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Simple and Effective Algorithm for Battery Assisted Quasi Z-Source Inverter for Standalone PV-Pumping Systems

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Abstract: *A QZSI with an energy storage system is developed for standalone applications. A controller based on the battery-assisted Quasi Z-Source Inverter model is designed to achieve both MPPT from the solar panels and to control the battery State of Charge (SOC). The control strategy will control both MPPT and Battery SOC through the shoot-through duty ratio (D) and Modulation index of the inverter (M). The simple boost modulation technique is adopted for the inverter switching strategy. The performance of the designed system is verified using simulation.*

Keywords **:** *QZSI; energy storage; PV-pumping; simple boost*

I. INTRODUCTION

Integration of renewable energy into the electrical grid turns to be a must in order to solve the increased consumption and demand of electrical energy. One of the most promising energy resources is the solar energy. However, solar energy harvesters have a high initial cost, large spaces, and as efficiency as low as approx. 20% at most. In order to maintain that efficiency, the interfacing systems (i.e. voltage regulators, inverters, etc.) must attain a very high efficiency.

There are two kinds of solar energy harvester namely; standalone system and grid connected system. Standalone systems are used in far areas and sites, hence it is very common to be used in the oil and gas industry sites. However, due to load and supply fluctuation, standalone system need to be connected to a large energy storage system leading to a reduced reliability and increased space and cost. On the other hand, Grid connected systems do not require an energy storage system. Moreover, the energy harvesters improve the grid capabilities. The grid connected systems however have their own complexity and cost represented by phase locked loops PLL for synchronization, active ad reactive power control and extra protection circuits. Both systems are multistage system that in turns exhibit reduced reliability and efficiency. In the present research standalone applications will be concentrated on.

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In (Peng, 2003), the Z-source inverter was first introduced. As previously mentioned, it gained a wide interest due to its features represented in less active devices and improved efficiency. A comparison between conventional two stage inverter and ZSI was introduced in [2] proving the improved efficiency. In [3] different states of operation were investigated. Impedance network sizing was investigated also in [3] showing different effects on the operation of ZSI. Application of ZSI in solar based applications and fuel cell application was introduced in [4-5]. However, the discontinuous nature of the DC current drawn from the solar panels limits the use of such topology with renewable energy [5].

QZSI was then introduced in 2008 by Peng and Anderson [6]. The impedance network of ZSI was modified to build four new configurations to fit different applications. Cascading impedance network was introduced in [7] for cases with reduced solar output voltage. This method suffers from increased sizes of the impedance network but it compensates the reduced voltage by increasing the boosting factor. A design Guide was introduced in [8] in order to determine the impedance network parameters. In 2010, the QZSI was introduced in grid connected applications. The technique adopted was introduced to achieve MPPT capabilities ensuring maximum utilization of solar energy injected in the grid. A hybrid method of active power and reactive power control strategy with Quasi Z-source inverter (QZSI) in single phase grid connected photovoltaic (PV) systems was introduced in [9]. A battery assisted QZSI was introduced in [14] to reduce fluctuation in the output voltage of solar panels during day time. The QZSI was also used a battery charger and the control strategy exhibits MPPT capabilities for grid power applications. References [14] and [15] discussed the power flow control and battery management of the same topology. Reference [16] contributed to another energy-stored QZSI by paralleling a battery to capacitor C1. Those studies did not disclose a dynamic model-based controller design for the battery-assisted QZSI in Fig. 1, and sinusoidal PWM (SPWM) technique was only employed.

As shown in [20] – [24], different control strategies were proposed for traditional impedance source inverters. The focus of these control strategies is to maintain a constant DC link input voltage, or capacitor voltages, or alternatively tracking maximum power point. Those techniques utilize shot through duty ratio and modulation index to guarantee the achievement of their goals.

These references are suitable to account for when dealing with battery assisted QZSI, however paralleling battery with one capacitor will alter circuit performance [25].

For example, battery will enforce capacitor voltages to be fixed and inductors current will not be equal any more. Hence, effectiveness of control methods introduced will be limited in achieving their final goal under variation of PV panel irradiation and temperature. In addition, these control strategies will face challenges in using only two degrees of freedom in order to maintain or control three variables, namely, dc link voltage, MPPT of PV panels, and output power [16].

In this paper; QZSI with energy storage system will be designed, and validated by the operation in the standalone mode while monitoring Batteries SOC. QZSI will be controlled such that it maintains a MPPT by disturb and observe technique (changing shot through duty in the direction that maximizes energy extracted from the solar panel) for standalone application. Simple boost modulation technique will be adopted along with PI based controllers to control QZSI.

II. ANALYSIS OF QUASI Z-SOURCE INVERTER

In this section the analysis of quasi z source inverter with battery parallel to C1 is conducted. This configuration is selected as it is exhibits an extended battery range for discharge as stated in reference [16].

A. Shot through mode

In this mode, the inverter will be short-circuited through one of its legs or through combination of two legs or even thorough the three legs according to the current capability of the inverter as in fig. 1(a), this case is called the shoot-through state. accordingly, the diode is switched off due to the reverse voltage. Equivalent circuit of the system is depicted in fig. 1(b). During this mode, the circuit equations are shown as follows

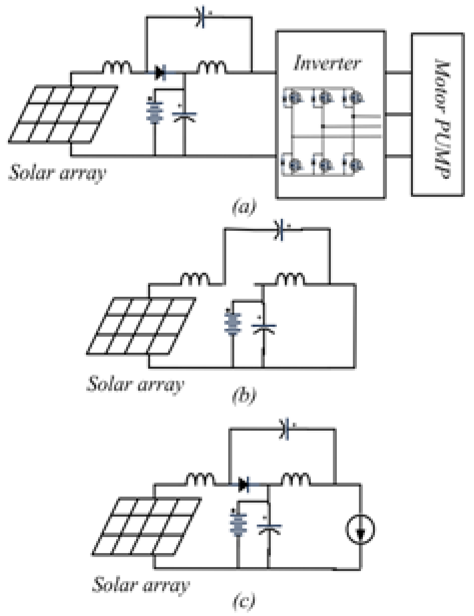

Fig. 1 Battery assisted QZSI with battery parallel to C1 (a) circuit configuration (b) during shot through (c) during non-shot through

$$C\frac{dV_{C1}}{dt} = i_B + i_{L2}\text{-}i_d \tag{1}$$

$$C\frac{dV_{C2}}{dt} = i_{L1}\text{-}i_d \tag{2}$$

$$L\frac{di_{L1}}{dt} = V_{in}\text{-}V_{C1} \tag{3}$$

$$L\frac{di_{L2}}{dt} = \text{-}V_{C2} \tag{4}$$

B. Non-shot thorough mode

In this mode, the inverter will operate as a normal inverter in one of its six active states and two zero states. This mode in known as the non-shoot-through state. The diode of impedance network conducts and carries a continuous current, and the equivalent circuit of the system is shown in fig. 1(c). During this interval, the circuit equations are shown as follows

$$C\frac{dV_{C1}}{dt} = i_B + i_{L2}\text{-}i_d \tag{5}$$

$$C\frac{dV_{C2}}{dt} = i_{L1}\text{-}i_d \tag{6}$$

$$L\frac{di_{L1}}{dt} = V_{in}\text{-}V_{C1} \tag{7}$$

$$L\frac{di_{L2}}{dt} = \text{-}V_{C2} \tag{8}$$

Therefore, the average voltages and currents of the battery and dc link voltage to be

$$V_{pn} = V_{batt} + V_{C2} = \frac{1}{1-2D}V_{in} \tag{9}$$

$$V_{batt} = \frac{1-D}{1-2D}V_{in} \text{ and } V_{C2} = \frac{D}{1-2D}V_{in} \tag{10}$$

$$i_{batt} = i_{L2}\text{-}i_{L1} \tag{11}$$

The voltage VC1 of capacitor C1 will be nearly equal to the battery voltage Vbatt if the voltage drop on the battery's internal resistance is ignored. Thus from (9), (10), and (11), the dc-link peak voltage Vpn will be

$$V_{pn} = 2V_{batt}\text{-}V_{in} \tag{12}$$

The output power of the inverter can be controlled by manipulating the desired output voltage, while the output peak phase voltage of the inverter is the same like previous mode.

III. BATTERY ASSISTED QZSI SYSTEM CONTROL ALGORITHM

In this section, a new control system design for standalone application is proposed. The proposed control algorithm achieves 3 different objectives.

The first objective is maximum power point tracking, direct control of v_{batt}, and controlling power flow of the pump.

As shown in fig. 2, The power flow of the complete system is presented under different conditions of battery state of charge. The control algorithm is divided into three points: Battery management system; PV MPPT; and Motor control. Battery management system is added to protect battery against overcharging nor being depleted. PV MPPT is used to guarantee operation at MPPT condition. The motor control will achieve the power balance between the three main systems; PV panels, battery, and pump. The complete system flow chart is shown in fig. 3

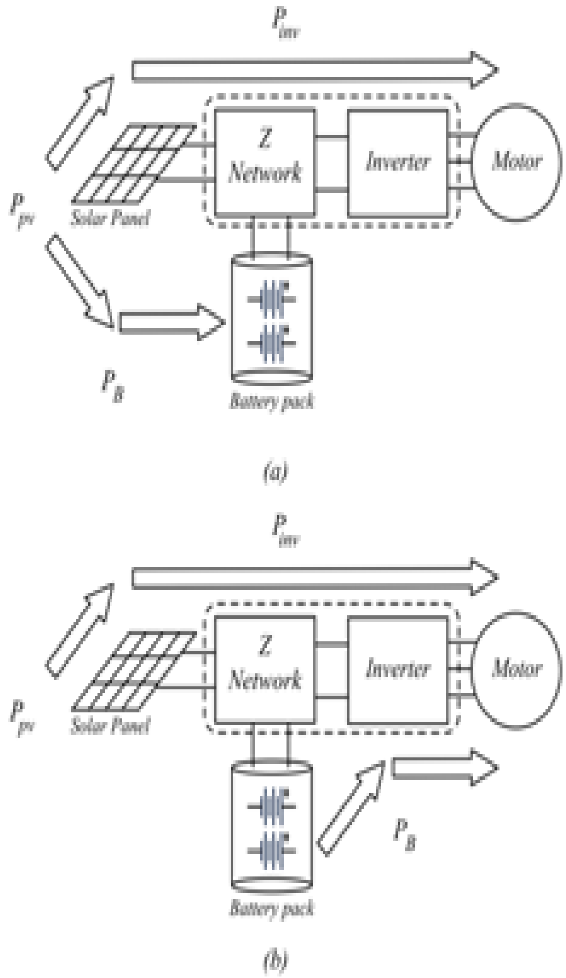

Fig. 2 Different power flow schemes with battery assisted QZSI

A. Battery Management System

According to the battery SOC, there will be two situations:

- If the battery is in charging mode which means that the state of charge hit the limit of minimum SOC, the program control objectives is to determine the battery power and load power is the dependent variable. In this case it is assumed that the power generated from PV will never be greater than the rating of the load and battery combined due to proper sizing of the complete system parameters. The duty ratio is determined according to the MPPT tracking system while the modulation index is selected according to the battery state of charge.

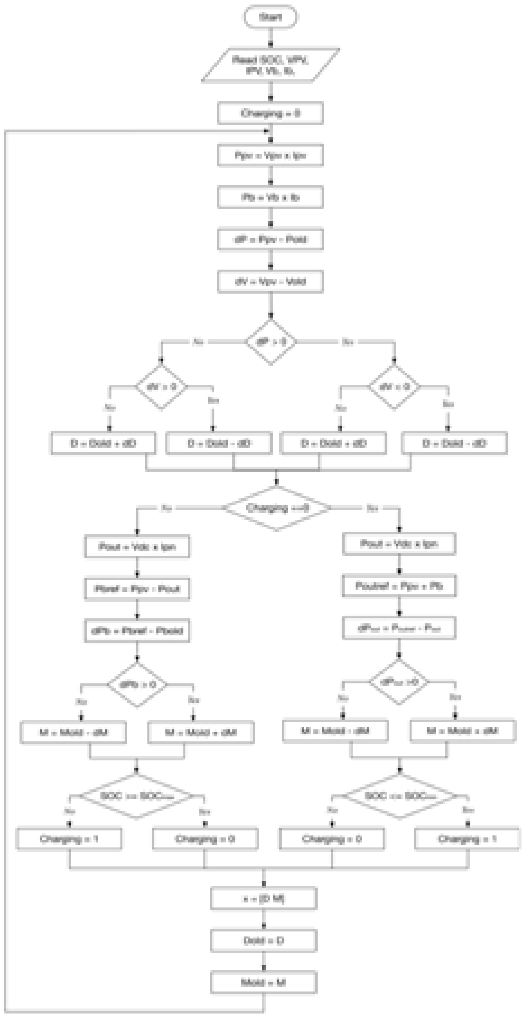

Fig. 3 complete system flow chart

- If the battery is in discharging mode which means that the state of charge hit the limit of maximum permissible SOC, the program control objectives is to determine the load power and battery power is the dependent variable. In this case, the same condition applies that is the power generated from PV and battery power will never be greater than the rating of the load due to proper sizing of the complete system parameters. The duty ratio is determined according to the MPPT tracking system while the modulation index is selected according to the battery state of charge.

B. PV MPPT

The most known MPPT algorithm is perturb and observe. The idea of this algorithm -from its name- is to make a small perturbation in the system and observe the effect of this perturbation on the power -as the purpose is to maximize the power-. If the power increase then this perturbation will be applied again, if the power decrease then the perturbation will be reversed. This sequence continuous until the system reaches its maximum power point. Shoot-through duty ratio is used as perturbation element because it has a major effect on the system voltages as explained in section II.

Equations (9) and (10) indicate that there is a negative relation between the shoot-through duty ratio and the input voltage which is the PV array voltage in the current system. So, to increase the PV array voltage, duty ratio has to be decreased and vice versa.

Perturbation algorithms provide good performance in MPPT. It is simple to implement and can work blindly without the need to have information about the PV array. On the other hand, the perturbation action still exists even when the system reaches the maximum power point. The system continues to perturb around the maximum power point which decrease the performance of the system and affect the output waveforms.

C. Motor-pump set control

In pumping system, the speed requirement is not high, the continuity of the water flow is more important. More power will give more water flow which is critical to the rural areas. As there is a battery installed in the system, the load should be able to absorb the power generated from both sources PV and battery.

The motor load is a pump, the load torque T_L can be presented by the following equation:

$$T_L = k\omega_r^2 \tag{13}$$

where k is the pump constant that depends on the size of the pump.

In scalar control, the magnitudes of voltage and frequency can be controlled to control the torque and the flux of the motor. Induction motor has an inherent coupling effect i.e. both torque and flux are functions of voltage and frequency, which means that changing the voltage will affect the torque and the flux. This effect decreases the dynamic performance of the scalar control. On the other hand, scalar control is simple to implement. Then by using V/f control speed can be directly controlled; controlling the torque and speed of the pump hence controlling the power absorbed by the system as shown in 14

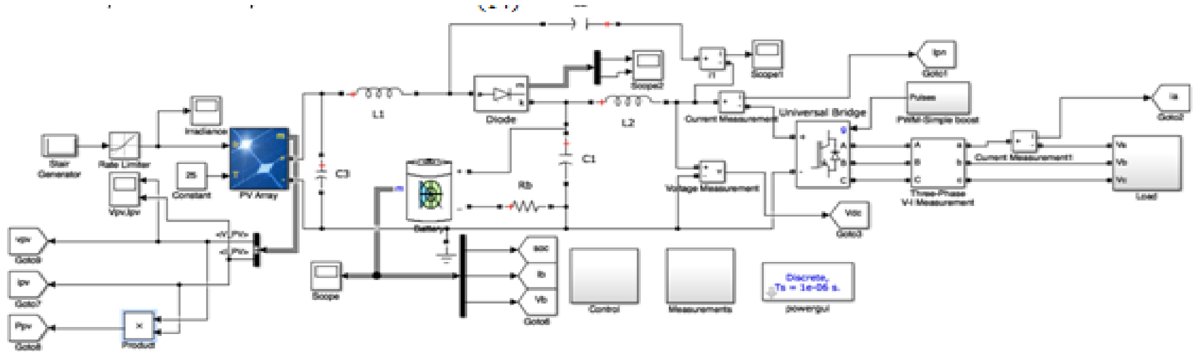

Fig. 4 complete Simulink model for battery assisted PV pumping system

$$P = k\omega_r^3 = 3VIcos\varphi \tag{14}$$

IV. SIMULATION RESULTS

In this section, a model representing the PV-pumping system shown in previous chapter will be simulated to verify the control technique. The model was developed using MATLAB/SIMULINK environment as shown in fig. 4

The values of the system parameters under rated power condition are listed in Table I. Induction motor values have been set according to the available induction motor in the Matlab Simulink preset values fitting 60Hz system. The PV array is selected such that the motor operates at its rated power when the PV array is working at its maximum power.

The system will be simulated subject to irradiance change that changes from 1000 w/m2 to 500w/m2 after 5 seconds.

A. MPPT performance investigation

Fig. 5 shows the overall PV voltage, current and power using step change of d equals 1e-6. The figure shows the system is able to reach MPPT in different insolation as indicated in the power curves. It should be emphasized that the system is sized such that the PV panel power is larger than the rated power of the system and battery charger power. The system shows that the solar panel reaches 4.5 kw at 1000w/m2, and 2.4 kW at 500 W/m2 which is corresponding to the MPPT of the panels. The perturb and observe controller problem is that it causes the system to oscillate around the maximum power point and this justifies the oscillation of the power.

System Parameters' Values at Rated Power Conditions

Parameter			Value
PV Array	@ 1000 W/m2	V_{mpp}	611 V
		I_{mpp}	7.5 A
		P_{max}	4500 W
		V_{OC}	830 V
		I_{SC}	8.25 A
	@ 500 W/m2	V_{mpp}	630 V
		I_{mpp}	4.2 A
		P_{max}	2400 W
		V_{OC}	780 V
		I_{SC}	4.25 A
QZSI		L	10 mH
		C	110 µF
Induction Motor		Rated RMS $V_{L\text{-}L}$	460 V
		Rated Frequency	60 Hz
		Rated power	4000 W

B. QZSI performance investigation

Fig. 6 shows QZSI modulation index as well as the change in the duty ratio of the system. Rate of change in duty ration depends on the step of change, as the step of change increase, duty ratio changes faster. The figures indicate that the modulation index is always less than or equal to 1-D which is consistent with the control technique and there is no overlapping between both controls. The duty ratio increase as well as the modulation index with the increase of the irradiance of the system.

C1 and C2 voltages under different irradiance conditions are shown in fig. 7 as well as inductor current in fig. 8. C1 voltage is clamped to the battery voltage which is selected to be 775V; and the voltage is clamped around 838V including voltage drop across the resistance of the battery. As the power decrease, capacitor C2 voltages decreases because they are related to the output voltage and the output voltage is related to the motor power. Inductor currents are shown to be always positive and not equal due to the existence of the battery.

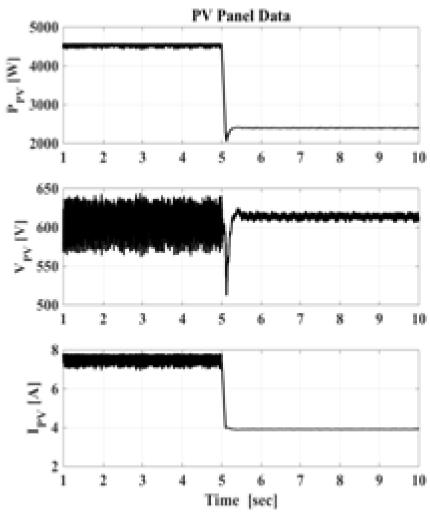

Fig. 5 PV panel (a) power (b) voltage and (a) current

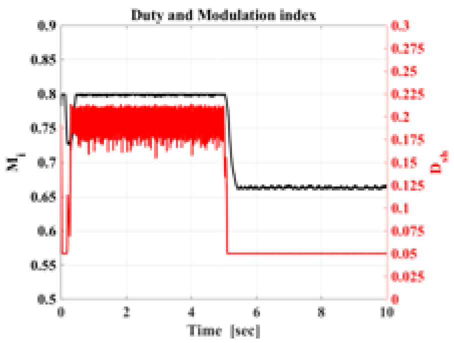

Fig. 6 duty ratio and modulation index of QZSI

C. Battery performance investigation

Fig. 9 shows state of charge, voltage as well as battery current of the system. The figure indicates that battery state of charge decrease when the battery is discharging at low intensity conditions. However, the battery start charging when the irradiance increase. the variation is small as the period of the simulation is in seconds. The oscillation of the battery current is due to the absence of the inductance in the battery current path. This is due to the simplicity of the charging circuit of the battery.

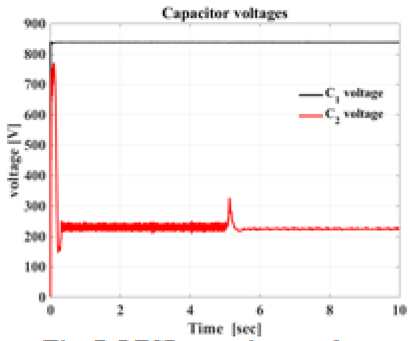

Fig. 7 QZSI capacitors voltage

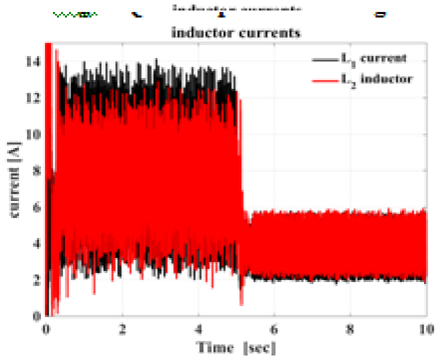

Fig. 8 QZSI inductors current

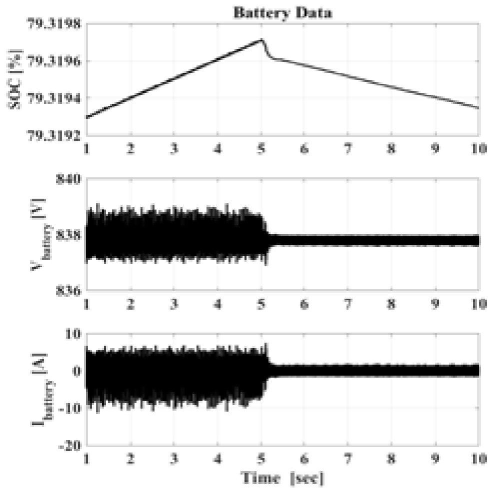

Fig. 9 Battery state of charge, voltage and current

D. Motor performance

Fig. 10 shows motor line-line voltage and phase currents. Fig. 11 shows the speed of the motor change with respect to changed irradiance; when the power and voltage increase, the speed correspondingly increase which fulfil the constant V/f control technique.

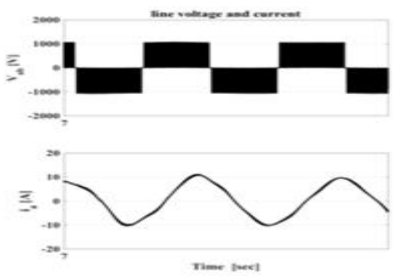

Fig. 10 Motor line voltage and current

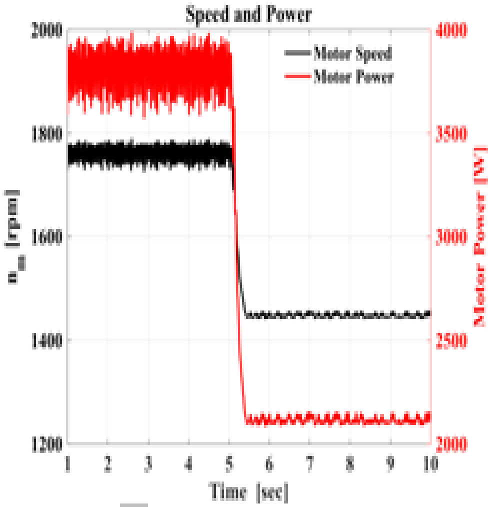

Fig. 11 Motor speed and power

V. CONCLUSIONS

In this paper, a battery assisted Quasi Z-source inverter was developed in a PV-pumping system as a replacement to the traditional two-stage converter (Boost converter + Voltage source inverter). Analysis and mathematical model of QZSI has been presented. The analysis was conducted with battery positioned shunted with C1.

The overall control of the PV-pumping system with QZSI was introduced. This algorithm shows ability to reach MPPT under different conditions. Also the battery was indicated to be able to charge and discharge under different conditions. The modulation index was chosen to be less than or equal to maximum allowable value $1 - D$ to prevent overlap between both control loops. The simulation results were consistent with the analysis. The results verify the proposed QZSI control technique that provide continuous current in the inductors and charging discharging profile for the batteries. The disadvantage is the high ripples in the battery current due to the simplicity of the circuit.

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