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Application of Quasi Z Source Inverter on Electric Vehicle with Regenerative Braking

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ABSTRACT: Electric vehicles design and development are very much important when compared to conventional diesel/petrol driven vehicles due to the fascinating reasons below. 1. EVs are more efficient at turning energy into miles driven. 2. They are greener than gasoline powered vehicles as they do not involve carbon emission throughout the operation. 3. They are powered by electricity which can be produced from multiple energy resources and they can also be powered by renewable energy resource as primary source. 4. EV drive trains are much more efficient than ICE drive trains because ICEs are thermodynamic systems with efficiencies limited by heat cycle they operate under. The National Household Travel Survey says that an average car is driven for 42miles per a day (15000miles/year) is well within the range of almost all available electric cars and future models will have 10 times this range or more. If driving range is an issue in using the EVs, it can be overcome by regenerative braking (RB) strategy. RB can improve energy usage efficiency and can prolong the driving range of EV. Due to the constant torque operation and optimally efficient conversion of electrical to mechanical energy, brushless DC motor (BLDC) are widely used in EVs. This paper proposes the way of increasing the efficiency of EVs by the usage of BLDC motor with regenerative braking and the PI control strategy of BLDC motor as well and the results are verified using MATLAB.

KEYWORDS: Electric Vehicles, BLDC motor, regenerative braking

I. INTRODUCTION

Methods of reducing air-pollution have become the great challenge with the emergence of energy crisis. Nowadays, fossil-fueled automobiles are the major transportation tools. But it is necessary to find transportation tools which green, energy are saving and zero pollution. Therefore, Electric Vehicles (EVs) have grown at an accelerated way nowadays [1–3]. But the main

difficulties for commercialization of EVs such as short driving range. Charging battery pack is quite time consuming one and driving range is of only short distance are the major problems for EVs. Thus in order to overcome those shortages effective battery utilization and advanced motor control have become an important issue for EVs [4–6].There are three major parts in a Pure Electric Vehicle: they are 1. The power battery pack (usually series of energy-storage unit), 2. The driving motor [can be induction motor (IM) or brushless direct-current motor (BLDCM) or switched reluctance machine (SRM) [7], *etc.*], and 3. The power converter controller. Among all the driving motors, the brushless direct-current (BLDC) motor has many advantages over other motors such as brushed DC motors, induction motors and switch reluctance machines. It has the merits of simple construction, high efficiency, high starting torque, noiseless operation, high speed range last but not least electronic commutating device, *etc.* that's why the brushless DC motor are widely used in EVs [8,9]. Conventional EVs use mechanical brakes to increase the friction of the wheel for fast and safe deceleration purposes. Thus, the kinetic energy of braking operation is wasted. With this problem in mind, this paper will discuss how to convert the kinetic energy wasted during braking into electrical energy that can be recharged to the battery pack. As a result, this regenerative braking can realize electric braking and energy saving applications as well.

Khastgir [12] has presented a method for implementing a regenerative braking strategy without adding complex electronic systems like anti-locked braking system (ABS) and also with no changing the existing mechanical braking system of a low cost conventional vehicle which is converted to a low-cost hybrid electric vehicle (HEV) can

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be used for front axle applications especially. Sankavaram [13] proposed a detecting and faults diagnosing systematic data-driven process in the regenerative braking system of HEVs. Results show that highly accurate fault diagnosis is a possible one with pattern recognition-based techniques. A well-structured H2/H∞ controller is put forward for a battery EV [14,15], here the experimental results yield that the driving range can be prolonged 4% when using H∞ controller instead of traditional proportional-integral (PI) controller, under the same operations. Only problem in that is the implementation of H∞ controller needs quiet complex mathematic computations. By considering the uncertain parameters during modeling of the system, well performing state feedback H∞ controller can be provided [16]. So far, there are many articles that illustrates the concept of regenerative braking of EVs [2, 3, 10, and 11].

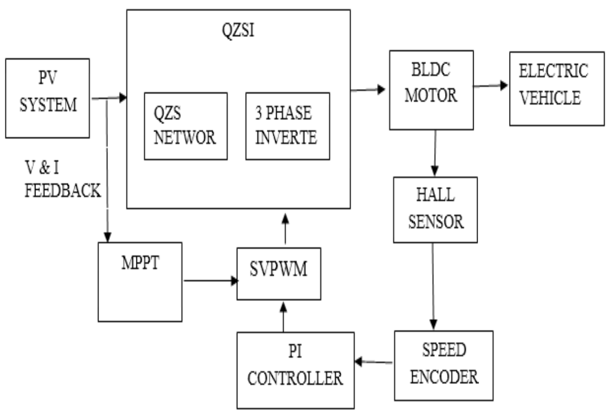
The regenerative braking concept can be characterized as given below by taking aforementioned information in mind. They are, 1. Usage of the additional energy storing components (ultra-capacitor pack) to absorb the instantaneous braking energy. Consequently, the battery pack and ultra-capacitor form a hybrid power supply system (HPSS), and its descriptions can be found in [17–19]; 2. A bidirectional DC-DC power converter for improving the DC-link voltage of the power converter, i.e., for boosting control [20, 21]; 3. Realization of braking energy using the driving power converter itself for charging control, and the energy-regeneration control is achieved by using different control strategy, as found in [22,23].

To summarize the aforementioned methods, this paper will concentrate on the ways of realizing regenerative braking technology by employing PI control. As the Quasi Z Source Inverter (QZSI) is used for the voltage boost, inversion, and storage in a single stage, it yields high efficiency compared with other conventional inverter technologies. Switching states of power semiconductor devices (MOSFET preferably) in QZSI are controlled by the output of controller. This paper is summarized as below. In section 2, overall regenerative braking system configuration of EV with QZSI, BLDC motor, and PI control is presented. In section 3, how to track maximum power from the solar panel is explained. Here the PAO (Perturb and Observe) algorithm is taken for that purpose. In section 4, construction and working of QZSI is presented. In section 5, the speed control of BLDC motor and also how the regenerative braking takes place during the deceleration of EV are explained. In section 6, MATLAB simulation with the output are given in a detailed manner. Finally, conclusion concludes this paper.

II. REGENERATIVE BRAKING SYSTEM FOR A BLDC MOTOR BASED ELECTRIC VEHICLE

In this section, the overall project design is illustrated. Figure 1 shows the system configuration of the electric vehicle. It can be clearly seen that it contains a PV panel, a QZSI, a permanent magnetic brushless DC motor and a controller. Two pedals, one is responsible for acceleration and the other is in charge of electric brake control are the additional parts, both of them would input an adjustable voltage ranging from 0V to 5V. Position information of the rotor is given by Hall signals. Here the simulation of electrical vehicle is illustrated by applying negative torque to the BLDC motor.

Figure 1. System configuration of electric vehicle (EV) using brushless direct-current motor (BLDCM).



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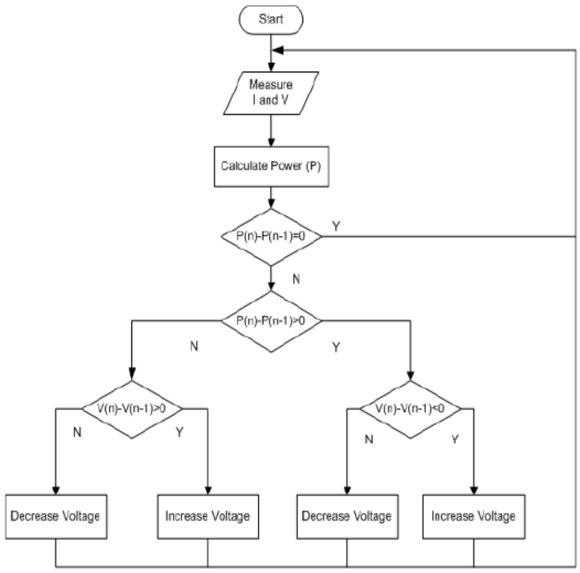
III. PERTURB AND OBSERVE ALGORITHM

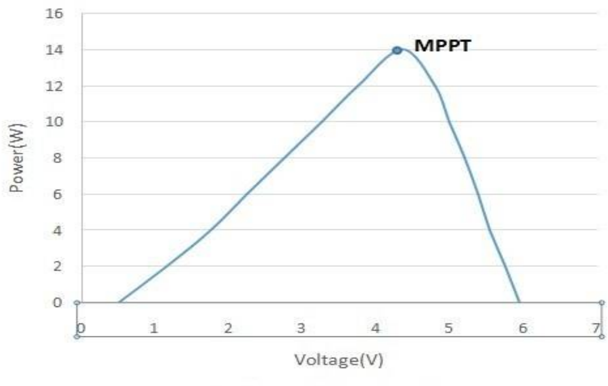
The Maximum Power Point Tracking (MPPT) is a technique which is used in power electronic circuits to extract maximum energy from the Photovoltaic (PV) Systems. Photovoltaic power generation are becoming more important in the recent decades due its numerous benefits such as need of few maintenance and environmental advantages and fuel free. Even though, there are two major barriers for the use of PV systems, they are low energy conversion efficiency and its high initial cost. In order to improve the energy efficiency, it is important to work PV system always at its maximum power point. Many researches are conducted and suggested different methods for extracting maximum power point. Here one of the MPPT algorithms called perturb and observe is used.

Figure 2. Perturb and Observe algorithm flowchart



The most commonly used MPPT algorithm is P&O method. It only uses simple feedback arrangement and little measured parameters. By this method, the module voltage is periodically given a perturbation and then the corresponding output power is compared with that at the previous perturbing cycle [17].

Figure 3. Perturb and Observe algorithm model graph



A slight perturbation is introduced into the system by this algorithm. This small perturbation causes the power of the solar module change. After this, if the power increases due to the perturbation then the perturbation is continued in the same direction itself. After the peak power is obtained at MPP is zero and next instant decreases and henceforth the perturbation reverses as shown in Figures 5 and 6.

Once the stable condition is arrived the algorithm oscillates around the peak power point. To maintain the

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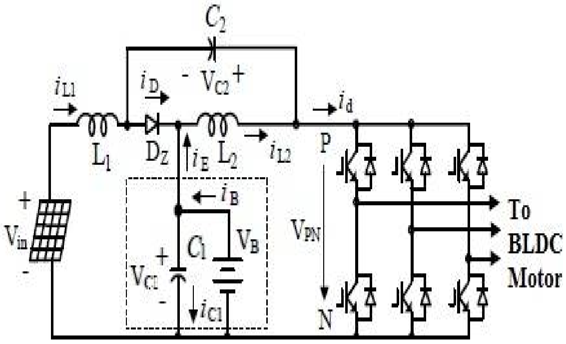
power variation small the perturbation size remains very small. This method is advanced because it sets a reference voltage of the module corresponding to the peak voltage of the module. Then a PI controller acts to transfer the operating point of the module to that particular voltage level. Even though some power loss due to this perturbation and fail to track the maximum power under fast changing atmospheric conditions it still remains very popular and simple method to track maximum power from the PV module.

IV. CONSTRUCTION AND OPERATION OF QZSI

An energy stored QZSI can balance the stochastic fluctuations of PV power injected to the grid/load. The voltage boost, inversion and energy storage are integrated in a single stage inverter. With no need of any additional dc/dc converters or components, only by connecting the battery in parallel with capacitor *C*2 of the qZSI, it is able to 1. Produce the desired output ac voltage to the grid/load, 2. Regulate the battery SOC (state of charge) and 3. Control the PV panel output power (or voltage) to maximize energy production, simultaneously. However, the battery paralleled with the capacitor *C*2 makes the circuit quite different in working. For example, the inductor currents are no longer equal during battery charging and discharging processes and the capacitor voltage is clamped by the parallel battery. It leads to limitation of the conventional control method's ability to achieve a constant dc-link peak voltage.

Figure 4. Energy stored quasi z source inverter for BLDC motor



During the solar irradiation and PV panel's temperature change randomly, the dc-link peak voltage will fluctuate accordingly. And also, it faces a challenge to simultaneously control three independent variables, they are the output power, the MPPT of PV panel, and the dc-link peak voltage, using only two parameters, i.e., the shoot-through duty cycle and the modulation index. If we connect the battery in parallel to the capacitor *C*1, as shown in Fig.1, they possess following characteristics: 1. If we control two power flows, the third one will automatically matches the power difference, according to the power equation (1). 2. There are three power sources/consumers such as PV panels, battery and the grid /load.

$P\text{in}-P\text{out}+P_B=0$ (1)

Where *P*in, *P*out, and P_B are the PV panel power, the output power of the inverter, and the battery power, respectively. Here the power *P*in is always positive because the PV panel is a one directional power supply. When absorbing energy P_B is negative and positive when battery delivers it, and *P*out is positive only when the inverter injects power to the grid.

A. Operating Modes of QZSI in Continuous Conduction Mode

There are two operating modes in the continuous conduction mode (CCM) which are explained brief below.

Mode I: shoot through state

In this mode the inverter is short circuited via any one phase leg or combinations of any two phase legs or all three phase legs in Fig. 1 and it is known as the shoot-through state. In short, in this mode, switches of the same phase in the inverter bridge are switched turned on simultaneously for a very short duration.

Figure 5. Shoot through state of Energy stored quasi z source inverter for BLDC motor

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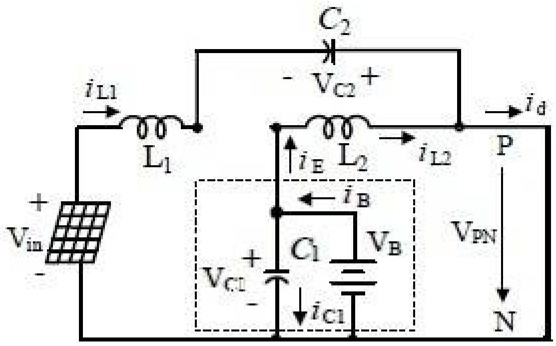
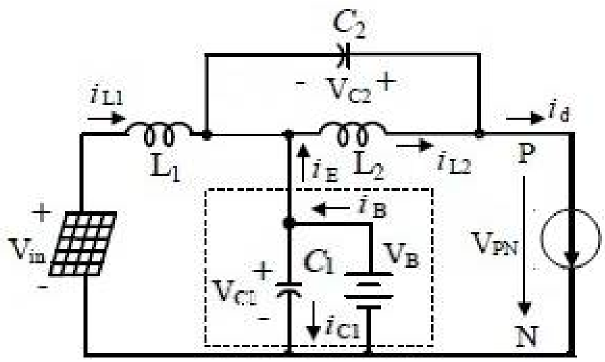


But the source however isn't short circuited when attempted to do so because of the presence of LC network (quasi) which boosts the output voltage. Thus the DC link voltage during the shoot through states, is boosted by a boost factor, whose value which highly depends on the shoot through duty ratio for a given modulation index.

Mode II: non-shoot-through state

This mode makes the inverter operate in one of the six active states and two traditional zero states, which is referred as the non-shoot-through state. In this mode, the switching pattern for the QZSI is similar to that of Voltage Source Inverter (VSI). What makes the QZSI behave similar to a VSI in this mode is that the input dc voltage is available as DC link voltage input to the inverter

Figure 6. Non-Shoot through state of Energy stored quasi z source inverter for BLDC motor



V. BLDC MOTOR CONTROL AND REGENERATIVE BRAKING

The derivative part increase the effect of noise In case of motor speed control. So the most industrial applications didn't use any derivative parts in the controllers and thus in industrial applications a PI controller is the one used to come over the noise issue and to increase the system stability. Here the derivative part gain will be zero, and a PI controller will be used.

Controllers that are incorporated are a PI controller for speed control and a P controller for current control. As shown in Fig. 10 the actual speed and subtracted from reference speed is given as input to the speed PI controller and the output of it is subjected to current limiter and that acts as the current reference. From the reference current, actual current is subtracted and error is given input to the current P controller. This dc output of the P controller is compared with a continuous triangular pulse of 40 kHz. Finally we get the output which is varying duty cycle that is anded with gate pulse to produce a pulse-modulated wave that triggers the inverter to generate required voltage to maintain the speed at varying load torques and at speed reference condition

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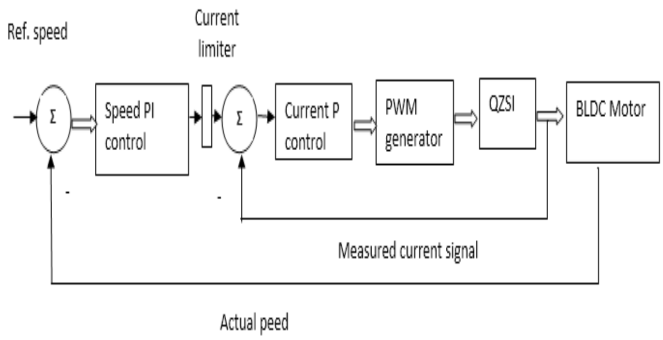
Figure 7. PI control for BLDC motor



The regenerative braking of BLDC motor can be achieved by the reversal of current in the motor-battery circuit during deceleration, on taking advantage of the motor acting as a generator, and thus redirecting the current flow into the supply battery. The same power circuit of Figure 2 can also be used with a suitable switching strategy. A simple and efficient method is the independent switching in conjunction with the pulse-width modulation (PWM) in order to implement an effective braking control method [9]. By independent switching, all electronic switching devices are turned off while applying regenerative braking. All the bottom switching devices are made on for 120 degree portion of the cycle, with respect to the flat top part of the phase EMF. By this time all top switches are kept turned off. PWM method is used to control the level of regenerative braking by changing the duty cycle of the PWM.

VI. SIMULATION AND RESULTS

In this section, we will provide the simulation results by using QZSI and PI controller. In figure 8, the MATLAB representation of the whole system including PV panel, QZSI, BLDC motor with PI control and regenerative braking system is given. Initially the PV panel gives the input voltage of 12V. In figure 10, the PV panel with PAO algorithm is given. Here the PV input voltage into the system is 50.37V. It is shown in the figure 10 itself. This PV input voltage is given to the QZS network where it is boosted up is shown in figure 9. The output voltage waveform is taken from scope 3 and is shown in figure 11.b.

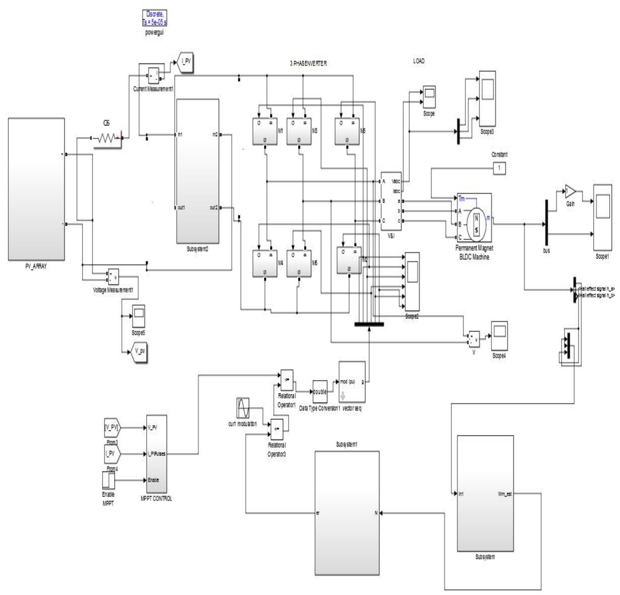


Figure 8. RBS system for BLDC motor driven EV

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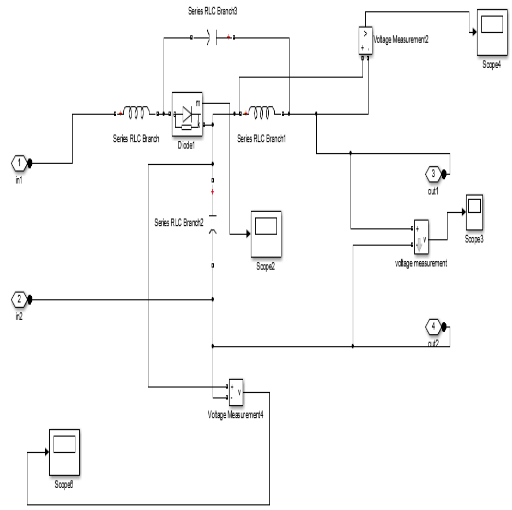
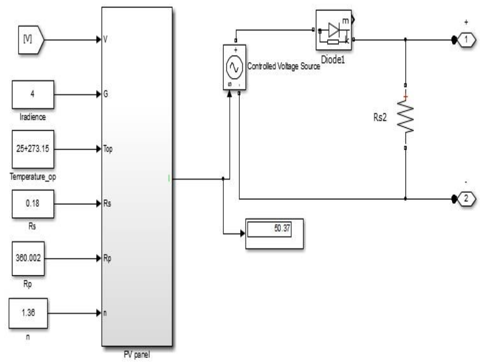
In order to clarify the total system working, it is necessary to compare speed-torque wave form of BLDC motor shown in figure 11.a with the output voltage waveform of QZS network.

Figure 9. Quasi Z Source network



In speed torque curve, it is shown that from the time period of 0.7s, the rotor reaches its maximum speed of 1500 rpm. At this time, in the output voltage waveform of QZS network, there is an increase in the voltage from 0V to <400V. This is due to the boosting up nature of the QZS network. From 12V, we are able to get a boosted voltage of 400V which is 97% gain.

Figure 10. PV system with PAO algorithm



Now observing the figure 101.b we can see that, from 0.7s, the BLDC motor starts to decelerate. Thus from this time, the regenerative braking action must take place.

Figure 11. a. speed-torque waveform of BLDC motor. **b.** output voltage waveform of QZS network **c.** input voltage and current waveform of BLDC motor

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Figure 11.a

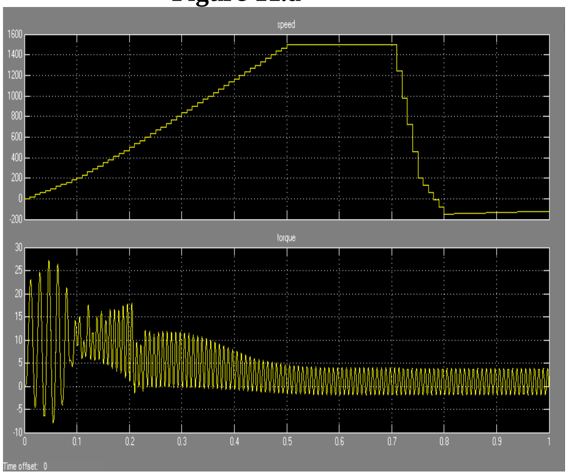


Figure 11.b

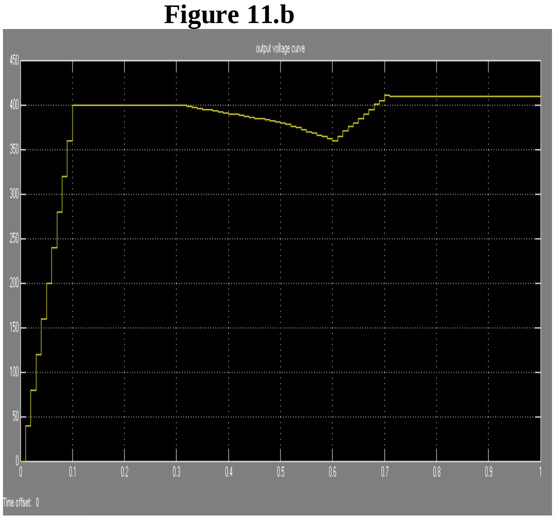
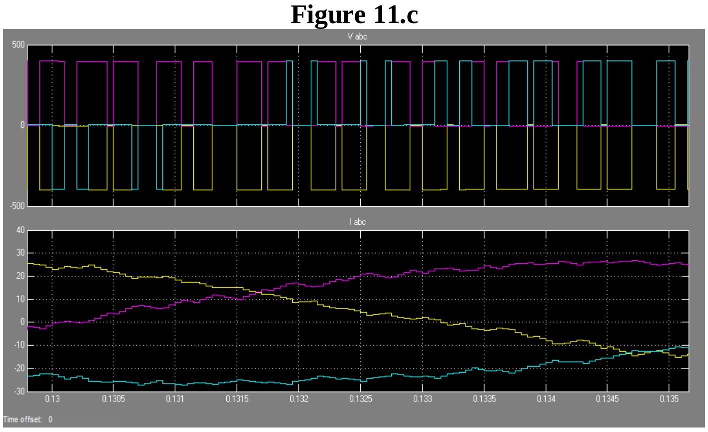


Figure 11.c



The output of the QZSI is fed into the BLDC motor and is shown in figure 11.c. It is shown in the figure 11.a that a slight increase in voltage (>400V) which is nothing but the regenerated voltage kept stored in the Quasi Z Source network.

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VI. CONCLUSION

Regenerative braking can minimize the wear of the brake pads, and thus extend the driving range of EVs and also reduce the maintenance cost considerably. Operating principles and the equivalent power circuit of EVs under regenerative braking control are designated in this paper. The performance of the BLDC motor based regenerative braking system has been realized by PI controller. The quasi Z source regulates and also boosts up the voltage level. Regenerated energy is stored in the battery across the QZSI. This method of energy regeneration could achieve good dynamic performance, robust stability and improvement in the driving range.

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