

Enhancing EV Regenerative Braking with PMSM and Knight Inverter for Bi-directional Traction control

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Abstract— Electric vehicles (EVs) frequently employ permanent-magnet synchronous motors due to their numerous advantages, including attractive torque-speed characteristics and higher efficiency. The regenerative braking strategy, that recovers kinetic energy in deceleration operation, is an effective technique to recharging the battery and thereby extends the operating and dynamic range of EV. In this paper, a field-oriented control with torsional oscillation damping method approach that considers all forces acting on an EV on an incline is utilized to calculate the shaft torque. To optimize the electromagnetic torque, the stator current's d-axis component is kept at zero, and the 3- ϕ stator winding voltages are produced in accordance with the demands of the EV. The novel Knight multilevel inverter with PD-PWM control technique is utilized as a bi-directional traction converter to improve harmonic performance. MATLAB/Simulink simulations validate the proposed regenerative braking technique across acceleration, deceleration, and constant speed operating modes.

Index Terms— Electric vehicles, Multilevel Inverter, Permanent-Magnet Synchronous Motors, Torsional oscillation damping method.

I. INTRODUCTION

Over the past few decades, there has been growing interest in electric vehicles (EVs) due to rising fuel consumption, noise levels, and harmful emissions [1]. The transport industry was the largest source of greenhouse gas (GHG) emissions in 2019, accounting for 27% of all emissions in the UK, according to the Transport and Environment Annual Report 2021. As a result, road transportation, which includes passenger automobiles, heavy-duty and light commercial vehicles, released 122 million tons of CO_2 equivalents [2]. In addition, since 1990, the need of both diesel and gasoline in the European Union has steadily increased. EVs have the potential to significantly reduce gasoline consumption and greenhouse gas emissions. The three main categories of EVs are hybrid EVs (HEV), battery EVs (BEV) and plug-in hybrid EVs (PHEV). BEVs are considered pure EVs because they are powered only by electricity, whereas HEVs and PHEVs use both electricity and gasoline or diesel [3]. The essential parts of a BEV include the high and low voltage battery system, Electric Propulsion System (EPS), transmission system, and battery charger, which is generally an isolated DC-DC converter subsequent to an AC-DC converter [3].

The EPS consists of a traction converter and either an AC or DC electric motor. For a long time, DC motors dominated primary EV propulsion systems [4], but they were enduring by issues such as carbon brushes, low power density, and low efficiency.

As a result, induction machine (IM), brushless DC (BLDC) and permanent magnet synchronous machines (PMSM), have become the most widely used types of motors due to their improved performance. The PMSM, in particular, offers benefits such as a high torque-to-volume ratio and a more compact motor design. In practice, PMSMs have demonstrated their ability to deliver smooth dynamic performance, full torque at low speeds, high efficiency at higher speeds, and excellent dependability [5]. When it comes to EV power converters, inverter such as Neutral-Point Clamped, Flying Capacitor, Cascaded H-Bridge, and Modular inverters are promising options for driving motors, particularly as intermediate bi-directional traction converters, because they produce a staircase voltage waveform on the AC end. Compared to traditional multilevel inverter (MLI), the novel Knight MLI proposed in [6] achieves better performance. In addition to requiring lesser-sized filters on both the AC and DC ends, these converters provide nearly a staircase output voltage waveform on the AC end leads to lower THD%, reduced total harmonic distortion (THD), increased efficiency, and reduced electric stress on power semiconductor devices. The primary obstacles to BEV advancement are limited battery and driving range, higher cost, inefficiency, low power density, and insufficient charging infrastructure. Regenerative braking and the integration of renewable energy sources into EVs are viable solutions to these problems. With regenerative braking, kinetic energy is converted into electrical energy, which can either be stored for later use or used immediately [7].

The Knight MLI is utilized as the bi-directional traction converter in this paper because of the excellent benefits previously highlighted. The structure of this paper is as follows: Sections II and III cover the PMSM modelling and provide an overview of the regenerative braking concept, respectively. Section IV presents a brief outlet of the pros and challenge for the traditional and suggested Knight MLI. The MATLAB simulation outcomes are presented in Section V. Section VI concludes the paper.

II. PMSM MODELLING

The mathematical model of the PMSM is necessary before going into the specifics of the FOC approach that is being described in this section. Consequently, the synchronous reference frame, also known as the dq-axis, is employed, resulting in voltage and current variables that remain constant. As a result, step signals or constants are chosen for the reference dq-axis signals [8]. Therefore, this serves as the primary reason for the widespread use of PI controllers in PMSM drive systems. The dynamic equations of the PMSM in the rotor flux reference frame and stator voltage can be represented by

$$V_{ds} = R_s i_{ds} + \rho \lambda_{ds} - W_e \lambda_{qs} \quad (2.1)$$

$$V_{qs} = R_s i_{qs} + \rho \lambda_{qs} - W_e \lambda_{ds} \quad (2.2)$$

$$\lambda_{ds} = L_s i_{ds} + \lambda_m \quad (2.3)$$

$$\lambda_{qs} = L_s i_{qs} \quad (2.4)$$

By incorporating equations (2.3) and (2.4) into equations (2.1) and (2.2), we derive equation (2.5) and (2.6) as shown below.

$$V_{ds} = R_s i_{ds} + L_{ds} \frac{d}{dt} i_{ds} - W_e L_{qs} i_{qs} \quad (2.5)$$

$$V_{qs} = R_s i_{qs} + L_{qs} \frac{d}{dt} i_{qs} - W_e (L_{ds} i_{ds} + \lambda_m) \quad (2.6)$$

where λ_{ds} , λ_{qs} , and λ_m represent the flux linkage of the d-axis, q-axis component and the flux linkage of the stator winding respectively. V_{ds} and V_{qs} are the d-axis and q-axis voltages, R_s and L_s are the stator's resistance and inductance. i_{qs} and i_{ds} are q-axis current and d-axis current and are the L_{qs} and L_{ds} are the dq- axis inductance. Also W_e is the electrical speed corresponding to the frequency of stator voltage.

The electromechanical equation of the motor is described as follows,

$$T_e = \frac{3P}{2} i_{qs} [i_{ds} (L_{ds} - L_{qs}) + \lambda_m] \quad (2.7)$$

$$T_e = T_l + J \frac{dW_m}{dt} + B W_m \quad (2.8)$$

where T_e and T_l are the electromagnetic and the load torque respectively; P represents the number of pole pairs in the motor, W_m denotes the rotor's mechanical rotational speed, B represents the friction coefficient, and J stands for the moment of inertia

Based on equation (2.1), the resulting stator voltage magnitude (V) and angle (θ) can be represented as shown in equations (2.9) and (2.10)

$$V = \sqrt{V_{ds}^2 + V_{qs}^2} \quad (2.9)$$

$$\theta = -\tan^{-1} \frac{V_{ds}}{V_{qs}} \quad (2.10)$$

Equation (2.1) and (2.2) evident that the magnitude of the stator voltage is directly related to the machine's speed. While this direct relationship is sufficient to control the machine's rotation, Regulation of the angle must also be taken into account. By combining voltage (V) and angle (θ) regulation, the PMSM can achieve higher torque and lower current.

III. OVERVIEW OF REGENERATIVE BRAKING CONCEPT

Electric machines' kinetic energy is released using armature coils and additional brake resistors in conventional passive dynamic braking. The idea behind regenerative braking using a Knight converter is similar to conventional dynamic decelerating operation; the only differences are that no extra power switches or resistors are needed. The decelerating procedure can be categorized as either variable speed decelerating or constant speed decelerating depending on the driving conditions. When driving downhill, consistent speed braking is typically needed, although variable speed braking frequently happens throughout the general deceleration process. Most of the kinetic energy is transformed into heat and dissipated into the atmosphere during friction braking. To increase battery life and driving range, EVs with regenerative braking can transform the kinetic energy into electrical energy and store it for later use [9]. Fig. 1 illustrates the general topology of a battery electric vehicle (BEV) in both accelerating and braking modes. Common components of BEVs include controllers, motors, power converters, traction system and high-voltage (HV) battery packs. The power flow in accelerating mode (between the battery pack and motor) and regenerative braking mode (between the motor and the HV battery pack) is shown in the figure by the green and red arrows, respectively.

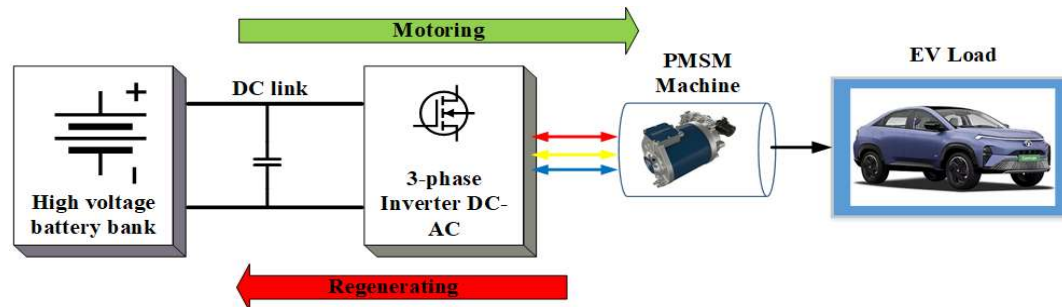


Figure 1. Block diagram representation of the power flow during acceleration and braking modes

Principle of Regenerative Braking in PMSM

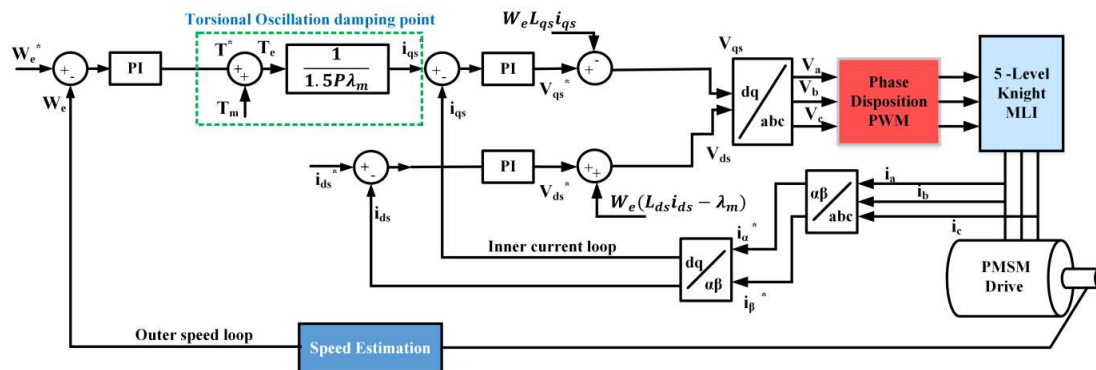


Figure 2. Block representation of PMSM drive with modified FOC

FOC measures the stator phase currents, turns them into a complex vector, and then creates a coordinate system that revolves with the machine's rotor and Fig: 2 depict the FOC scheme for the PMSM. In this coordinate system oriented to the rotor flux, the rotor flux linkage is controlled by the real x-axis component of the stator current vector i_d .

The motor torque is managed by the imaginary component i_q along the y-axis, Keeping the d-axis component current to zero ($i_d=0$) enables maximal torque-current control for the PMSM. Based on FOC, electric brake control is achieved either by adjusting the speed to follow an upward reference and gradually approaching zero, or by applying a negative q-axis current in accordance with the needed braking torque [10].

The input power, output power and electromagnetic torque (T_e) can be defined as

$$P_{in} = V_{ds}i_{ds} + V_{qs}i_{qs} \quad (3.1)$$

$$P_{out} = T_e W_e \quad (3.2)$$

$$T_e = \frac{3P}{2} \lambda_m i_q \quad (3.3)$$

The power losses of the electric machine are defined as

$$P_{losses} = i_d^2 R + i_q^2 R \quad (3.4)$$

$$P_{in} = P_{out} + P_{losses} \quad (3.5)$$

$$P_{in} = \frac{3P}{2} \lambda_m i_q W_e + R(i_d^2 + i_q^2) \quad (3.6)$$

To identify the sections of regenerative braking P_{in} is fix to zero, indicating that zero power is being drawn from the DC source. The following equation (3.7) is an expression for i_q in terms of i_d .

$$i_q = \frac{-\frac{3P}{2} \lambda_m W_e \pm \sqrt{(\frac{3P}{2} \lambda_m W_e)^2 - 4R^2 i_d^2}}{2R} \quad (3.7)$$

The equivalent T_e is expressed as

$$T_e = \frac{3P}{2} \lambda_m \left(\frac{-\frac{3P}{2} \lambda_m W_e \pm \sqrt{(\frac{3P}{2} \lambda_m W_e)^2 - 4R^2 i_d^2}}{2R} \right) \quad (3.8)$$

The equation (3.8) describes the T_e within the deaccelerating mode. To determine the limits of this operating mode, the equation (3.8) is solved to determine the maximum and minimum deaccelerating torque (braking torque).

$$\frac{dT_e}{di_d} = 0, i_d = 0 \text{ and } i_q = \frac{-3P\lambda_m}{4R} W_e \quad (3.9)$$

The corresponding T_e is provided by

$$T_e = \frac{-(\frac{3P\lambda_m}{4})^2}{R} W_e \quad (3.10)$$

$$\nabla P_{in} = \begin{bmatrix} \frac{dP_{in}}{di_d} \\ \frac{dP_{in}}{di_q} \end{bmatrix} = \begin{bmatrix} 2Ri_d \\ \frac{3P}{2} \lambda_m W_e + 2Ri_q \end{bmatrix} \quad (3.11)$$

Setting the gradient to zero and solving for both variables, i_d and i_q , gives a minimum power. And the i_d and i_q are as follows:

$$i_d = 0 \text{ and } i_q = \frac{-3P\lambda_m}{8R} W_e \quad (3.12)$$

The resultant T_e produced by these current commands is described by

$$T_e = \frac{-9P^2\lambda_m^2}{32R} W_e \quad (3.13)$$

IV. MULTILEVEL INVERTER

The schematic layout of the novel Knight multilevel inverter (MLI) is presented in Fig. 3. The neutral end, 'N,' is maintained at the central potential of the DC-link voltage V_{dc} , as illustrated in Fig. 3. The voltage rating of $1/4 V_{dc}$ is supported by the DC-link split capacitors C_1 , C_2 , C_3 , and C_4 . The Knight MLI eliminates the need for extra clamping diodes, quadratic switches, and series switches, using only twenty-four semiconductor power switches and twenty-four antiparallel diodes. Without the use of output transformers, the proposed MLI reduces output current and voltage harmonics by generating 9-level (9L) stepped line-to-line voltages. This MLI's ability to generate a staircase output voltage waveform on the AC end leads to lower THD%. Owing to their enhanced efficiency, reduced electric stress on power semiconductor devices, nearly sinusoidal current profile on the AC end, and the need for lesser sized filters on both the AC and DC ends, these MLIs are commonly used in high voltage and power applications, such as electric vehicles and renewable energy sources [6]. A brief comparison of the multilevel topologies is presented in Table 1.

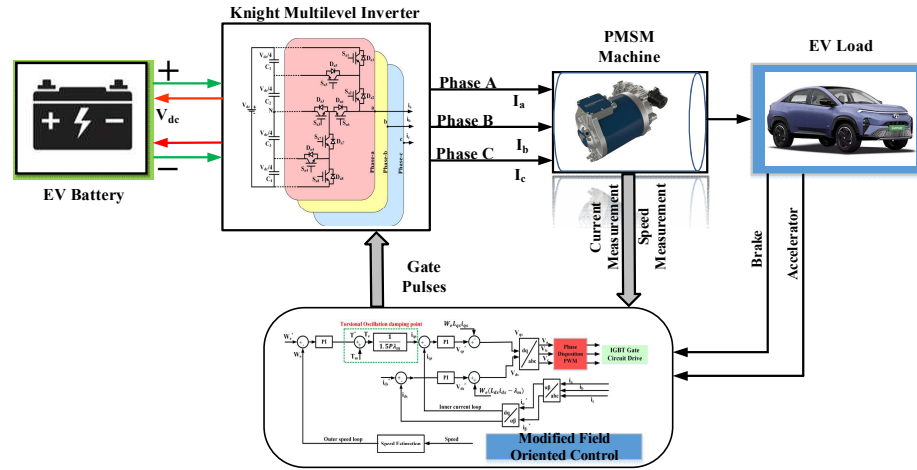


Figure 3. System configuration of the PMSM with modified FOC based EV

TABLE I: KEY PROS AND CONS OF VARIOUS TRADITIONAL MULTILEVEL TOPOLOGIES [11]

Topology	Pros	Cons
NPC	- Basic configuration and PWM strategy - Zero-sequence injection for controlling DC-link voltage imbalance	- Imbalanced usage of power semiconductor devices - Additional circuits are needed to balance the DC-link.
FC	- Self-floating DC voltage balance - Enhanced harmonic profile, and capability of tolerating faults	- Limited dynamic response of inherent DC voltage balancing - Numerous floating voltages
CHB	- Well-established topology. - Marketed by various companies - Capability of tolerating faults.	Requires an isolated DC source for each H-bridge
MMC	- Composed of a series of interconnected of simple power cells, with capability of tolerating faults - A easy gate driver generation technique - Equalization of balanced average power loss along with floating DC voltage balancing	Difficult data acquisition and communication, along with sophisticated hardware required to activate the converter
Knight inverter [6]	- It provides a simple way to advance and reach an extensive number of levels. - Ensures equal power sharing - Delivers good harmonic profile - Includes reduce control and design complexity	DC-link voltage balancing needed

V. SIMULATION OUTCOMES

The regenerative braking system, utilizing a modified FOC control approach, is employed in the MATLAB /Simulink software with the constraints detailed in Table 2 and Table 3. Simulations are conducted using a

Knight inverter as the bi-directional traction converter. Simulation results for the PMSM drive system with the Knight inverter, aiming on the d-axis current during motor and regenerative braking modes is shown in Fig: 4 and Fig: 5 presents the 3- ϕ currents of PMSM drive during motoring and regenerative braking modes.

Fig:6(a) and Fig: 6(b) presents the Simulation outcomes of the PMSM drive system with the Knight inverter during motor and regenerative braking modes of q-axis current and Torque respectively. The battery output voltage is presented in Fig:7(a) and the Fig:7(b) presents the PMSM speed and state of charge (SOC) and voltage of the battery, showing charging and discharging, is depicted in Fig:7(c). The Fig: 7 are divided into three modes, each through the following notes:

Mode 1: In this mode, the PMSM operates as a motor, and the battery's SOC decreases (discharging mode) as the speed increases from 0 to 2500 rad/s during the period of 0.1 to 0.5 sec, due to both speed and torque are positive.

Mode 2: During the period from 0.5 to 0.7 sec, with a speed constant of 2500 rad/s, both the speed and torque remain positive.

Thus, the PMSM continues to function as a motor, leading to a decrease in the battery's SOC, indicating it is in discharging mode.

Mode 3: In this mode, from 0.7 to 1 sec, as the motor speed decreases to zero from 2500 rad/s, the speed remains positive while the torque becomes negative. As a result, the PMSM functions as a generator, which leads to an increase in the battery's SOC, indicating it is in charging mode.

TABLE II: PMSM MOTOR SPECIFICATIONS [12]

Parameter	Symbol	Values and unit
Number of poles	P_n	3
Stator Resistance	R_s	6.5m Ω
d – axis Stator inductance	L_d	0.538mH
q – axis Stator inductance	L_q	0.538 mH
Maximum speed	N_{max}	4500RPM
Flux Leakages	λ_m	0.162 wb
Rated speed	N_s	3000RPM
Rated Torque	T	15.3 Nm
Rated power	P	80KW
DC-link voltage	V_{dc}	700V
Inertia	J	0.0005KgM ²
Friction co-efficient	F	0.00008N.m.s/rad

TABLE III: BATTERY SIMULATION PARAMETERS

Battery	Type	Parameter	Value
	Lithium ion	Nominal voltage (V)	597.2V
		Cut off Voltage ($V_{cut-off}$)	447.88
		Fully charged voltage	700V

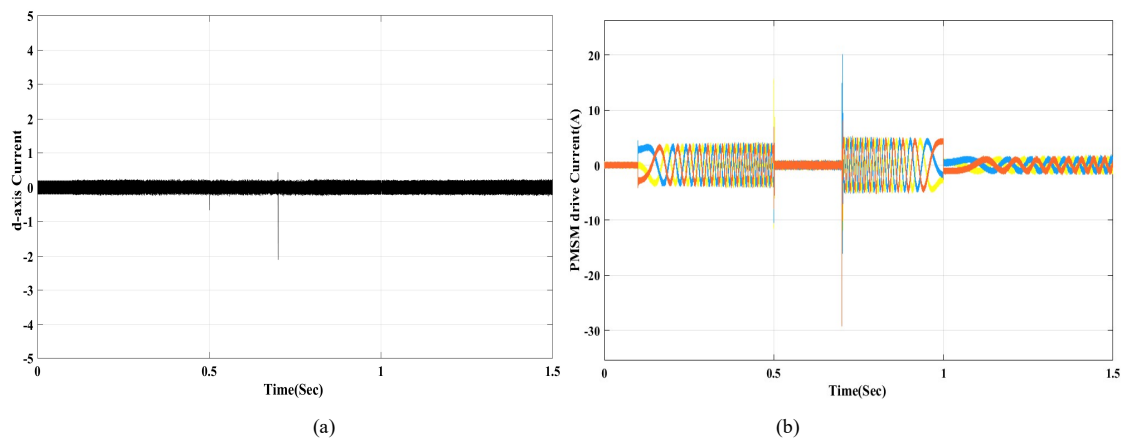


Figure 4. Simulation outcomes for the PMSM drive system with suggested Knight Inverter: a) d-axis and b) 3- ϕ stator current (A) during Motor and Regenerative braking operations

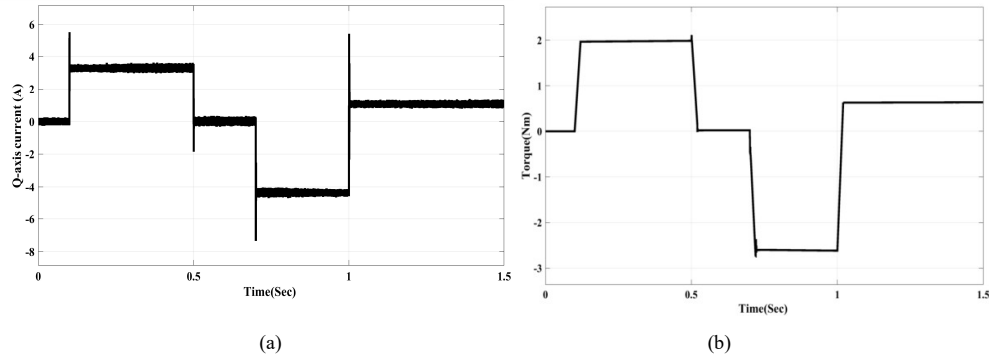


Figure 6. Simulation outcomes for PMSM drive system with suggested Knight Inverter during Motor and Regenerative braking operations: (a) q-axis current (A); (b) Torque (N-m)

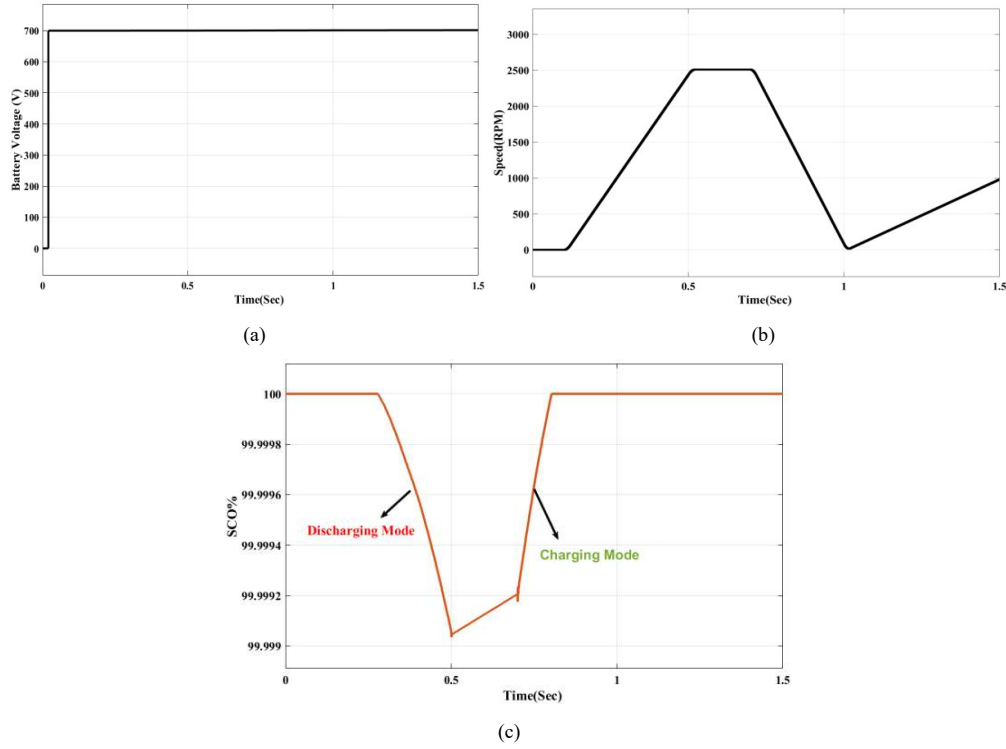


Figure 7. Simulation outcomes for PMSM drive system with suggested Knight Inverter during Motor and Regenerative braking operations : (a) Battery output, (b) Speed (RPM) and (c) SOC%.

VI. CONCLUSION

In this paper, a PMSM dynamic modelling and modified regenerative braking strategy is presented. An extensive analysis profile of all forces affecting an electric vehicle (EV) on incline is used to determine the shaft torque. The 3- ϕ stator winding voltages are produced in accordance with the demands of the EV. The motor torque is controlled by the d-axis stator current component and the rotor linkage flux is controlled by the d-axis and q-axis components of the stator current. This suggested approach has been validated across all operational modes, including acceleration, braking and constant speed. The Knight multilevel bi-directional traction converter is employed to reduce THD in the output current, thereby improving efficiency. Furthermore, the Knight multilevel allows for better deployment of battery segments and enhances the EV's dependability. The acceleration and deceleration operations are evaluated through MATLAB simulation outcomes, which confirmed the strategy met the regenerative braking mode necessities.

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