to existing control methods, the proposed one has better performance on harmonics suppression with an uncomplicated control algorithm, thus would be suitable for its application in vehicle chargers with bi-directional power flow between the vehicle batteries and the three-phase AC bus of a microgrid. The future work mainly includes the implementation of an EV charger prototype to testify the charging performance and conversion efficiency in a Power Hardware-In-Loop (PHIL) testing platform, suppression of the input current spikes and the advanced control in unbalanced load cases.

7 REFERENCES

1 X. Fang, B. Ma, G. Gao and L. Gao, "Three phase trans-Quasi-Z-source inverter," CPSS Transactions on Power Electronics and Applications, vol. 3, no. 3, pp. 223-231, Sept. 2018.

2 Liu Hongchen, Ji Yuliang, Zhao Dan, Chengming Zhang, Patrick Wheeler, Fan Guolei, "Z-source matrix rectifier," IET Power Electronics, vol. 9, no. 13, pp. 2580-2590, May 2016

3 M. S. Diab, A. A. Elserougi, A. M. Massoud, A. S. Abdel-Khalik and S. Ahmed, "A Pulsewidth Modulation Technique for High-Voltage Gain Operation of Three-Phase Z-Source Inverters," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 2, pp. 521-533, June 2016.

4 A. Abdelhakim, P. Davari, F. Blaabjerg and P. Mattavelli, "An improved modulation strategy for the three-phase Z-source inverters (ZSIs)," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, 2017, pp. 4237-4243.

5 A. Ayad, P. Karamanakos and R. Kennel, "Direct Model Predictive Current Control Strategy of Quasi-Z-Source Inverters," IEEE Transactions on Power Electronics, vol. 32, no. 7, pp. 5786-5801, July 2017.

6 D. Xinping, Q. Zhaoming, X. Yeyuan, and F. Z. Peng, “A novel ZVS Z- source rectifier,” Proc. 21st Annu. IEEE Appl. Power Electron. Conf. Expo., 2006, pp. 951–955.

7 J. Zhang, "Unified control of Z-source grid-connected photovoltaic system with reactive power compensation and harmonics restraint: design and application," IET Renewable Power Generation, vol. 12, no. 4, pp. 422-429, 19-Mar-2018.

8 B. Barathy, A. Kavitha and T. Viswanathan, "Effective space vector modulation switching sequence for three phase Z source inverters," IET Power Electronics, vol. 7, no. 11, pp. 2695-2703, 11 2014.

9 A. Abdelhakim, P. Davari, F. Blaabjerg and P. Mattavelli, "Switching Loss Reduction in the Three-Phase Quasi-Z-Source Inverters Utilizing Modified Space Vector Modulation Strategies," IEEE Transactions on Power Electronics, vol. 33, no. 5, pp. 4045-4060, May 2018.

10 W. Xu, M. Liu, J.W. Liu, K.W. Chan, K.W. Eric Cheng, "A series of new control methods for single-phase Z-source inverters and the optimized operation," IEEE Access, vol. 7, pp. 113786-113800, 2019.

11 W. Xu, K. W. Chan, N. H. L. Chan and J. Liu, "A modified control method for bi-directional Z-source converters," 2016 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, 2016.

12 A. Abdelhakim, F. Blaabjerg and P. Mattavelli, "Modulation Schemes of the Three-Phase Impedance Source Inverters—Part I: Classification and Review," IEEE Transactions on Industrial Electronics, vol. 65, no. 8, pp. 6309-6320, Aug. 2018.

13 A. Abdelhakim, F. Blaabjerg and P. Mattavelli, "Modulation Schemes of the Three-Phase Impedance Source Inverters—Part II: Comparative Assessment," IEEE Transactions on Industrial Electronics, vol. 65, no. 8, pp. 6321-6332, Aug. 2018.

14 IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Standard 1547, 2018.

15 T. Ma, M. H. Cintuglu and O. A. Mohammed, "Control of a Hybrid AC/DC Microgrid Involving Energy Storage and Pulsed Loads," IEEE Transactions on Industry Applications, vol. 53, no. 1, pp. 567-575, Jan.- Feb. 2017.

16 EVTV Monitor/Controller For Tesla Model S Battery Modules. Accessed: 10 Jan, 2020. [online]. Avaliable: http://media3.ev-tv.me/TeslaModuleController.pdf

17 BYD Fe Battery for HEV/EV, Accessed on 10 Jan, 2020 [online], Avaliable: http://www.produktinfo.conrad.com/datenblaetter/250000-274999/251704-in-01-en-BYD_LITHIUM_FE_BLOCK_12V_10_AH_B_BMS.pdf

18 L. HE, J.S. Wang, "A design approach of LC Filter used to Three-phase PWM Inverter Output," Electric Drive, vol. 43, no. 12, pp. 33-37, 2013.