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Modelling and Simulation of Hybrid Energy Storage for QZSI Inverter Applied in Induction Motor Drive

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Abstract*: Energy storage hybridization in electric vehicle drive is important as currently there is no single energy storage device which able to fully satisfy the power requirement of the drive operation. Electrical drive operation of electric vehicle requires a high energy storage device to achieve a longer distance, as well as high power capability for better acceleration and regenerative braking performance. Battery has long been used as a primary energy source in such application due to its high energy capacity but lack in term of providing high power during transient operation. Meanwhile, the supercapacitor is among the best storage device available in term of ability to disburse high power in short period and has a potential to be used with battery to complement the latter's disadvantage. The paper investigates on a newly proposed method of energy storage hybridization for quasi-Z-source inverter applied in induction motor drive. Objective of the work is to mitigate the current stress on the battery by combining it with supercapacitor to form a hybrid energy storage based on the integration of bidirectional DC/DC converter to the inverter. A 5kW induction motor drive system is designed, modelled and simulated with MATLAB/Simulink environment to evaluate the performance of the field-oriented control of the drive system of the induction motor and the newly proposed method of the hybrid energy storage system during the acceleration/regenerative braking. The results verify the benefit of the new method which effectively reducing the current stress of the battery up to approximately 50% during acceleration and regenerative braking with satisfactory performance of the speed and torque control of the motor.

***Keywords* : battery/supercapacitor hybrid energy storage, quasi-Z-source inverter, induction motor drive.**

I. INTRODUCTION

In Hybrid Electric Vehicle/Electric Vehicle (HEV/EV), the battery as energy storage device has long been used. The battery with higher energy density has a large capacity and provides a longer running time for the vehicle. There are various technologies of battery available in the market today, some them are more established and normally used for high power application such as the Lithium-ion battery. However, storing electric energy in batteries is afflicted with losses, limitations in power and usage. In HEV/EV, the electrical motor load can be steep and can contain high power surge during acceleration or regenerative braking where the handling of the fast charge/discharge rate of energy is carried out by the battery. As a result, the high power rush causes large amount of heat to be generated in the battery due to the power loss occurs in the equivalent internal resistor of the battery. Eventually this amplifies the battery internal resistance, thus lowering the efficiency and may cause a serious explosion if not controlled and handled properly. The battery life time dramatically reduced due to the fast power fluctuations and battery heating. This problem can be managed by a cooling system, which though will consume energy. However, it still affects the health of the battery, which directly influences the total lifetime of the batteries.

Meanwhile for the supercapacitor, with its ability to store the charges physically on the electrodes, has a higher power density compared with the conventional capacitor. It is very suitable for capturing the energy produced from the regenerative braking operation and quickly able to produce power during acceleration which is due to its higher recharging and discharging rate. Besides that, it has long life cycle due to the non-exist chemical variation on the electrodes. The life cycle of the supercapacitor is very well suitable to buffer load applications or high cycle charge and discharge applications as their life can exceed of more than hundreds of thousand cycles. Standard battery technologies such as lithium ion typically have a good life cycle of thousands of cycles, however, under normal operating the battery will not be fully discharged. In general, the supercapacitor can be applied in application that requires short period energy storage, power generation or energy recovery such as, cars, buses, cranes, elevators and trains. It is capable to store copious amounts of energy and can handle a high-power surge during high acceleration or torque demand compared to the battery.

The performance of the ESS in HEV/EV can be improved by increasing the voltage level of the ESS by adding number of the energy storage devices cell in series connection. Although the voltage level is increased, in parallel it deceases the efficiency of the motor drive system due to weight, size, which is obviously not a desirable option for a HEV/EV. The other option is to apply a dc-dc converter which has the ability to convert the voltage efficiently for fast power control.

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In order to utilize the energy storage devices to its maximum, a types dc-dc converter, far instances the boost or buck converter are necessary with sophisticated control of the power flow [1], which can be further improved with the use of proper strategies. The boost converter boosts up the voltage level of the ESS, while the buck converter functions to capture the regenerative braking current flowing back to the ESS. However, due to the present of diode in these converters, it does not inherent property of bidirectional power flow. In this case, it will require two stages of buck and boost converter, which will increase the size and weight of the system along with reduction in efficiency of the overall system [2]. As a strategy to overcome the limitation of one direction power flow of the dc-dc converter, the power MOSFET or IGBT with antiparallel diode is used to replace the diode to form a bidirectional switch that allows current to conduct in both direction with proper control of switching operation. Various types of bidirectional dc-dc converter as already discussed in the literature are applied for HEV/EV, such as the buck-boost bidirectional converter [3]-[4], bidirectional Cuk converter [5], half-bridge bidirectional converter [6]-[7] and buck-boost cascade bidirectional converter [8] as shown in Fig. 1.

Meanwhile on the inverter or drive side, as another option to the already established voltage-source inverter (VSI), the quasi-Z-source inverter (qZSI) has been widely studied with ability to produce a higher DC bus voltage [9]-[10] and overcomes the output voltage constraints of the conventional drive. Moreover, the qZSI also demonstrates fault-tolerant capabilities to shoot-through faults and voltage sags [11]. There are two methods so far exists in the literature. The previous works carried out in [12], [13], [14] in which the qZSI topology with battery as the secondary energy storage device is parallelly connected with either one of the impedance network’s capacitor. This enables the system to regulate the state of charge (SOC) of the battery and maximizing the energy production and can also produce the desired output ac voltage as required by the load simultaneously. However, it becomes a constraint for implementing the conventional control method, which is its ability in producing a flexible DC link voltage where by having the battery and capacitor in parallel, the capacitor voltage is clamped to the battery which does not change very much with the change in its SOC. In fact, the proposed method also has limitation in term of power discharge caused by the existing discontinuous current mode (DCM) [15], which limiting the power output of the inverter, thus reducing the flexibility to determine other components parameters such as the inverter’s DC link voltage.

From the limitations discussed above, a new method of hybridizing the energy storage system (HESS) consists of supercapacitor and battery for the drive of induction motor fed by the qZSI is proposed in this paper.

II. METHODOLOGY

Fig. 2 shows the diagram of the qZSI inverter driving an induction motor with the proposed hybrid energy storage method. The battery is set as the main energy source and the supercapacitor functions as a supportive energy source where it is connected to one end of the bidirectional DC-DC converter. The other end of the bidirectional dc-dc converter is connected to the capacitor C_1. The diode in qZSI is replaced with IGBT switch S_7 to realize a bidirectional flow of power into or from the battery. The converter is able to function in a boost or buck mode during forward or braking operation. Microcontroller platform based on dSpace 1104 is used to process the measured signals and producing the switching signals. Table 1 shows the values of parameters and specification of the designed system.

A. Field oriented control of IM and dual-loop controller for capacitor voltage control

In controlling the capacitor C_1 voltage, a dual loop control is applied in this work. Controlling the capacitor voltage V_{C1} at a certain fixed value allowing a balanced transfer of power between the energy source and the induction motor as a load [16]. As shown in Fig. 3, to control the V_{C1} and inductor current I_{L2}, the PI controller produces the value of shoot-through duty ratio d. On the motor drive side, the field-oriented control (FOC) is applied to the induction motor. By using the FOC method, it realizes a decoupled control of the torque and the machine flux by referring the (α,β) machine model to a rotating (d,q) reference frame aligned on the rotor flux vector whose magnitude and position are provided by a flux estimator [17]-[18]. The block diagram of the FOC is shown in Fig. 4 with the flux is controlled by the d-axis component of the stator current vector, and the speed is controlled by the q-axis current component.

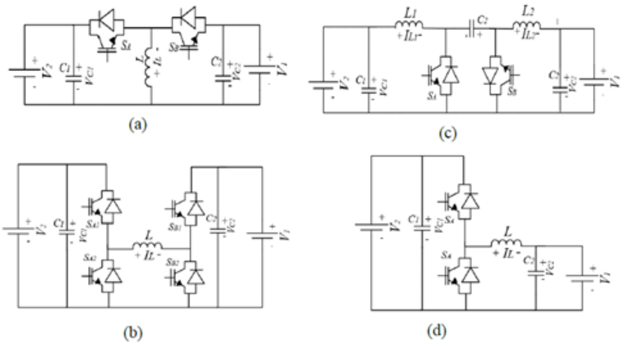

Fig. 1. DC-DC converter (a) Buck/boost bidirectional converter (b) Cascade buck/boost bidirectional converter (c) Cuk bidirectional converter (d) Half-bridge bidirectional converter.

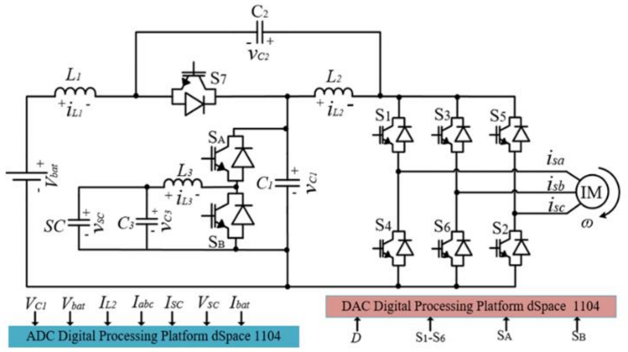

Fig. 2. IM drive system fed by qZSI with hybrid energy storage.

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TABLE I. Specification and parameter for the designed system.

Parameters/Specification	Values
Capacity of battery	Lead acid 30 units x 12V (360V, 42Ah)
Supercapacitor capacity	400 F, 134 units x 2.7 V = 360 V
Bidirectional converter	$L_3 = 10$ mH, $C_3 = 220$ uF
qZSI network	$L_1 = L_2 = 4.7$ mH, $C_1 = C_2 = 1000$ uF
Switching frequency	10 kHz
dc link voltage control	C_1 controlled at 500 V, $d = 0.2 – 0.3$
Induction motor specification	
Voltage rating	380 V_{L-L}
Current rating	2.7 A
Inertia	0.0565 kg.m^2
Vicious friction	0.001 Nm/rad^{-1}
Inductance L_s, Resistance R_s of stator	$L_s = 0.4797$H, $R_s = 6.1\ \Omega$
Inductance Lr, Resistance Rr of rotor	$Lr = 0.4797$ H, $Rr = 6.2293\ \Omega$
Mutual Inductance, L_m	0.4634 H
Rated frequency	50 Hz

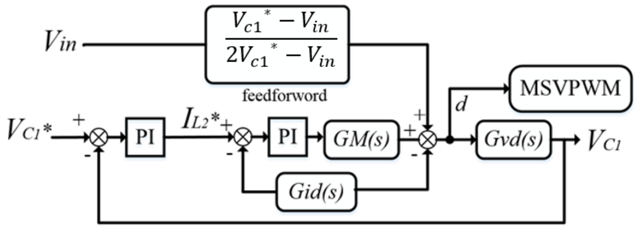


Fig. 3. Controlling capacitor voltage with dual-loop control.

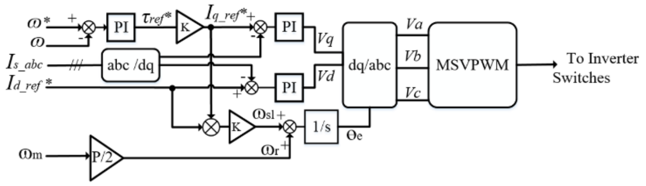


Fig. 4. Field oriented control of the drive system.

B. Current control of the hybrid energy storage during operation of charging and discharging

As shown in Fig. 5, α is the partial amount of reference signal I_{L2}^* magnitude which is relayed as a reference signal I_{sc}^* to the bidirectional DC-DC converter for controlling current of the capacitor during the buck or boost operation to reduce the flowing current into or from the battery. Fig. 6 shows the flow of power between the battery, the supercapacitor and the motor during the operation of motoring and regenerative braking. Supercapacitor current I_{sc} is controlled through the regulation of the inductor L_3 current I_{L3}.

For developing the controller for the supercapacitor current control, the small signal modelling of the bidirectional dc-dc converter during the charging and discharging operation is analyzed. Fig. 7 and Fig. 8 shows the equivalent circuits of the dc-dc converter in charging operation (buck mode) and discharging operation (boost mode) respectively. From the figures, V_H is the voltage of the output side of the dc-dc converter with input resistance of R_1, V_L is the voltage of the input side of the dc-dc converter with output resistance of R_2, R_{ON} is the ON switch resistance, R_L is the inductor internal resistance and C_L is the capacitance of the supercapacitor with voltage V_{SC}.

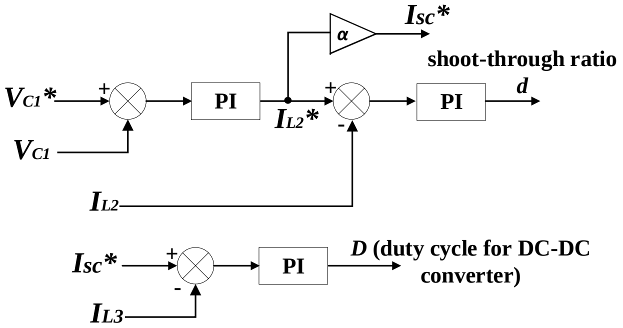
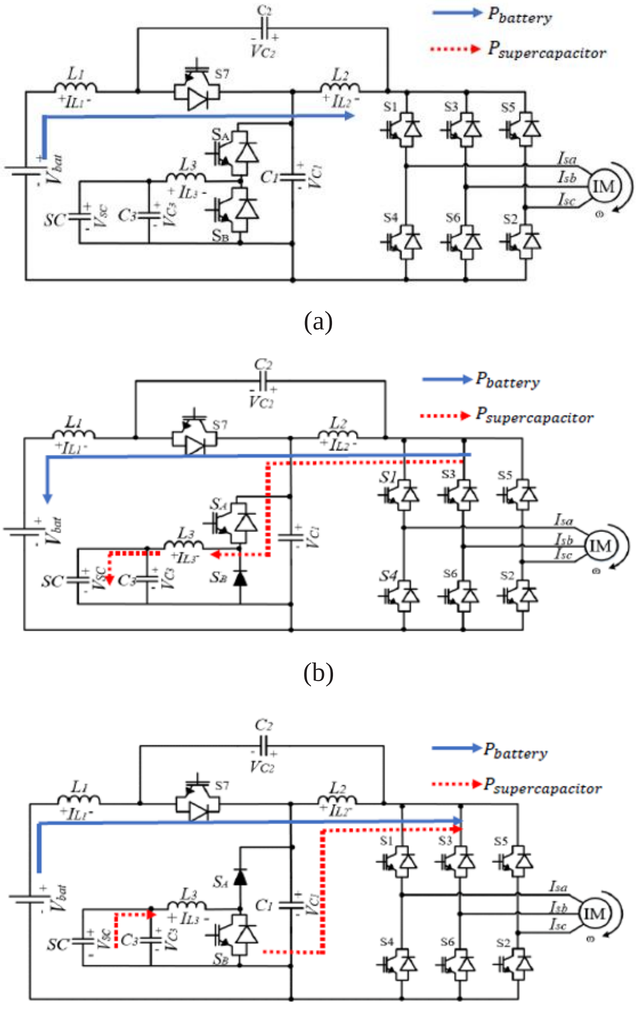


Fig.5. Current control for the supercapacitor.



(a)

(b)

(c)

Fig.6. Power flow of battery and supercapacitor storage to IM drive; (a) Mode 1: stand-by mode; (b) Mode 2: charging; (c) Mode 3: discharge.

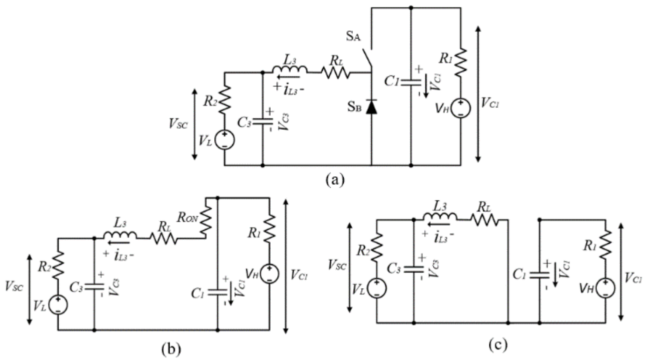


Fig. 7. Bidirectional converter (a) Buck mode (charging) (b) ON state (c) OFF state equivalent circuit.

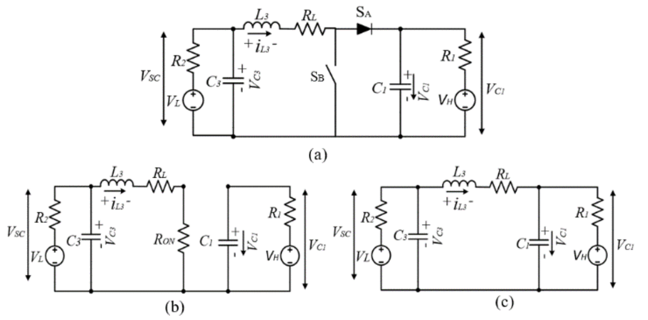


Fig. 8. Bidirectional converter (a) boost mode (discharging) (b) ON state (c) OFF state equivalent circuit.

In charging operation mode when switch S_A is ON,

$$L_3\frac{d_{iL_3}}{dt}+i_{L_3}\left(R_{ON}+R_L\right)=V_{C1}-V_{SC} \tag{1}$$

$$C_1\frac{dV_{C1}}{dt}=\left(\frac{V_{C1}-V_H}{R_1}-i_{L_3}\right)\qquad C_3\frac{dV_{SC}}{dt}=\left(i_{L_3}-\frac{V_{SC}-V_L}{R_2}\right) \tag{2}$$

In charging operation mode when switch S_A in OFF,

$$L_3\frac{d_{iL_3}}{dt}+i_{L_3}\left(R_L\right)=-V_{SC} \tag{3}$$

$$C_1\frac{dV_{C1}}{dt}=-\left(\frac{V_{C1}-V_H}{R_1}\right)\qquad C_3\frac{dV_{SC}}{dt}=\left(i_{L_3}-\frac{V_{SC}-V_L}{R_2}\right) \tag{4}$$

In discharging operation mode when switch S_B is ON,

$$L_3\frac{d_{iL_3}}{dt}+i_{L_3}\left(R_{ON}+R_L\right)=-V_{SC} \tag{5}$$

$$C_1\frac{dV_{C1}}{dt}=\left(-\frac{V_{C1}-V_H}{R_1}\right)\qquad C_3\frac{dV_{SC}}{dt}=\left(i_{L_3}-\frac{V_{SC}-V_L}{R_2}\right) \tag{6}$$

In discharging operation mode when switch S_B is OFF,

$$L_3\frac{d_{iL_3}}{dt}+i_{L_3}\left(R_L\right)=-V_{SC} \tag{7}$$

$$C_1\frac{dV_{C1}}{dt}=\left(i_{L_3}-\frac{V_{C1}-V_H}{R_1}\right)\qquad C_3\frac{dV_{SC}}{dt}=\left(i_{L_3}-\frac{V_{SC}-V_L}{R_1}\right) \tag{8}$$

Based on equations (1) to (8), state space averaging model is used to obtain the inductor current i_{L3} to the control signal duty cycle *D* transfer function. A conventional PI controller as shown in Fig. 5 is used to implement a stable closed loop feedback system.

III. RESULTS AND DISCUSSIONS

Verification on the new energy storage installment method in term of mitigating the battery current stress in the induction motor drive fed by the qZSI is done via MATLAB/Simulink software. Fig. 9 shows the Matlab Simulink model used for the simulation. It consists of an induction motor which is fed by the qZSI inverter, applying the FOC for the drive control, and supplied by a hybrid energy storage combination of lead acid battery and supercapacitor. For the qZSI operation, Fig. 10 shows the shoot-through signal produced where the voltage of the dc-link is 0 V when the legs are short-circuited. It is shown that the current of the inductor is in continuous mode, which increases during the shoot-though states and decreases during non-shoot-through states.

Fig. 11(a) shows the speed transient changes from 500 rpm to 1450 rpm at *t*=1s during motoring operation. The FOC functions satisfactorily to control the speed of the IM with the stator current increases proportionally with the speed as shown in Fig. 11(b). As Fig. 11(d) shows, which compares the battery output current with and without the SC, it is shown that the SC helps in reducing the amount of the battery current during the acceleration. Current output I_{bat} without SC reaches peak of 2.5 A while with the SC, I_{bat} peaks approximately at a lower 1.2 A, reducing I_{bat} to half, where the SC complementing the rest of power required by the motor. The capacitor voltage control with dual-loop controller works effectively as shown in Fig. 12(a) as the V_{C1} is maintained at 500V while I_{L2} follows the reference current as shown in Fig. 12(b), and the DC link voltage is indirectly maintained at 640V in Fig. 12(c). In Fig. 12(d), the supercapacitor current I_{sc} is controlled approximately at peak value of 2 A before gradually returning back to 0 V.

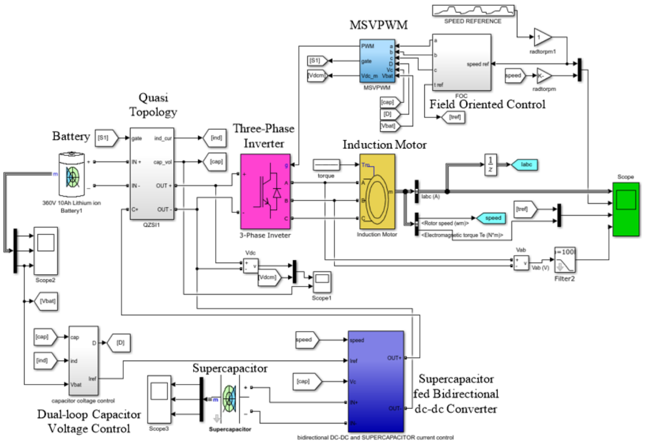


Fig. 9. Matlab Simulink model of the induction motor drive fed by qZSI with combination of battery and supercapacitor hybrid energy storage.

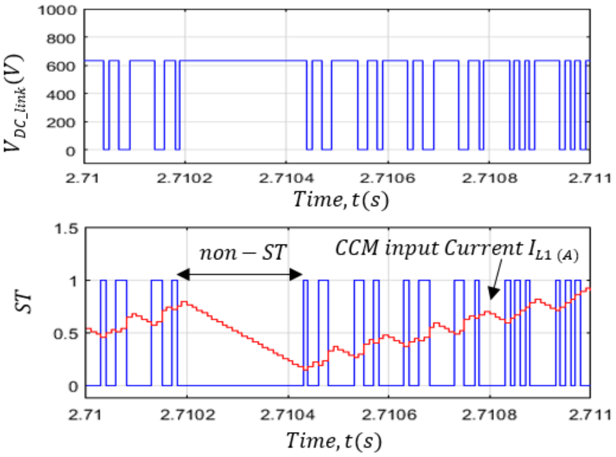
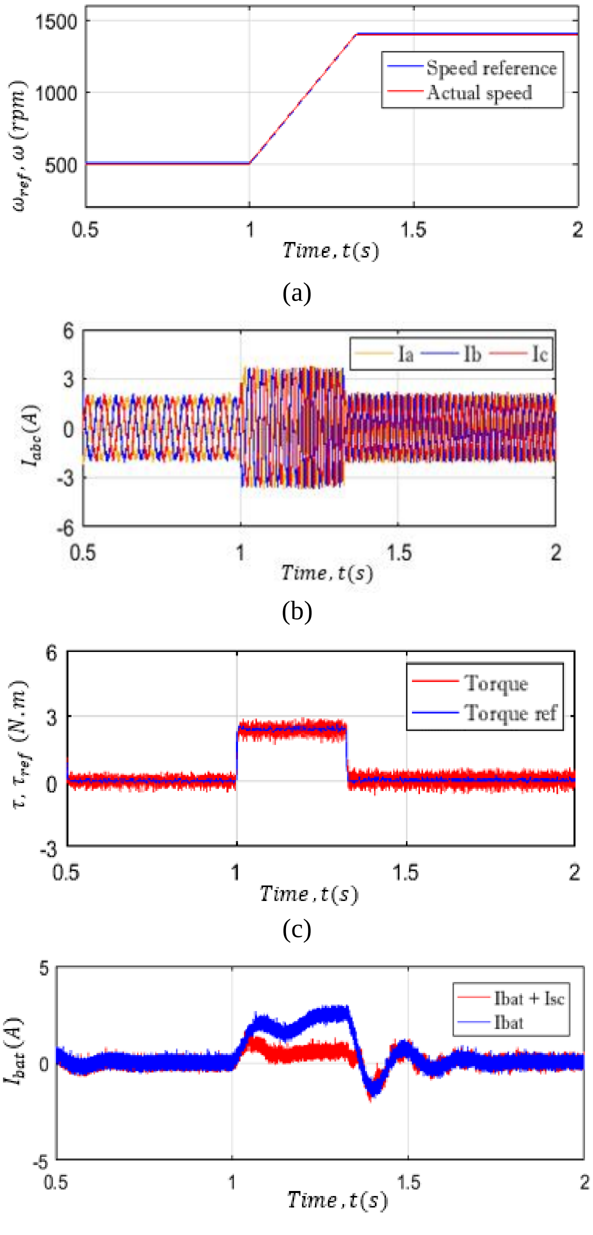


Fig. 10. The DC link voltage V_{dc} (top) and the shoot-through signal with CCM input current I_{L1}.



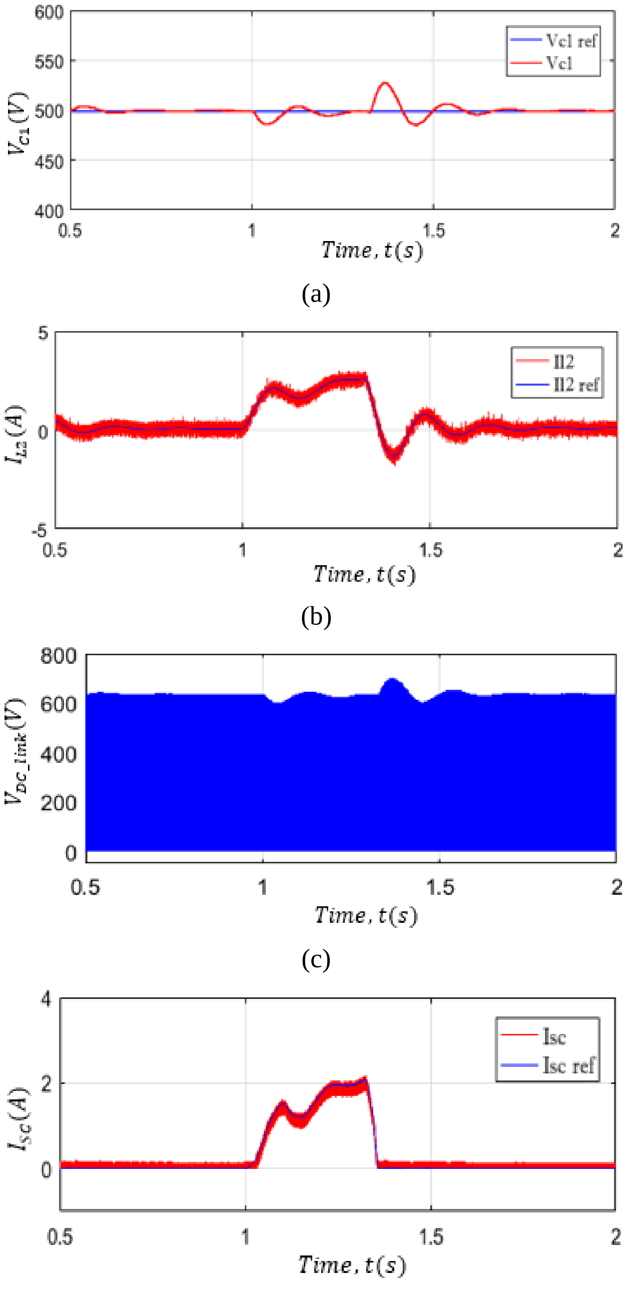
(a)

(b)

(c)

(d)

Fig. 11. Operation of motoring (a) Speed of IM; (b) stator current; (c) Torque; (d) comparison of battery current I_{bat} with and without ESS.



(a)

(b)

(c)

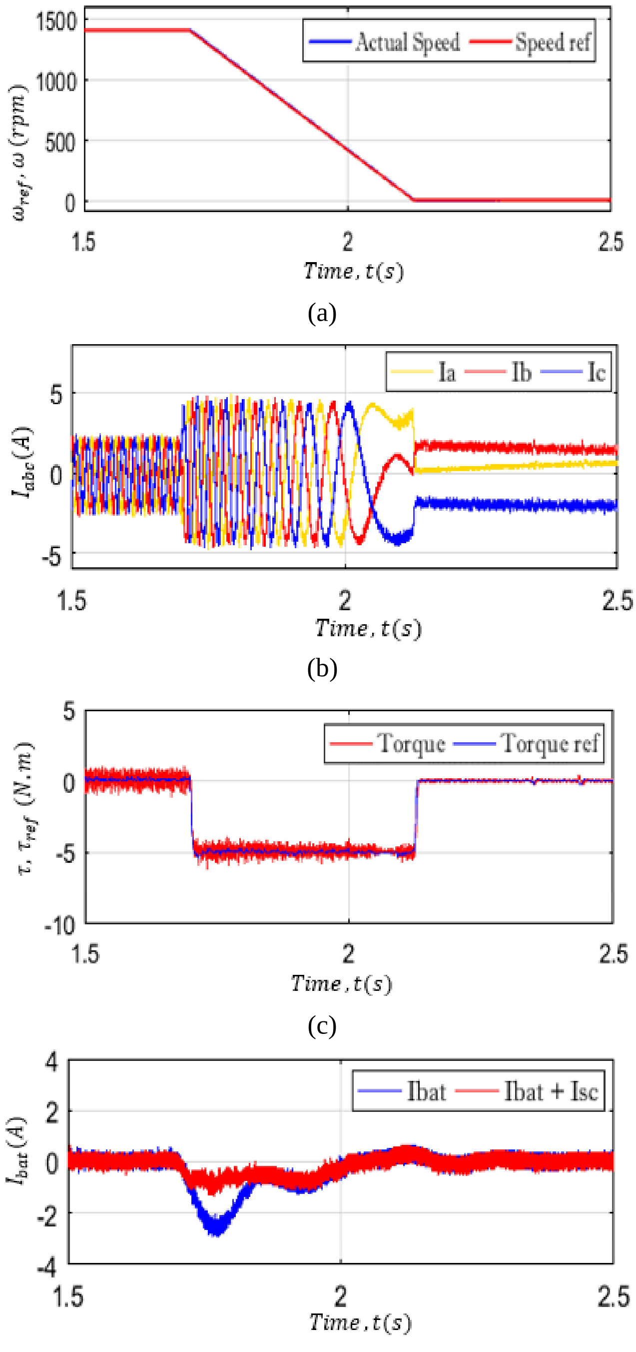
(d)

Fig. 12. Operation of motoring (a) the capacitor voltage, V_{C1}; (b) the inductor current I_{L2}; (c) the DC link voltage; (d) SC current I_{SC}.

During regenerative braking operation, power generated from the braking operation is sent back to the battery and supercapacitor to charge them. Fig. 13(a) shows the speed transient changes from 1450 rpm to 0 rpm at t=1.7s. The proper function of the FOC is shown through the stator current increment from around 0.5 A_{pk} to 2.5 A_{pk} during the speed change as shown in Fig. 13(b). From Fig. 13(d) which compares the battery current with the present and without the present of supercapacitor, it is shown that the SC helps in lowering the amount of the current flowing into the battery during regenerative braking. During the regenerative braking, I_{bat} without SC reaches peak of 2.5 A while with the SC, I_{bat} peaks approximately at 1 A, reducing it to approximately more than half.

The dual-loop controller

effectively controls the capacitor voltage as in Fig. 14(a) as the V_{C1} is maintained at 500 V while I_{L2} follows the reference current in Fig. 14(b), and the voltage across the inverter bridges is indirectly maintained at 640 V in Fig. 14(c). In Fig. 14(d), the supercapacitor recharges at 1.5 A peak current to reduce the amount of current flowing into the battery.



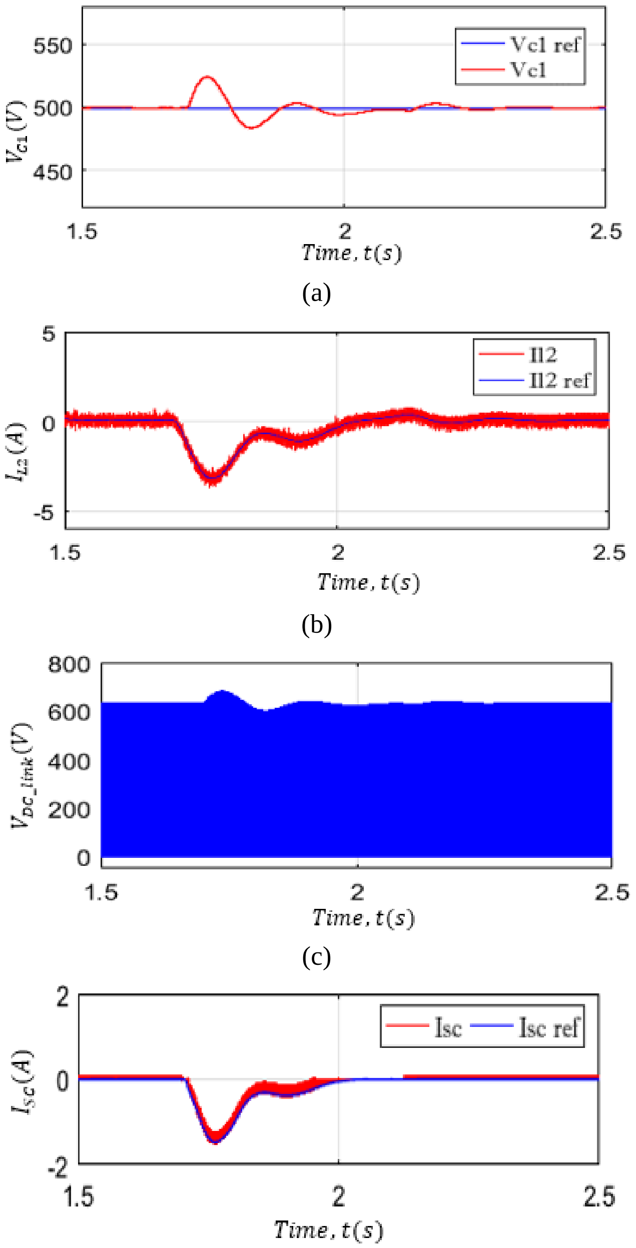
(a)

(b)

(c)

(d)

Fig. 13. Regenerative Braking mode (a) Speed of IM; (b) stator current; (c) Torque; (d) battery current I_{bat} comparison with and without ESS.



(a)

(b)

(c)

(d)

Fig. 14. Regenerative braking (a) The capacitor voltage, V_{C1}; (b) the inductor current I_{L2}; (c) the DC link voltage; (d) SC current I_{SC}.

IV. CONCLUSION

An induction motor drive fed by the qZSI inverter with a newly proposed method of integrating supercapacitor as a supportive energy source in realizing a battery/supercapacitor HESS has been presented. The system is designed at 5 kW power level, with modelling and simulation is carried out based on the Matlab/Simulink software. From the results of the simulation analysis carried out, it works satisfactorily as expected and able in reducing the stress on the battery current stress around 50% during the acceleration and regenerative braking operation, as well as good performance in speed and torque control of the drive. This current stress mitigation has contributed towards prolonging the battery life cycle as well as increasing the efficiency of the overall system.

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