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WIRELESS POWER TRANSFER TO ELECTRIC VEHICLES ALONG WITH REGENERATIVE BRAKING USING BATTERY-SUPERCAPACITOR COMBINATION

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Abstract : Wireless power transfer (WPT) has gotten a lot of attention in the present times and is going to become our potential future. From small power application scenarios such as charging a mobile phone to high power scenarios like charging an electric vehicle (EV), WPT is investigated as an option. The growing market share of electric vehicles raises questions whether it is possible to integrate wireless charging technology developed for low power applications into this high-power application. Furthermore, it should be investigated if the integration of regenerative braking into the overall system is possible. Several converters have been proposed to enable regenerative braking (RB). However, there is a lack of studies examining the interaction of both technologies on the system level. This paper proposes the integration of an inductive wireless power transfer (IWPT) system and a regenerative braking system into an EV. The merits of the proposed system are represented in scenarios where a considerable amount of power is lost due to frequent acceleration and deceleration. This paper describes the study of the system level integration of a regenerative braking system and a WPT system into an EV. It presents the design, development, and simulation of the complete system along with the brushless direct current (BLDC) traction motor. It shows the simulation model of the Inductive wireless power transfer system (two stage) to EV and acceleration/ deceleration phenomenon of BLDC motor. The speed and torque parameters of BLDC motor are the externally controlling variables of EV, having battery-supercapacitor (battery-SC) as storage devices during this transition period. Regenerative braking in BLDC motor can be observed when EV is under sudden deceleration motions consuming/producing excessive current where SC picks up the transients in place of the battery.**.**

***IndexTerms* -** Battery-supercapacitor combination, BLDC motor, hybrid energy storage system (HESS), regenerative braking system, super capacitor, vehicle charging, wireless power transfer.

I. INTRODUCTION

Global warming is an alarming issue. The world health organization (WHO) reports that global warming and climate change may cause serious damage to human health in the future. As a step towards a clean and green future, and as an advancement in the field of power electronics, WPT is under immediate focus. The world is upgrading to a better renewable technology and leaving non-renewable resources behind [1]. Green sustainable living is encouraged and the government is also providing subsidies for the public to choose sustainable products. Locomotive transportation systems which run on electricity, such as electric trains, which are known for energy saving means of transport, have existed for a while. Similarly, there exist EVs in the market which replace the internal combustion engines and operate using electric motors. An ideal energy storage system should have a high-power density, high energy density, low cost, large operating temperature range and a long lifetime. EVs are powered by single energy storage systems (ESS), that is, batteries. Batteries have limited power density, but long lifetime and they are not cheap to often replace [2]. Battery as an energy storage unit takes longer to charge than a usual gasoline powered vehicles as batteries are charged through cables at charging stations. However plug-in charging of EVs is considered troublesome when the weather is rainy, snowy or windy. Hence, it is suggestible to switch to WPT for an easy charging option. A WPT system enables the driver to park the EV above the static coil until the battery is charged. Without the need to connect cables to the EV, WPT is an easier solution to charge the battery [3]. Charging a battery from grid to vehicle (G2V) and back from vehicle to grid (V2G) is the topic of interest to researchers because it enables full utilization of EV battery. V2G helps regulate the shortcomings or unbalanced power in the grid side, irregularities in households and stabilizing intermittency in wind power [4]. Another merit of the EV system is that it enables regenerative braking which is the subject in focus. The braking mechanism in a hydraulic braking system converts the braking energy into heat energy [5]. Whereas in an EV, energy from RB can be converted back into electric energy. When the brake pedal is depressed in the system, the motor is allowed to run as a generator for a short period of time. During this period of time, slowing down of the vehicle allows the power to be absorbed back into the storage unit which is otherwise wasted in form of heat energy.

Here, the energy storage unit is comprised of a battery and a supercapacitor (SC). An SC is used along with a battery that helps in enhancing the battery lifetime and performance as frequent charging and discharging may deplete its lifetime. Hence, the regenerative braking energy is diverted into the SC for storage [6]. Unlike batteries, SC has higher power density. Therefore, there is no chemical reaction taking place which enables rapid charging and discharging of the SC.

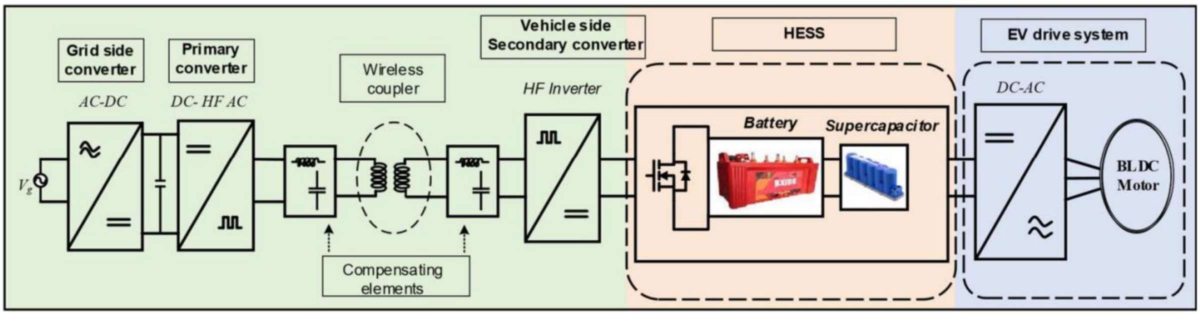

Fig. 1. Block diagram of WPT based EV with regenerative braking of BLDC motor (using battery-SC combination).

SCs have higher power density, greater lifetime and are faster compared to batteries. Therefore, SCs are suitable to use as a part of hybrid energy storage unit which can balance the shortcomings of batteries. Supercapacitors have been in use since 1950s and the first hybrid bus in Europe, using SC at 640V came into existence in Nuremburg, Germany. Since then, SCs functioning became popular to store regenerative braking energy, to supply transients in the system and as a solution to protect battery from frequent charge and discharge. Although, one cannot replace a battery storage unit with an SC pack because, they have low power density which does not support the EV for very long, they can combine battery with an SC pack to upgrade the storage system. In general, battery provides power for long term whereas SC provides short term high - current output. As the electric vehicle requires short-term torque for acceleration, the SC in the circuit provides short term high current demands only and average power requirement is fulfilled by the battery [5]. The aim of the study in this paper is to develop an energy efficient regenerative braking operation for improving battery life, all while the WPT system is connected to the circuit. This paper encompasses a review of the existing research studies in regenerative braking system (RBS) and WPT in sections II and III respectively. Section IV explains the proposed research study with the help of circuital diagrams. Section V focuses on the control method implemented in this study. Section VI briefly explains the simulation studies and section VII concludes the paper.

II. REGENERATIVE BRAKING SYSTEM

Several converters have been proposed to restore the regenerative braking energy in the battery-SC storage unit, also known as hybrid energy storage system (HESS). The conventional energy storage systems are constructed by connecting a single or multiple level dc-dc converters directly linked to the dc-link. These dc-dc converters are used to control the power transfer between battery or SC based on the need for supplying the vehicle or charging/ discharging from transients.

Many topologies related to HESS claim to provide various advantages. The proposed system in [9] is a HESS where a battery, alone, is allowed to supply power directly to the vehicle when the SC voltage level is below battery voltage level. This system is economical only for low bus voltages. The cost of the system increases with increase in SC size, that is when higher bus voltages come into picture. The research in [5] proposes a HESS where an SC is connected in parallel to the inverter causing high inrush currents to flow during the start. Although, the experiment involves a limiter resistance in series to the inverter and SC, the SC is uncontrolled. Even though a converter is present, the SC is not controlled through the converter, causing voltage and current instability during large transients. Another study in [10] proposes, a fuzzy logic-based control having state of charge (SOC), speed of the motor and brake current as control inputs. A Proportional Integral Derivative (PID) controller is used to produce constant torque in the motor. This topology, however, may reduce the lifetime of the battery by frequent charging and discharging. The system in [11] proposes the integration of WPT into an Electric Scooter using a battery and SC combination. It suggests inducing a small negative current for a short time period to enhance battery life. However, this method is considered as less flexible considering the diode bridge rectifier that does not have controlled power transfer and compensation topology.

III. WIRELESS POWER TRANSFER

WPT systems help reduce the greenhouse-gas emissions, quiet in operation and less wear and tear of mechanical parts as compared to fuel-powered vehicles. They also do not have long cables which enables flexibility in charging. Hence, these systems have become the potential future, especially considering the reliability, sustainability and availability of energy resources. WPT schemes are classified based on various research areas such as, coil design, control strategy, compensation technique, resonant tank elements and converter topology. Including the above-mentioned classification, research studies have further brought in a development by having different WPT schemes. Therefore, the WPT schemes can be classified based on their control strategies as well. Authors of [15] proposed, a two layer predictive controller where the system picks up information regarding the direction of power flow, from surrounding utility grid/vehicle and chooses to operate in charging/discharging modes. Adding to this research study, [16] proposed a control strategy involving measured active and reactive power control. It involves working with parameters high frequency which further require high frequency bandwidth sensors. This paper works with a control strategy which helps to minimize the cost of the system overall, improve battery lifetime by adding an SC and recover power which is otherwise lost in form of heat. Further section elaborates the proposed system and its operating principles.

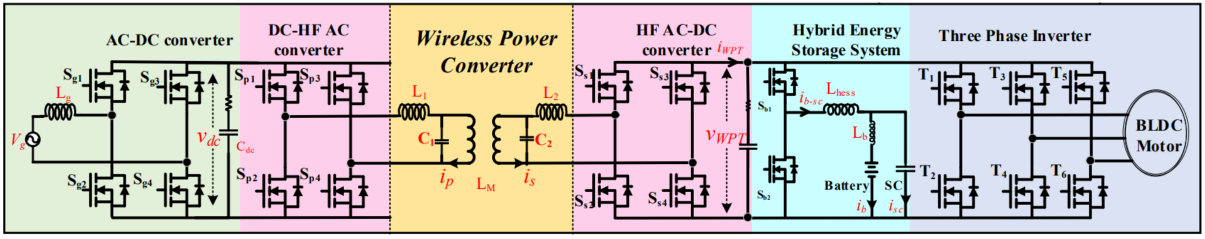

Fig. 2. Proposed IWPT-HESS configuration.

IV. PROPOSED SYSTEM

The WPT charging system proposed in [11] is connected to a battery-SC combination. The control scheme proposed in there, provides a period in each cycle, to induce short negative current in battery to improve battery life. However, its converter topology does not take regenerative braking into consideration. This paper proposes the integration of WPT with an HESS using a battery-SC combination as an energy storage system. In slopes, especially in hilly regions and in cities where there is stop-and-go traffic, the implementation of the proposed system can bridge the gaps between simultaneously charging the vehicle and storing the braking energy from the vehicle. The common point of contact for WPT and HESS is the dc-link. The proposed topology suits the 48V commercial E-vehicles such as electric scooters or electric rickshaws and other vehicles in low voltage range [11]. This is mainly helpful to the modern world because most of the population do not require high speed and endurance in day-to-day life [2][5][10]. The battery-SC are connected to dc-link via a converter as shown in Fig .2. The EV receives power from both HESS unit and WPT unit. Fig. 1 represents the block diagram of the proposed system with a BLDC motor in the EV drive train. It uses a battery-SC combination to store the energy from the regenerative braking system. It is important to maintain the dc-link voltage and current flow direction during operation of the system. Hence, a closed loop control structure is designed to control the system in various modes as shown in Fig. 3. Fig.2 shows the circuit diagram in detail representing the regenerative energy storage system. A bidirectional WPT system is connected to the battery-SC combination via a dc-link with the voltage being maintained. The battery is connected to the dc-link through a bidirectional DC-DC converter, having a voltage and an SC pack is connected to the battery with inductor as shown in Fig. 2. During the braking operation, the dc-link voltage is stabilized by controlling the switches (1, 2) in the HESS unit. The objective of SC is to absorb transients during varying speed circumstances, aiming at recapturing the braking energy as much as possible. This process aids in longevity of battery life [5] by using SC in storage system. The vehicle is operated at various speeds (as shown in Fig. 6) to allow the system to get into regenerative braking operation where the efficiency of the motor is maintained as a function of torque and speed of the vehicle.

V. CONTROL STRUCTURE

EV requires high current to support the torque requirement when it is in acceleration. In a similar way, it requires less current during deceleration. The SC in this system supports transients while increasing battery life. The BLDC motor in the system is rated at 65V 2kW. PI controller is used to maintain the dc-link voltage during regenerative braking mode. In the WPT system, the controlling schemes used are summarized as in Fig. 3. 4 are the switches associated with the grid side of the WPT system. A reference voltage of 65V is considered as the dc link voltage to be 65V. Fig. 3 shows the pulse generation for these switches. The grid side controller converts the ac input to dc and has fixed phase shift angle ($\emptyset$), equal to 180°.For the power to flow from grid to vehicle (G2V), the phase shift angle ($\emptyset$) and internal phase shift angle ($\emptyset$) should be controlled for the desired power (0) to flow. The active power and phase shift angle relation can be given as shown in (1), where M is mutual inductance between two coils (L1, L2)

$$P_0 = \frac{8M}{\pi^2 w_r L_1 L_2} V_d V_b sin\theta sin\frac{\emptyset_p}{2} sin\frac{\emptyset_s}{2}$$

$$\theta = \emptyset_x - \frac{\emptyset_s}{2} - \frac{\emptyset_p}{2}$$

The reference power)*+ is compared to the actual power and the difference in power is sent to the PI controller to generate $\emptyset$as shown in Fig. 3. Therefore, the secondary side Hbridge lags primary side H-bridge by an angle of $\emptyset$. The power control takes place by controlling the phase shift angle and hence no communication between two H-bridges is required for feedback. The dc-link voltage shared by the WPT system, the HESS and the converter on the battery-SC side is denoted by ,-.. BLDC motor control, including the bidirectional converter connecting battery-SC are given in Fig. 3. ,-. is compared to ,)*+ and the error is fed to a PI controller to generate reference current, "br*+. This reference current is further compared to the converter current "−1 and the error is fed to the inner PI controller to generate PWM pulses for b1-b2. The converter operates in a bidirectional manner allowing the HESS system to absorb the power from RB. As shown in Fig. 3, the speed of the BLDC motor, 23 is compared to the reference speed 2)*+ and the error is fed to the PI controller to generate the torque reference,)*+. The hall sensors input is decoded, mainly to find the rotor position during running condition and to multiply with the obtained.)*+ as output from PI controller and compared with input current to BLDC motor, "41. The obtained pulses are given input to switches (.1 − .6) in the inverter of BLDC motor.

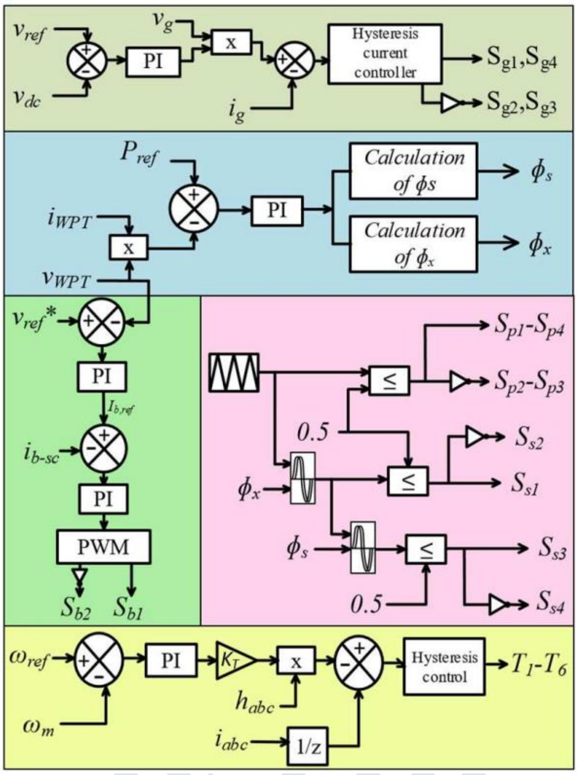

Fig. 3. Control structure of the proposed system

VI. SIMULATION STUDIES

TABLE I
SYSTEM PARAMETERS

Parameters	Values
WPT: Grid Voltage (V) Boost inductor (L_g) Primary inductor (L_1) Secondary inductor (L_2) Compensating capacitors (C_1, C_2)	65 V RMS 50Hz 5 mH 27.86 µH 27.86 µH 2.27256 µF
Battery pack: Type Terminal voltage (V) Capacity (Ah)	Lead-acid 48 V 140Ah
Supercapacitor pack: Terminal voltage (V) Capacitance	48 V 20 F
BLDC Motor: Terminal voltage (V) Current rating (A) Rated speed (rpm)	65 V 9A 3000 rpm

The simulation of the proposed configuration is done in MATLAB Simulink environment. The parameter values considered for simulating the given system is shown in Table I. The grid voltage is taken as 65V, and the same potential is considered in dc-link.

A. Wireless Power Transfer:

A WPT is simulated with a switching frequency of 20kHz, as considered for simulation. Fig. 4 shows the charging coil voltages and currents on both sides. The voltage of primary coil leads the secondary voltage, causing power flow from primary to secondary side. The voltage across the coils is alternating, having frequency as 20kHz. The secondary coil voltage is passed through secondary H-bridge, after passing through a compensation circuit. The reactive power of the resonant tank on vehicle side is almost zero because there is a phase shift of 90 degrees among the two H-bridges. This lag in H-bridge voltages provides the current to flow from grid to vehicle (G2V) operation. With increasing power level, the PI is so tuned that, there is steady state supply of power from WPT side, and the phase shift remains the same overall and therefore, the power quality is well maintained. However, even if we operate at resonant frequency, there will be some distortion power which remains as negligible amount of reactive power in the system. Fig. 5 shows the converter (H-bridge) voltages on both sides of the WPT coils. The quasi-square waveform on the secondary side is to meet the power requirement.

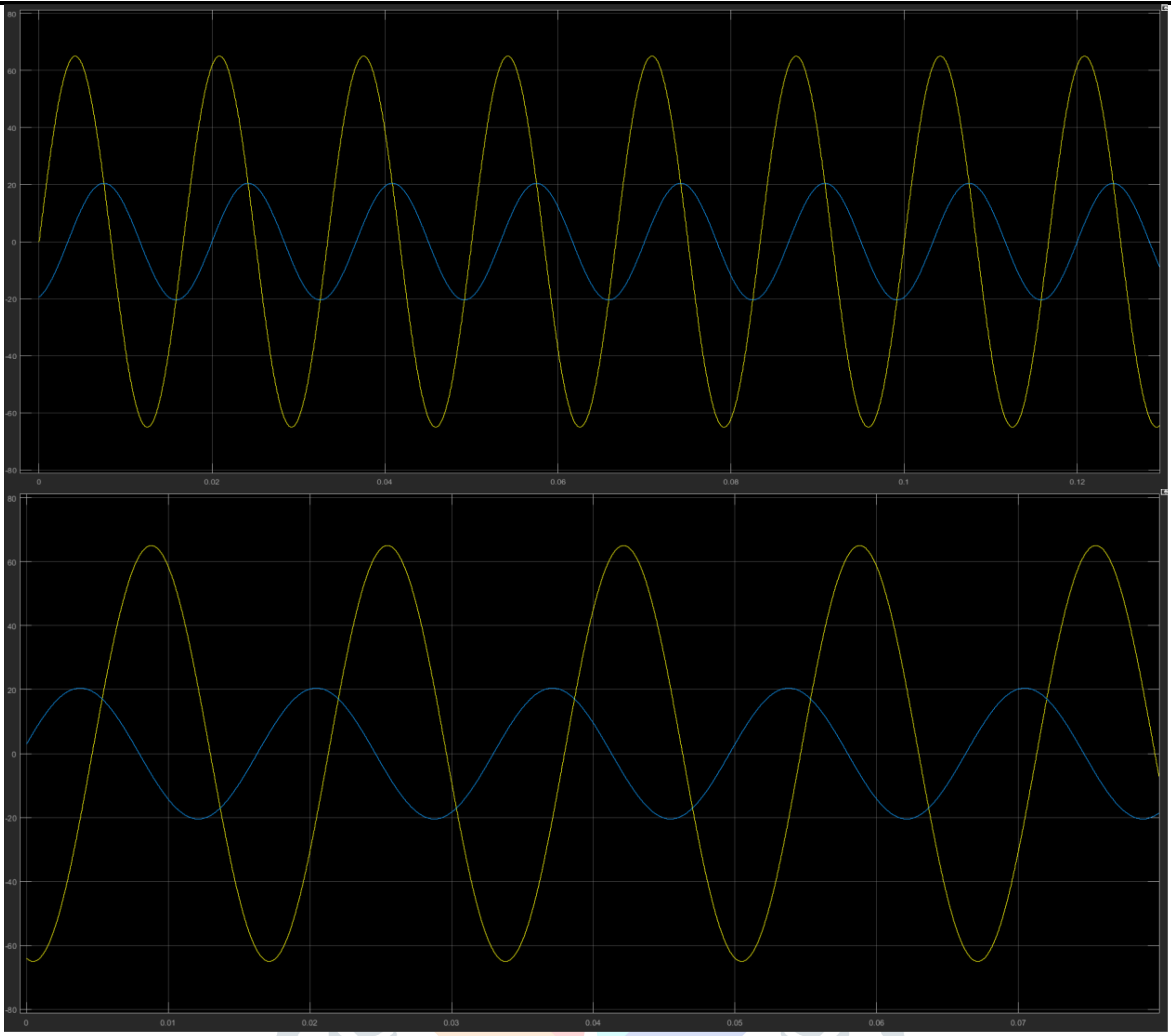

Fig. 4 Primary and Secondary coil voltages and currents.

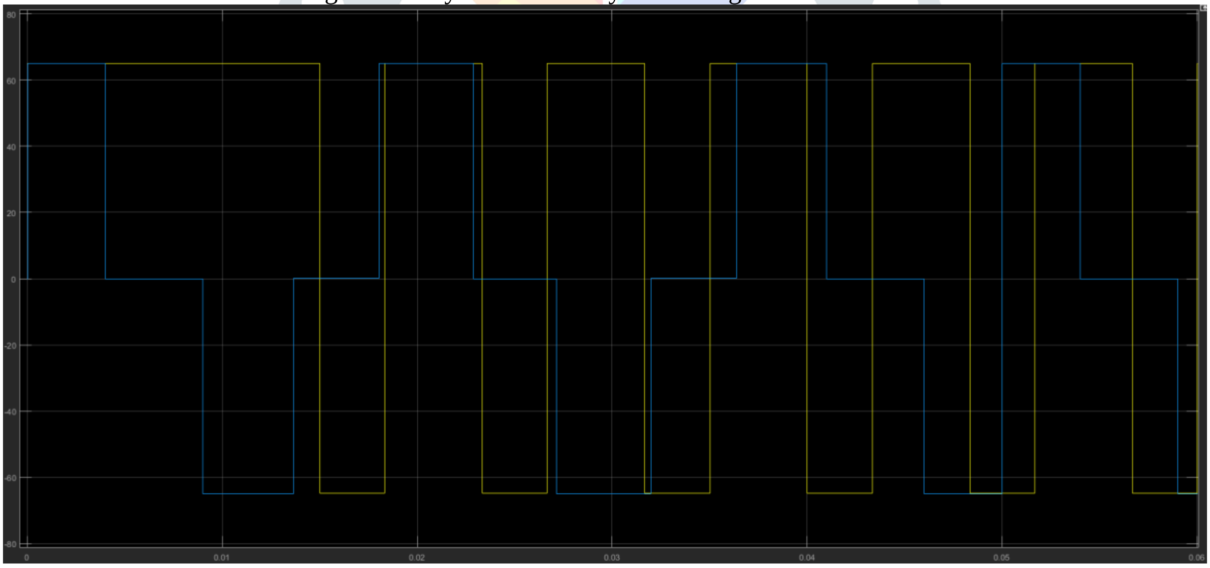

Fig. 5 Primary and Secondary H-bridge voltages.

Working of BLDC motor and Regenerative braking:

Apart from the mountainous region we also experience the frequent stop and go situation in cities too, where there is heavy traffic. Considering a drive cycle which provides justification for such a simulating environment gives us much ease to think closer to the real scenario. Hence, simulation studies have considered such scenarios and Fig. 6 shows the speed profile considered for simulation. A speed profile having sudden accelerating and decelerating motions causes transients on the storage side. These transients are absorbed by the SC connected to the system. In Fig. 6, the change in current supply from battery and SC during the transient period is depicted. The SC has high energy density and hence it is useful to aid battery's life [5]. This paper considers four different types of speed ranges: (1) when speed increases rapidly from low to high-speed range, (2) when speed decreases from high-speed range to low-speed range, (3) when speed goes from medium positive range to negative range and (4) when speed changes from negative range to medium positive range. The speed of the EV in hilly regions consists of slopes, including uphill movement which pushes vehicle into acceleration mode and the downhill movement allowing the motor into regenerative mode. Battery powered vehicles in these regions lead to frequent charging and discharging, hence when the SC is added in combination with the battery, it will take in the huge transients and lessens current stress on the battery. This is represented in Fig. 6, where we considered various driving scenarios.

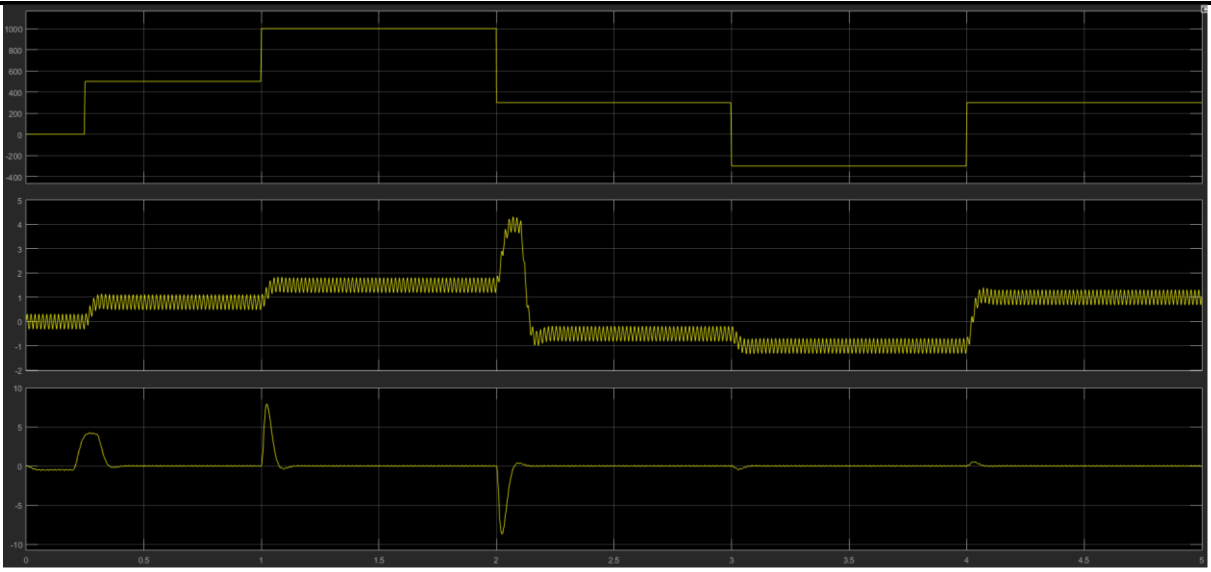

Fig. 6 Battery and SC current with varying speed.

It is observed from Fig. 6 that the speed of the motor reaching the given speed with fast response rate. HESS unit supplies power to the motor to reach the desired speed by increasing current, hence the transients observed during changing speed is compensated by HESS unit. SC current shows sudden increase in current while battery current is slowly rising. This is desirable response of the storage units, as SC absorbs the transients there will be no spikes in battery current. Fig. 7 represents the torque variation during the vehicle motion and corresponding dc-link voltage and WPT current connected to point of common coupling. The current contribution from the WPT to the whole system remains constant by delivering the power to the dc-link in the setup. The transients observed in dc-link (,-.) occur due to change in speed in the system. As there is variation in speed, the load torque is observed to be maintained at constant terms. The dclink voltage is maintained at 65V while the battery and SC are rated at 48V. The stator current profile of the BLDC motor is shown in Fig. 8. It is observed that the changes brought in by the change in speed of the motor reflecting in the stator currents. A zoomed version of the same is also represented in Fig. 8 to represent the effect of changing speeds. Power distribution to various sub-systems in the whole system is shown in Fig. 9. HES system is comprised of battery, SC and the bidirectional converter which is connected to the dclink. Power from WPT unit implies the power output from the WPT system that is connected to the dc-link. Power received by the BLDC motor is supplied by the HES system and the WPT system. We can observe from this figure the contribution of each one. To maintain the dc-link voltage during peak transients and to avoid high peaks in the battery current, the SC contributes and its current rises sharply, while the battery current rises more slowly.

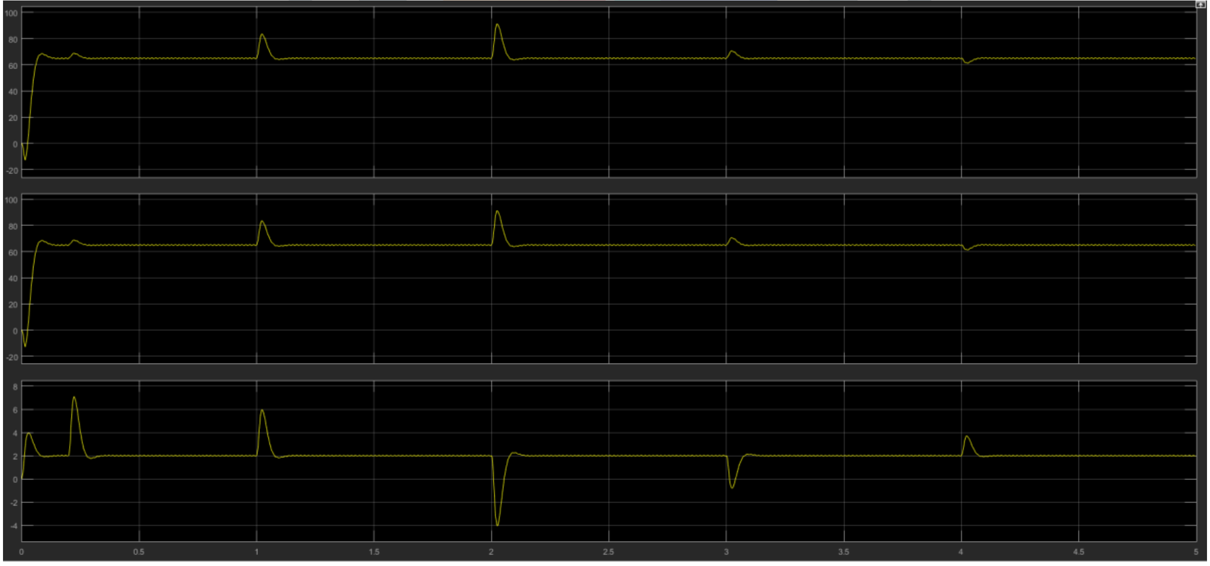

Fig. 7 Voltage and current across WPT and load torque.

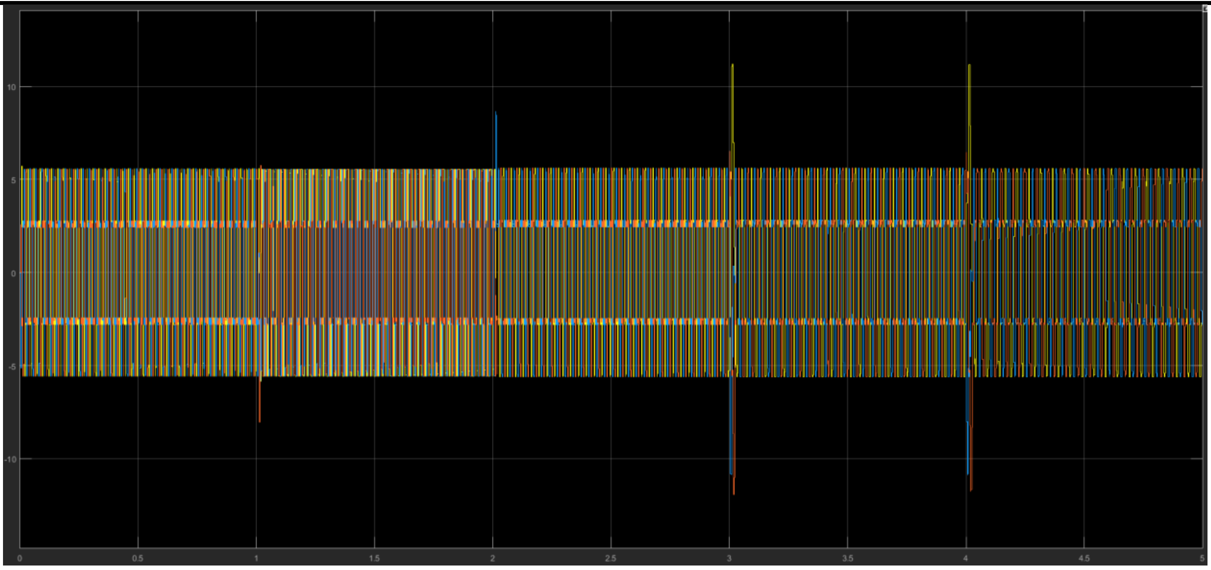

Fig. 8 Stator current behaviour with changing speed.

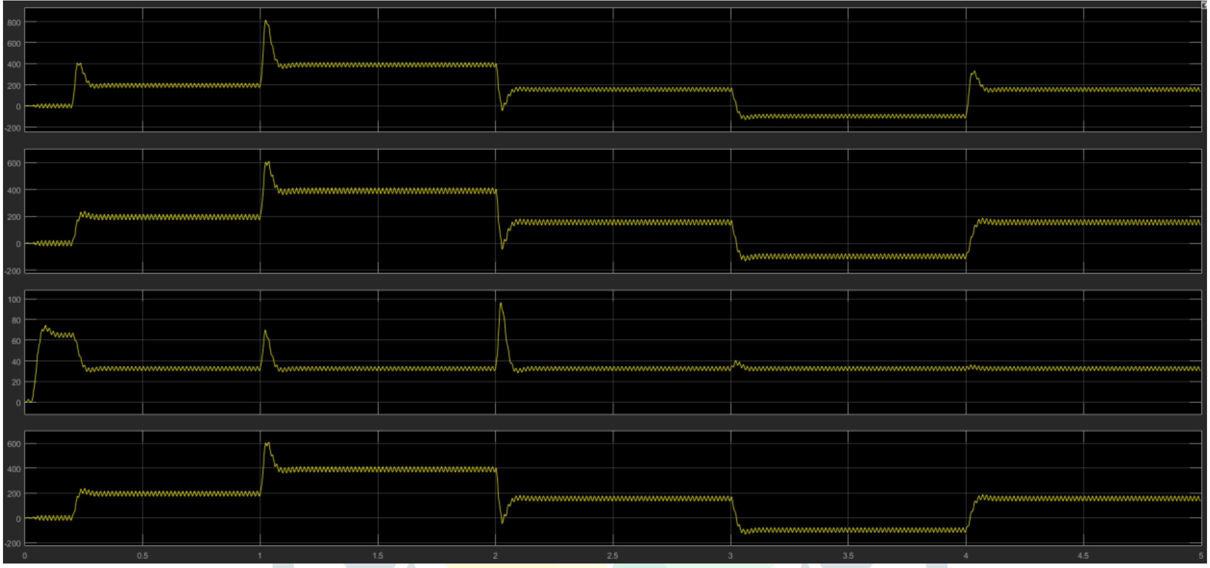

Fig. 9 Power distribution to storage units.

CONCLUSION AND FUTURE SCOPE

A bidirectional wireless power transfer to electric vehicles along with regenerative braking using a battery-SC combination is proposed. This system is modeled and simulated, and observations are presented for various operating scenarios. In comparison to other similar types of the regenerative braking schemes, the proposed method allows supercapacitor to react to transients and battery to react slowly. The battery lifetime can be improved by incorporating SC in the system. Thus, it can be concluded that the presented scheme can recover the braking energy and store it in the SC and battery, enabling efficient operation of the HESS. The proposed system can be converted into a dynamic WPT system with simultaneous power transfer capabilities. Providing flexibility to the system via making it dynamic and improving the compensation topology would be more beneficial and helps in saving lifetime of battery in EVs.

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