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Optimized Wireless Power Transfer and Energy Storage in Electric Vehicles Using Battery–Supercapacitor System

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***Abstract*:** The shift towards electric vehicles (EVs) has brought significant attention to key challenges such as prolonged charging times and inefficient energy efficiency [1]. Therefore, this paper proposes an optimized control strategy that integrates Wireless Power Transfer (WPT) with a HESS consisting of a battery and a SC. [2],[3]. The primary goal is to extend battery lifespan and enhance energy utilization and under Regenerative Braking conditions [4]. A detailed simulation is conducted using MATLAB/Simulink for an EV powered by a Brushless DC (BLDC) motor. The results illustrate that the supercapacitor effectively absorbs transient currents, thereby minimizing battery stress and contributing to improved system longevity. Additionally, the optimized control strategy holds a stable DC-link voltage and ensures efficient power delivery under varying driving scenarios. This approach promotes smart energy management and holds promising potential for building scalable and sustainable EV infrastructure.

Keywords- Wireless Power Transfer, Electric Vehicles, Hybrid Energy Storage System (HESS), Regenerative Braking, supercapacitor (SC), BLDC motor

I. INTRODUCTION

As the world progresses towards green mobility solutions, electric vehicles (EVs) are leading the fast-forward. However, there are two significant drawbacks: long charging time and inefficient use of energy, particularly in urban driving conditions with a lot of acceleration and deceleration [1]. Wireless Power Transfer (WPT), providing constant contactless charging, along with Regenerative Braking (RB) whereby energy can be recovered in deceleration. The impact of WPT and RB technology has a great potential to enrich the efficiency of EV overall systems [2].But traditional energy storage battery-only systems can struggle to keep pace with the rapid energy up-and-down oscillations that typify city driving [3],[4]. Static lightning versus mobile lightning: We are driven to this HESS by this drawback of batteries and use a SC by the supercapacitor with a battery together. While the SC manages the high-frequency energy transients, the battery covers the longer-duration power demands [5].The proposed study investigates the collaboration of WPT and RB in a power system with a HESS, which is a composition of a battery with a supercapacitor. Managing high transient currents means the battery gets less stressed with the supercapacitor [6].

II. WIRELESS POWER TRANSFER

An alternative is Wireless Power Transfer, where an inductive coupling unit is situated between a coil mounted on the ground and a coil situated in the EV. In this system, high-frequency AC power is transmitted and received through those coils and converted to and stored in the HESS. An inverter converts the grid voltage into high frequency AC, which is transferred by the means of resonant inductors and capacitors. A PI controller maintains the DC-link voltage equal to 65V, while by adjusting the phase shift between both inverter bridges, seamless energy transfer takes place without directly communicating between coils. The mutual inductance and phase shift angle between the inverters determine how much power is delivered through the WPT system, and this can be stated as follows:

$$P_O = \frac{8M}{\pi^2 \omega_r L_1 L_2} V_d V_b \sin\theta \sin\frac{\phi \cdot p}{2} \sin\frac{\phi_s}{2} \qquad (1)$$

$$\theta = \phi_x - \frac{\phi_s}{2} - \frac{\phi_p}{2} \quad (2)$$

The grid side controller changes AC input to DC and has a set phase shift angle (∅) of 180°. To move power from grid to vehicle (G2V), you need to adjust the phase shift angle (∅) and internal phase shift angle (∅) to transfer the desired power (P_o). equation (1) shows how active power and phase shift angle are linked, with M representing the mutual inductance of two windings (L1 L2).

III. REGENERATIVE BRAKING

Regenerative Braking enables an EV's motor to work as a generator when the vehicle decelerates, turning into electrical energy from kinetic energy. This energy is harnessed and stored in the HESS. The supercapacitor is key in this respect, sucking up all the fast current surges that would otherwise have stressed the battery. In regions with a lot of high-speed driving, short duration, hilly roads, the dual-storage system significantly increases the energy utilization rate. Meanwhile, the bidirectional converter manages the energy transfer of the system among motor, SC and battery, stabilizing the overall performance.

IV. SYSTEM WORKFLOW

This paper addresses a proposed architecture within electric vehicles (EVS), which consists of a Wireless Power Transfer (WPT) system and a HESS, composed by a battery and a supercapacitor (SC). This arrangement allows for bidirectional energy flow during charging and regenerative braking. The main objective is to keep a stable DC-link voltage while correcting that power depending on different driving conditions like acceleration, deceleration and regenerative braking.

The EV receives energy from either the WPT network or HESS. The SC provides instant power while the battery will be for sustained effort over time. During a braking scenario, the kinetic energy is harvested from the rotation of the rotor and used to turn the motor-as-generator, and the energy from the process is deposited to the SC, due to its high-power density, and eventually balanced through the Li-ion battery with the help of a bidirectional DC-DC converter.

The WPT system interfaces with the HESS through a common dc-link, and voltage stability is maintained using a control strategy covered in the next section. This setup is especially helpful for driving in urban areas and on hilly terrain where frequent start-stop motion or slope-related acceleration and deceleration is common.

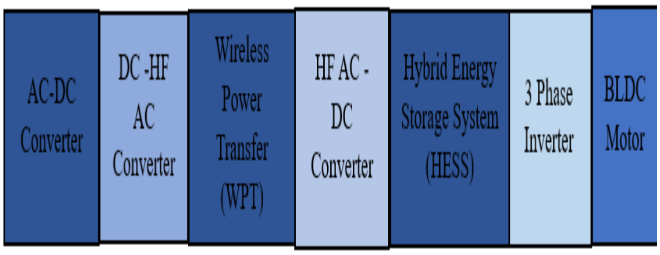

Fig 1: Proposed WPT – HESS Configuration

V. CONTROL STRATEGY- PROPOSED SYSTEM

In order to provide the regulated operation of the WPT-HESS system as shown in Fig 1. A cascaded Proportional-Integral (PI) control structure is employed. The outer PI loop controls the DC-link voltage and the inner determines the current distribution with via the SC or the battery. This message-based hierarchical structure allows for fast dynamic response and stable operation under large variations of load.

The WPT system functions via a phase-shift modulation technique, regulating power transfer between primary and secondary coils without direct connection. The direction and amplitude of power flow are controlled by the phase angle difference (Δφ). A PI controller modifies the phase angle in accordance with the comparison of the reference power and real power.

The BLDC motor is controlled by monitoring its speed and torque. The system compares the actual speed with the target speed, and any difference is processed by a PI controller to produce the right torque command. It also uses Hall sensors to detect the rotor's position, which is important for keeping the motor running smoothly and in sync. The converter between the battery and supercapacitor works both ways, allowing energy to flow during acceleration and braking. This control technique helps the supercapacitor quickly handle sudden energy surges, protecting the battery and helping it last longer.

VI. SIMULATION AND RESULTS

Table 1 Key System Specifications

Component	Specification
Wireless Power Transfer	
Supply Voltage Boost Inductor Lg Inductance of the Primary Coil $L1$ Inductance of Secondary Coil $L2$ Resonance Capacitors $C1, C2$	RMS of 65 V at 50Hz 5 mH 27.86 µH 27.86 µH 2.27256 µH
Battery	
Battery Type Rated Voltage Capacity	Lead-acid 48 V 140 Ah
Supercapacitor Module	
Nominal Voltage Capacitance	48 V 20 F
Brushless DC Motor	
Operating Voltage Current Rating Nominal Speed	65 V 9 A 3000 rpm

The MATLAB Simulink environment is used to simulate the suggested arrangement. Table 1 lists the parameter values taken into the account for simulating the specified system. The grid supply voltage is assumed to be 65V, and the dc-link takes the same potential into account.

6.1 Wireless Power Transfer

In the WPT simulation, power moves to the secondary coil from primary coil at a switching frequency of 20 kHz. A 90° phase shift reduces reactive power by compensating the secondary coil's voltage before it enters the H-bridge shown in Fig 2. Stable power transfer and effective Grid-to-Vehicle (G2V) functioning are made possible by this phase lag. In order to preserve steady-state performance and power quality, the PI controller adapts as power increases. Reactive power is decreased when running at resonance, although the system still has some distortion. The converter (H-bridge) voltages on either side of the WPT coils are displayed in Fig 3.

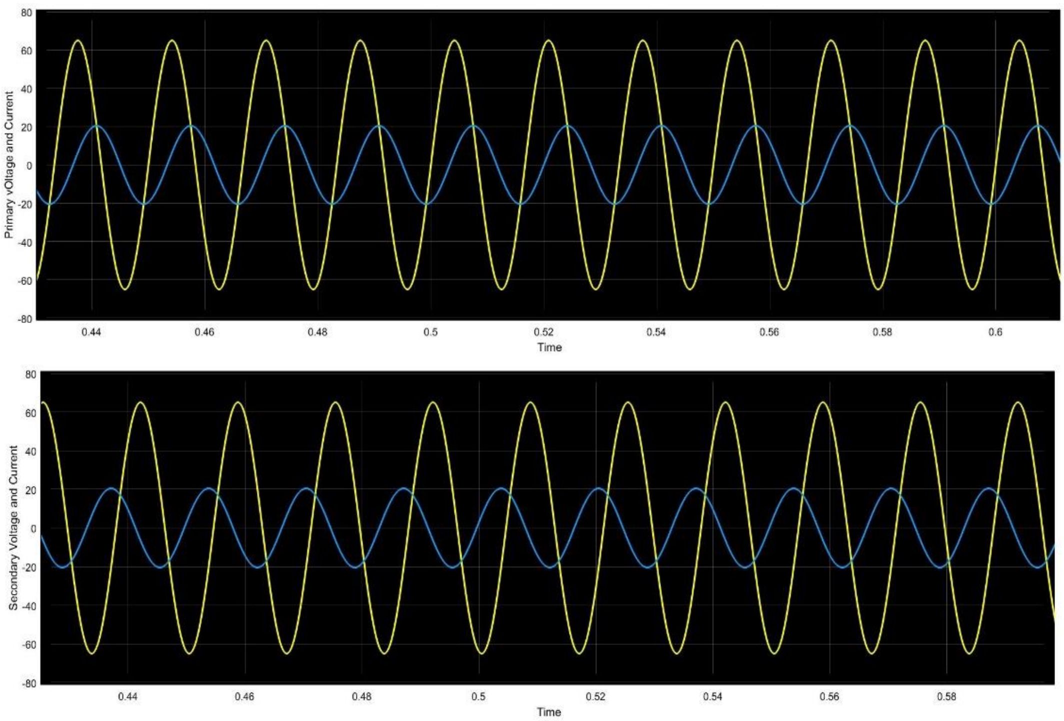

Fig 2: Primary Coil and Secondary Coil Voltage and Current

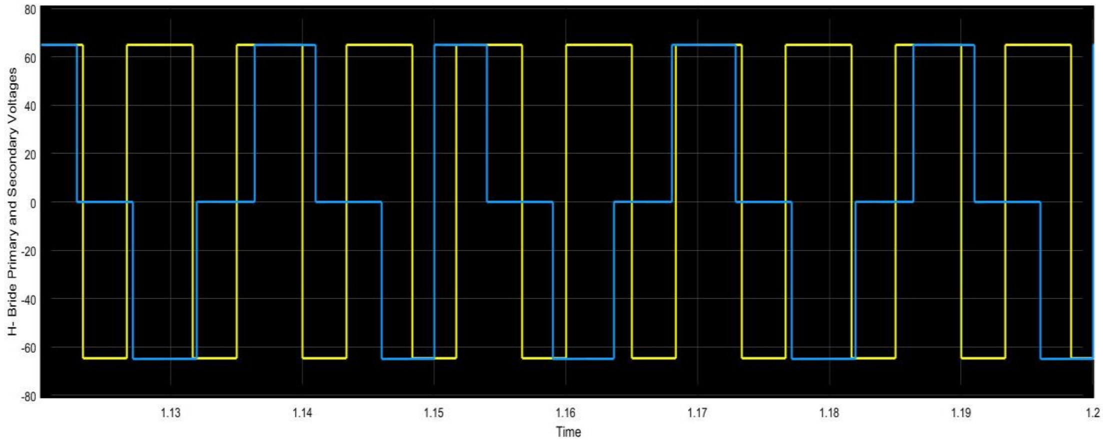

Fig 3: H-bridge Primary and Secondary Voltages

6.2 BLDC motor and regenerative braking

Using a dynamic speed profile, the simulation takes into account genuine EV situations, such as mountainous terrain and urban stop-and-go traffic. Transients are introduced by abrupt accelerations and decelerations, and the supercapacitor (SC) efficiently handles them. The battery lasts longer because to the SC's rapid response to current increases. The HESS (battery + SC) guarantees efficient transient correction and smooth motor performance during abrupt speed changes as shown in Fig 4. The system's power flow is stabilized using WPT (Wireless Power Transfer), which keeps the current at the dc-link constant. Variations in the motor's torque and stator current demonstrate how rapidly the BLDC motor reacts to changes in speed. A bidirectional converter connected to the dc link balances the power from the WPT and HESS, as shown in Fig 5 &6.

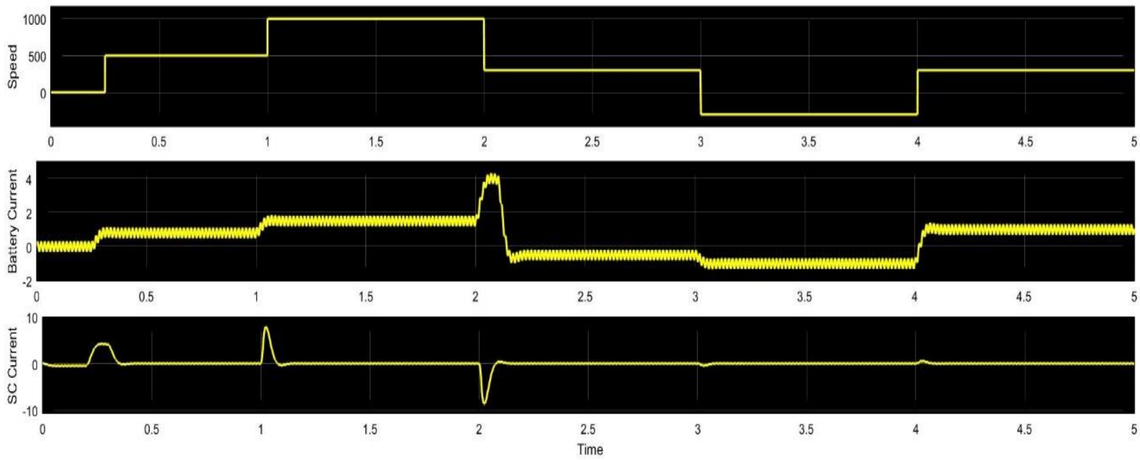

Fig 4: SC and battery current at varying rates

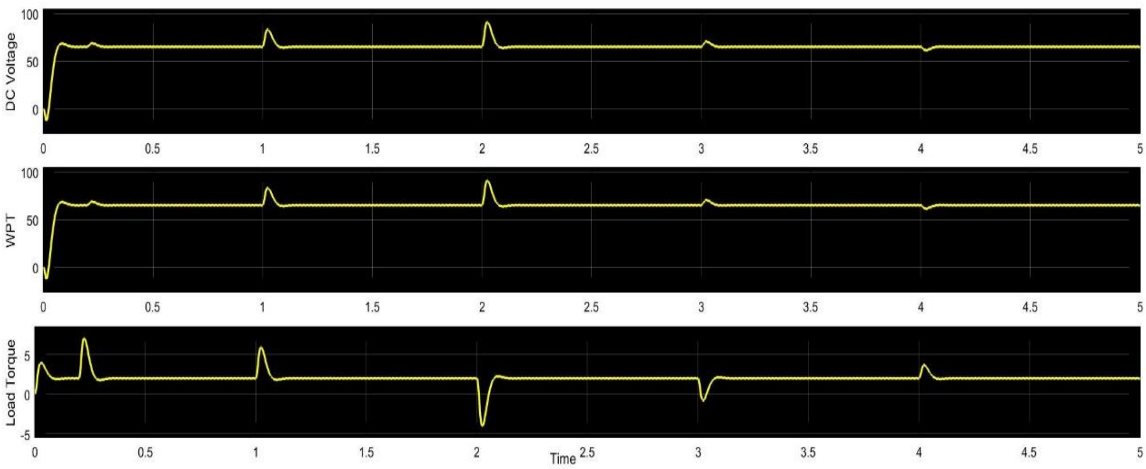

Fig 5: Current and Voltage across Torque and WPT

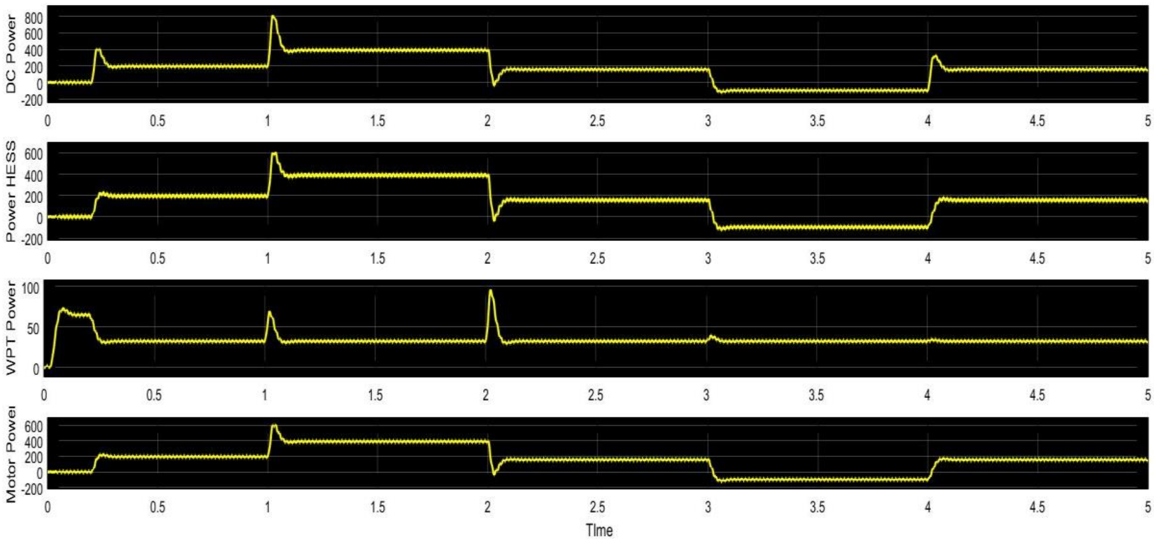

Fig 6: Power Transfer between the Motor, HESS, WPT, and DC-Link

VII. CONCLUSION AND FUTURE SCOPE

For bidirectional WPT and regenerative braking in EVs, a battery-SC hybrid system is suggested. Longer battery life is achieved by having SC handle transients while the battery controls constant loads. Braking energy is effectively stored by the system in the battery and SC. It can be expanded to include simultaneous power transfer and dynamic WPT. Improved compensation design increases overall efficiency and improves flexibility.

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