A multi-functional converter based switched reluctance motor drive for electric vehicle

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ABSTRACT

Owing to the resilience and ease of control, switched reluctance motors are commonly utilized in electric vehicle drives. This paper provides a topology for a multi-functional power converter for switched reluctance motor based electric vehicle drive with driving, braking and charging potentialities. With efficient control algorithms, a single power electronic converter is used for motoring, regenerative braking, and charging of the battery bank, resulting in a cost-effective power electronic interface. The front-end voltage control and current control of the switched reluctance motor (SRM) are used to achieve open loop and closed loop speed control during driving mode. Re-generation is made possible through restricted switching of phases in negative torque region. A bridgeless rectifier converter is built in battery charging mode by combining the SRM's two-phase windings with the prevailing power devices of an integrated power converter, eliminating the need for additional inductors and charging units. Simulations are run in MATLAB/Simulink, and simulation results are used to validate the control schemes for all modes.

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1. INTRODUCTION

Owing to outstanding fault-tolerant capabilities, and strong starting torque, control flexibility and precision the switched reluctance motor (SRM) is extensively used for electric vehicles (EV) applications [1]–[3]. For increasing the system operational performance, several SRM power converter topographies [4]–[7], such as R-dump converter, C-dump converter, C-dump with freewheeling transistor converter, asymmetric converter, series converter, and parallel type converters have been utilized. Reduced component topologies were presented [8]–[11] for driving SRM where accurate steady performance was achieved. A close-packed power converter that performs several energy conversion functions is highly demanded in general. Traditionally, an unsymmetrical half-bridge converter [12], is used to modulate control of EV switched reluctance drives. Whatever the case may be, this type of converter is only capable of driving and regenerative braking necessitating the use of a separate battery charger for charging. Several improved converters have been developed describes a buck front-side DC to DC converter, a three-phase common high side switched asymmetric half-bridge converter, and a single-phase active rectifier for charging operation integrated power converter [13]–[17]. The boost converter can adjust and enhance the bus voltage in driving mode, and the stored energy by the winding could be recovered to energy source [18]. Integrated battery charging capable converter for electric vehicles (EVs) that use only four switches for driving and charging is presented [19]. A three-phase intelligent power module [20] is used to build a modified common high side switch converter. This converter may increase performance and enable charging. A bi-directional buck/boost converter and the common high side switched asymmetric half bridge converter make up this converter, which provides perfect acceleration/deceleration, reversible driving, and braking characteristics [21]. A buck circuit, with combining of a capacitor with energy storing elements, battery packs, and an SRM are all combined into a modern converter, according to [22]. With enhanced excitation and demagnetization voltage, a variety of driving operation modes can be accomplished. The hybrid drive with cascading of multi-port drive is presented in [23]. A converter system which allows for variable power conversion between the generator/AC grid, battery bank, and motor, as well as battery management system is presented in [24]. The double-break converter which provides AC as well as DC charging is developed [25]. Thus, various existing topologies stated above suffer from integration of all the three functions of charging, braking and driving into single converter with efficient current control.

Rest of the paper is organized as follows. Section 2 presents converter configurations for three modes. Section 3 presents control strategies for three modes. Section 4 presents simulation results and section 5 presents conclusion.

2. CONVERTER CONFIGURATIONS

2.1. Topology of the multi-functional converter

The multi-functional converter is developed, in which a single converter is set for open and closed loop speed control in driving mode, battery feeding through regeneration, and battery charging. Voltage control is accomplished with a front-side buck type DC to DC converter, and phase excitation is accomplished via a common high-side switch based asymmetric converter. For closed loop speed control, a front-side DC-DC converter is switched to apply the appropriate voltage, and current control is provided by a common high-side switch asymmetric converter for SRM. The same converter with limited excitation is used to feed energy from the winding to the energy source. For battery charging, two-leges of the converter, as well as SRM phase windings, are utilised as charging filters. In this mode, the converter is used to drive the engine and charge the batteries simultaneously. The circuit connections of the proposed multifunctional converter are shown in Figure 1.

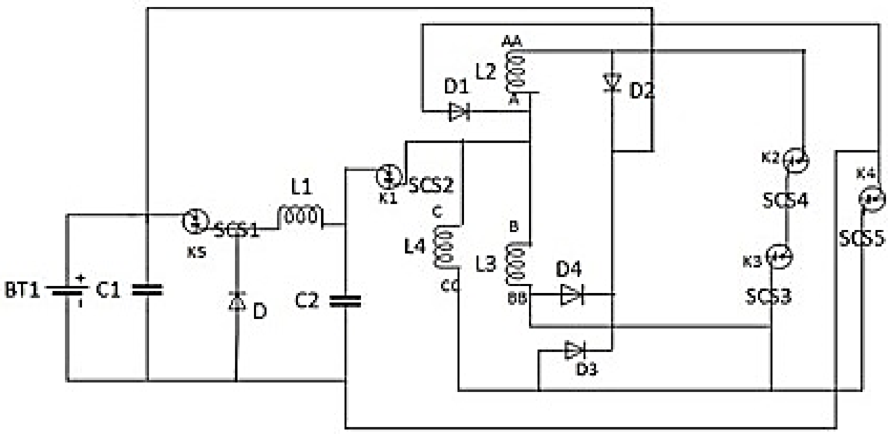


Figure 1. Multi-functional power converter

2.1.1. Driving mode

Figure 2 shows the illustration of excitation, free-wheeling and de-magnetization of phases A and succeeding excitation and freewheeling of phase B during driving mode. The equivalent circuits and the current flow are shown in Figure 3. The phase-A voltage equation will be demonstrated as (1) and incremental inductance can be given represented as (2) and (3).

$$U\ bus = Rik + Link\ \frac{di_k}{dt} + ik\ w\frac{\partial L(\theta,i_k)}{\partial \theta} \tag{1}$$

$$Linc = L(\theta,i_k) + i_k\frac{\partial L(\theta,i_k)}{\partial i_k} \tag{2}$$

$$For\ Off\ state, 0 = Ri_k + L_{inc}\frac{di_k}{dt} + i_k w\frac{\partial L(\theta,i_k)}{\partial\theta} \quad (3)$$

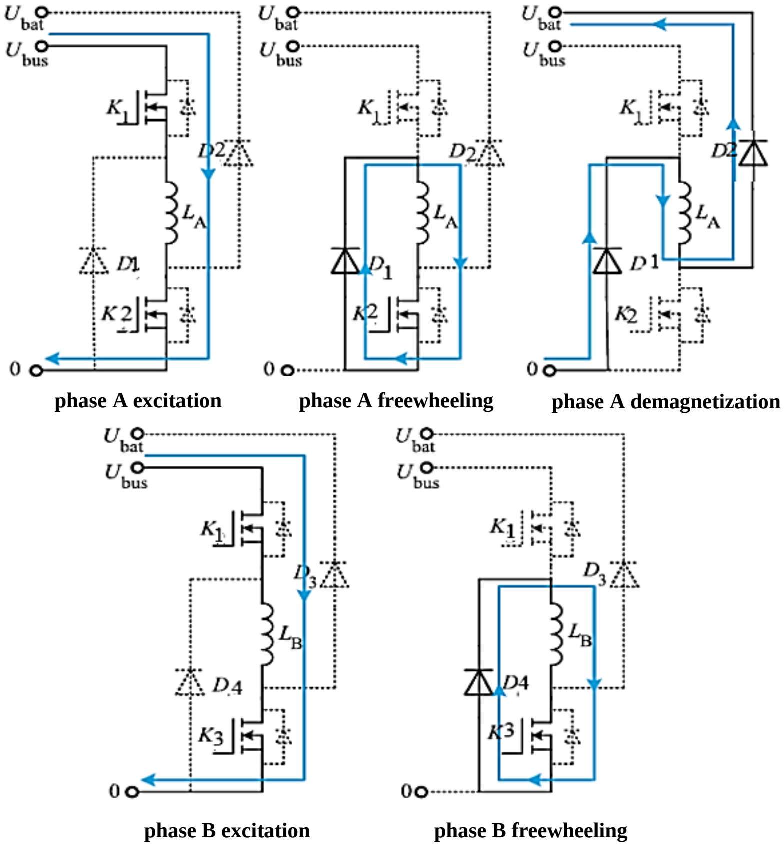


Figure 2. Illustration of phase excitation and de-magnetization

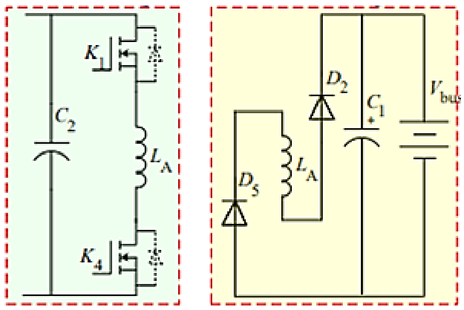


Figure 3. Operation states of under battery regenerative braking

2.1.2. Regenerative braking operation

The SRM drive might be configured as a generator in regenerative braking mode. The required current for regeneration can be produced with restricting the excitation angle of each phase, as shown in Figure 4. When the excitation is seized for phase-A, the developed current freewheels through D1 and D2 develop and charges the battery. Figure 5 shows corresponding circuits for the motoring and generation modes.

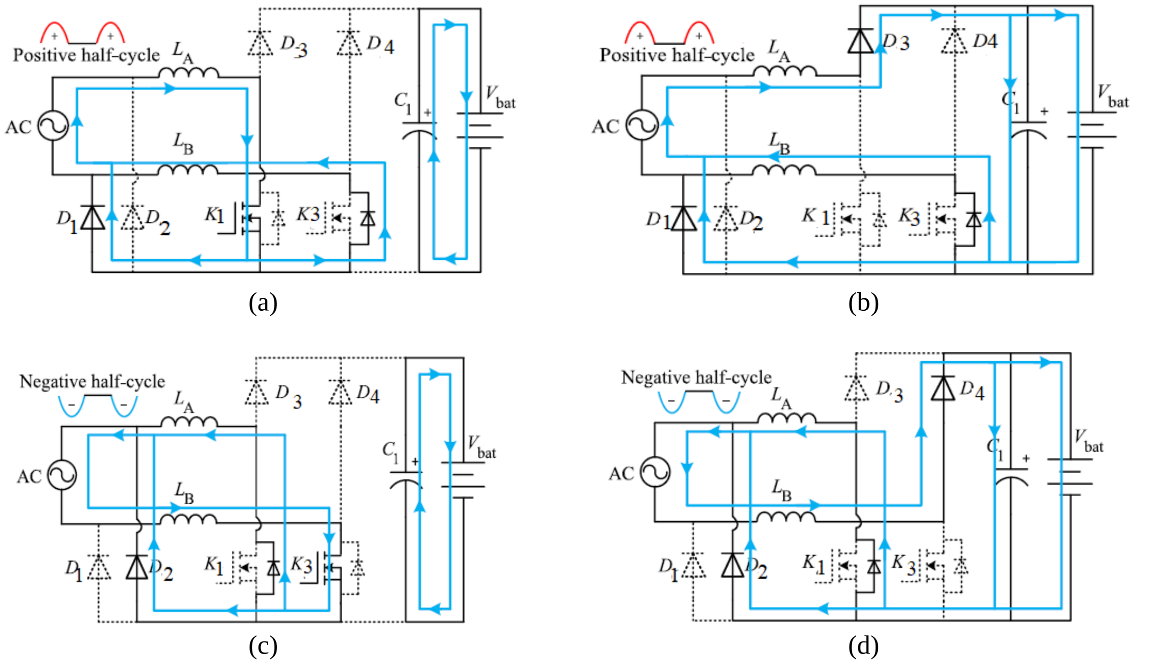


Figure 4. Illustration of sub-modes of charging operation (a) mode 1, (b) mode 2, (c) mode 3, and (d) mode 4

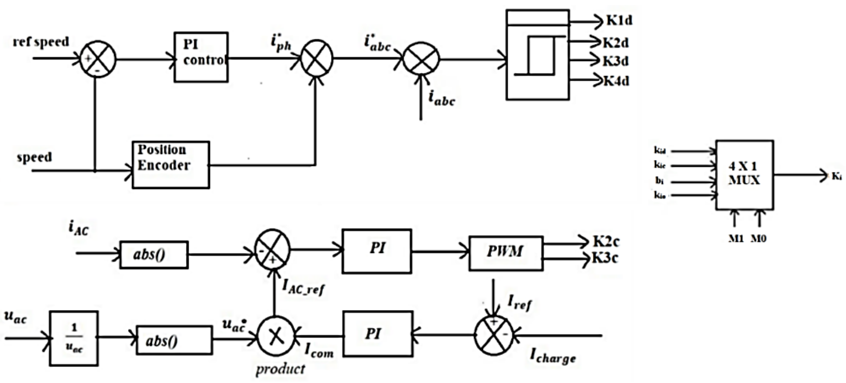


Figure 5. Control structure for driving and charging operations

2.1.3. Battery charging operation

With all power switches under OFF state except K1 and K3, the A, B phase windings will enable the charging. The rotor shall be mechanically locked in this mode. The source inductor is charged while capacitor is discharges into battery in mode 1, with K1 and K3 turned off, charged source inductor and capacitor together discharge into battery. Mode 3 and mode 4 depicts the similar operation as mode 1 and mode 2 respectively for negative half cycle of source voltage.

3. CONTROL STRATEGIES

Closed-loop driving mode control: In this mode the duty of the buck converter is made one and the closed-loop speed control is achieved through current control of CHSAHBC. As shown in Figure 5, the measured speed is contrast to reference speed and the error is fed to proportional integral (PI) controller to obtain current magnitude command. Rotor position sensor provides phase excitation sequence. Thus, instantaneous reference current command is generated and is compared to measured current. The error is fed to hysteresis current control which generates gating pulses for respective switches in each phase.

Battery charging operation: as shown in Figure 5, the charging current feedback loop is the outer loop, and it uses a PI controller to regulate the error between the reference current and the feedback charging current. An inner loop is also included to accomplish power factor correction (PFC) function. The actual value of the AC source voltage UAC* is multiplied by the outer loop control instruction Icom to generate

IAC_ ref. Another PI controller is used to adjust the tracking error between the IAC_ ref and the absolute value of the direct measured AC input current i_{AC}, and the resulting pulse-width modulation (PWM) signals are utilized to operate the two power switches at the same time.

4. SIMULATION RESULTS

A Simulink model have been implemented in a 6/4 structure SRM drive shown in Figure 6 for verifying the effectiveness of multi-functional converter and its control strategies under various operating modes. The responses for speed control for open loop driving mode is shown in Figure 7. The phase currents were balanced, torque ripple was minimal and variation in speed in proportion to input voltage control through buck converter are observed in Figure 7(a). The speed variation is achieved over large range without duty range stress on the converter as seen from Figure 7(b).

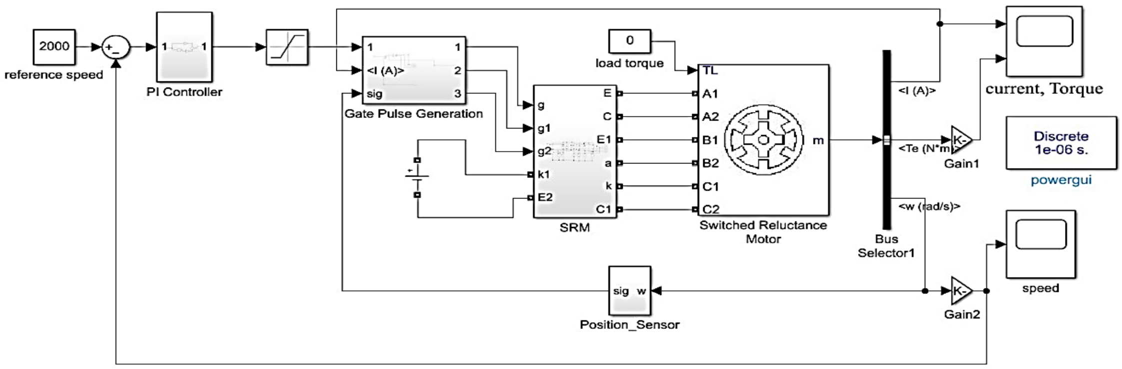
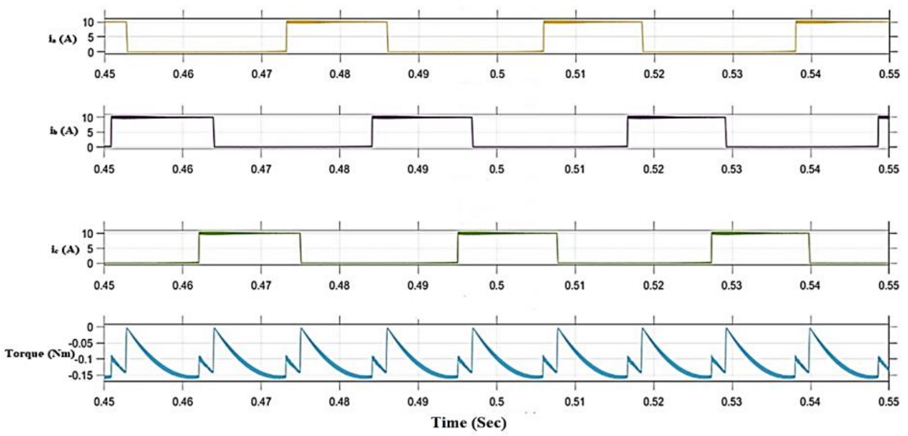
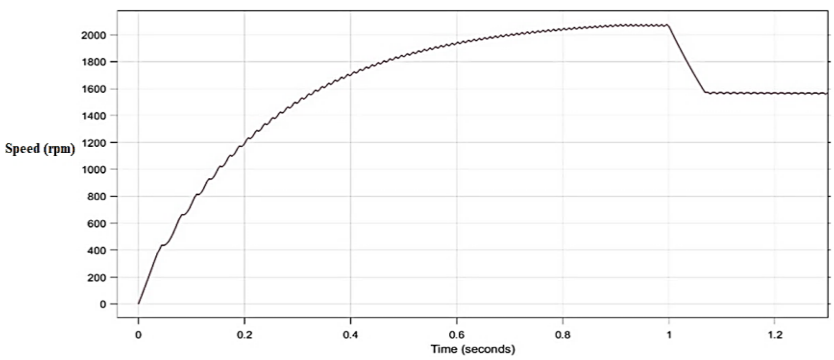


Figure 6. SIMULINK schematic of multi-functional converter based SRM drive



(a)

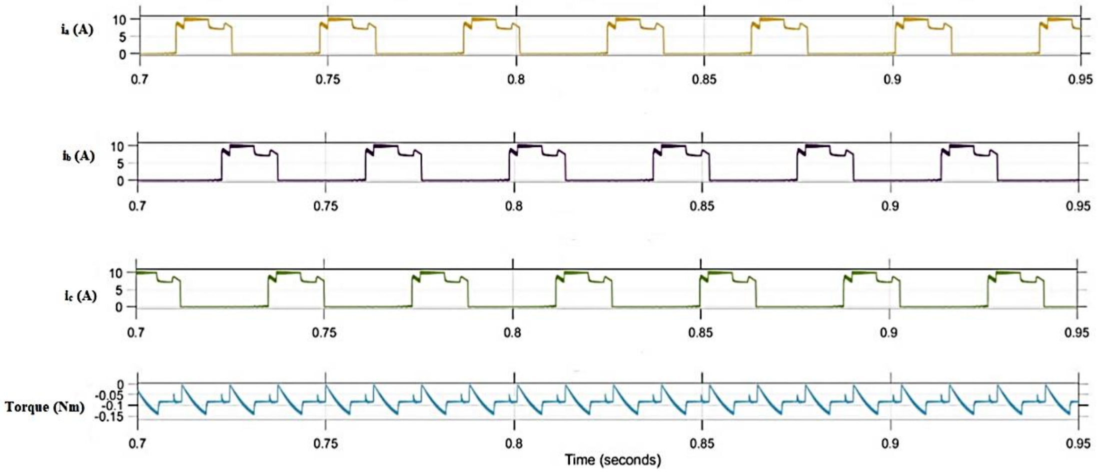


(b)

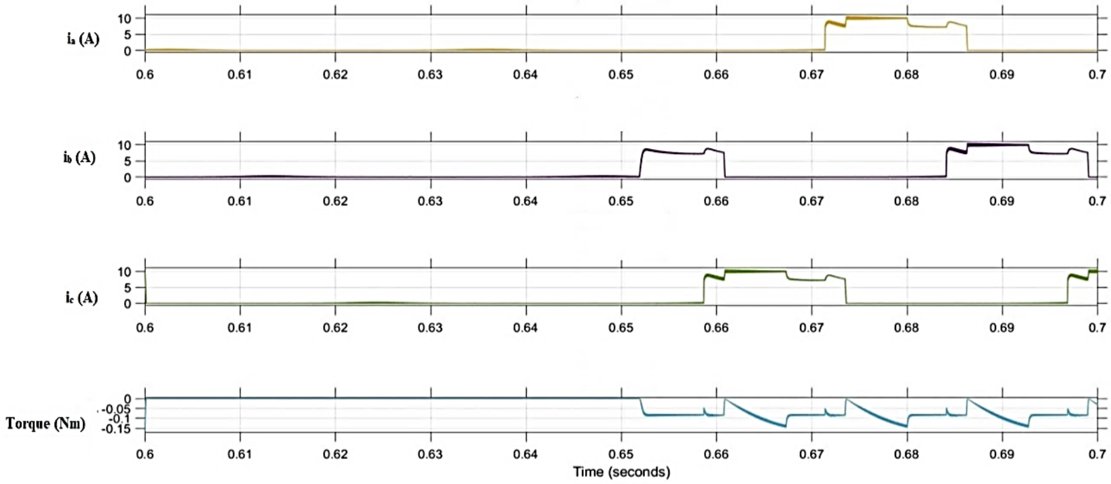
Figure 7. Open loop driving operation (a) phase currents and torque for 2000 rpm and (b) speed response for step change in speed command

Simulation results for closed loop driving mode control shown in Figure 8. The phase current developed were balanced and were in limit. The torque has an appreciable ripple of 0.1 N-m for with current magnitudes are in proportion to applied speed command as observed from Figure 8(a). The transient response for torque phase currents and torque was shown in Figure 8(b) in which a good transient time of 0.004 sec was observed. The currents in all phases have an immediate response for change in torque. The closed loop speed control with acceleration time of 1.4 seconds for full speed command and less than 1 sec for step change in speed command is observed from Figure 9. The regenerative braking condition is simulated with battery to absorb the energy in the windings.

The controller switches each phase with restriction on to negative torque region which is observed form Figure 10. An increase in magnitude of currents at the instant of regenerative mode switching is also observed. The speed drops by 500 rpm within 0.07 sec. The simulation results for source voltage, current and battery voltage, current is shown in Figure 11. The voltage and current during charging of battery were shown in Figure 11(a) in which a quick transient was observed for change in mode of operation. The converter provides required voltage and current for charging operation. The source side current as observed from Figure 11(b) is in phase with supply voltage which proves the unity power factor operation for charging mode. Thus, an efficient charging is made possible with the converter. The controller tracks the reference current with minute tolerance. Thus, efficient charging control is achieved with source current total harmonic distortion (THD) of 0.9 percent. The required voltage and current for the battery are sufficiently provided by the converter which is rated for double the charging power. A comparison is made with existing integrated converters in terms topological and operational parameters as depicted in Table 1.



(a)



(b)

Figure 8. Steady state and transient waveforms for closed loop driving mode: (a) phase currents, developed torque and rotor speed; and (b) transient torque response

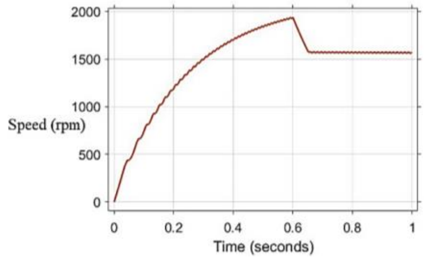


Figure 9. Tracking of speed command in closed loop operation

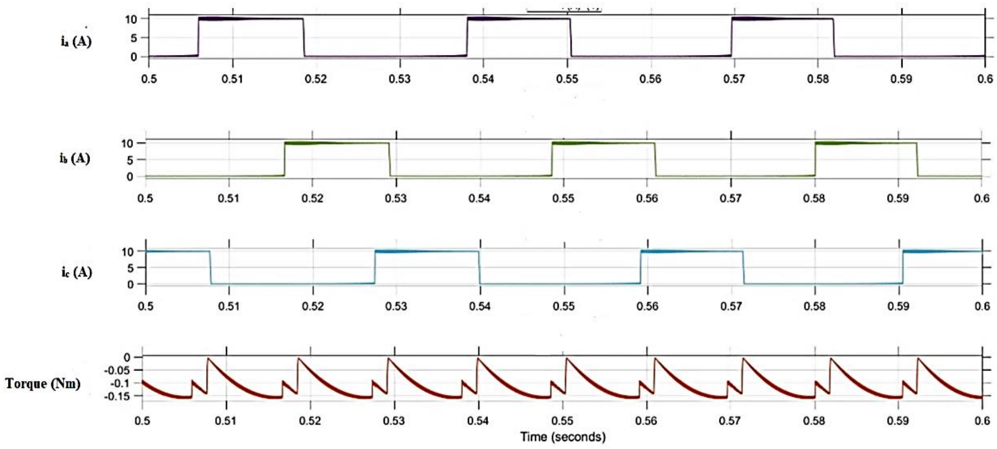
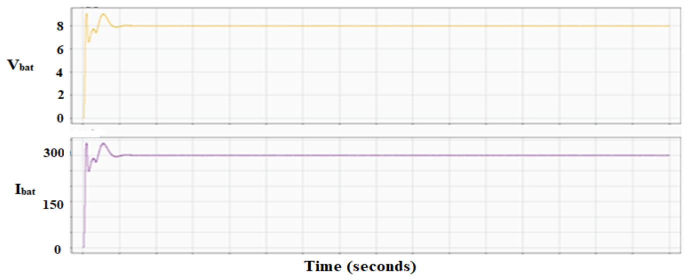
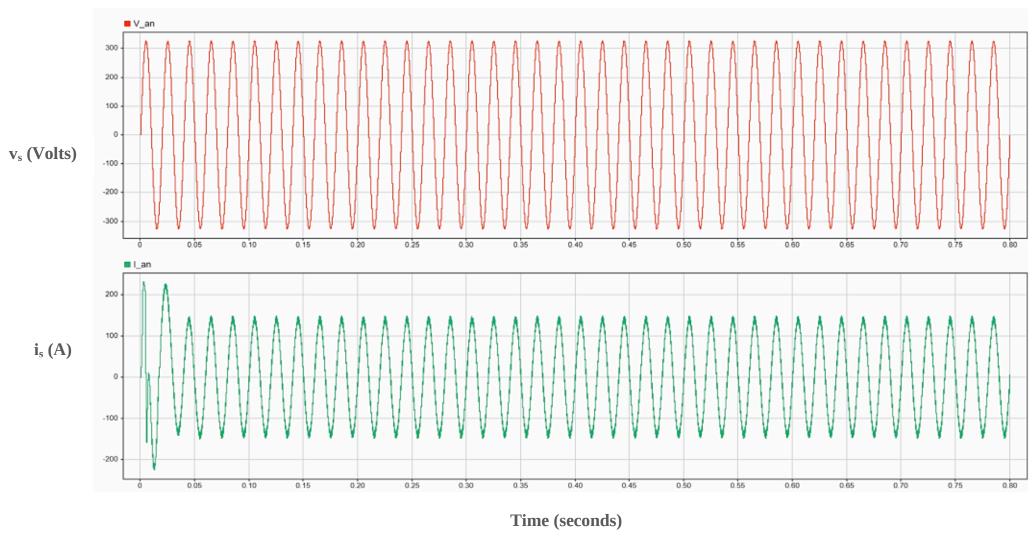


Figure 10. Phase currents and developed torque for regenerative braking mode operation



(a)



(b)

Figure 11. Charging process (a) battery voltage and current and (b) source voltage and current

Table 1. Comparison among integrated converter topologies

Topology	Proposed	[12]	[16]	[18]	[21]
Inherent regeneration capability	Yes	No	No	No	No
Single phase charging	Yes	No	No	No	Yes
Power factor correction	Yes	No	No	Yes	Yes

4. CONCLUSION

An integrated configurable power converter for driving, re-generative braking and charging of an electric vehicle drive system is developed. Control algorithms for all the closed loop and open loop speed control for driving mode, phase excitation control for re-generative braking and current control for efficient battery charging were designed. The simulation results in each mode verified the configuration, integrity, and control of the converter. Thus, an economic and efficient power electronic solution for SRM based EV drives is achieved

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