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Synergistic Integration of Modular Four-Channel 50 kW WPT System: Enhancing Fast EV Charging and PMSM Drive Integration

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ABSTRACT

This paper presents an innovative approach to electric vehicle (EV) charging and propulsion system integration through the development of a Modular Four-Channel 50 kW Wireless Power Transfer (WPT) System with Decoupled Coil Design. The system architecture is designed to facilitate rapid charging of EV batteries while also enabling seamless transition to Propulsion Motor Synchronous Motor (PMSM) drive application post-charging. The decoupled coil design ensures efficient power transfer while minimizing electromagnetic interference. Leveraging this integrated solution, the charging process is optimized for speed and reliability, enhancing the EV user experience. Furthermore, the seamless transition to PMSM drive application allows for immediate utilization of the charged EV battery for propulsion, ensuring maximum efficiency and functionality. MATLAB/simulation validation demonstrates the effectiveness of the proposed system in achieving fast EV charging and smooth integration with PMSM drive application, thereby offering a promising solution for future electric vehicle technology advancement.

Key words— Wireless electric vehicle (EV) charging, high-power, modular, decoupled coil design, misalignment tolerance, PMSM drive.

1. INTRODUCTION

Electric vehicle (EV) production has expanded internationally in recent years, driven by concerns about energy scarcity and pollution. It takes a long time to charge an electric vehicle's battery compared to filling up a gasoline-powered vehicle [1], and conventional conductive charging methods for EVs use thick gauge wires that are both hazardous and difficult to manage.

The aesthetic, safety, convenience, and completely automated charging process benefits of wireless power transfer (WPT), which primarily refers to inductive power transfer (IPT), have put it in the spotlight as a viable alternative to conductive charging in recent years [2]. While WPT has many potential uses, one major drawback is the lengthy time it takes to charge some types of electric vehicles and buses (e.g., public transportation) [3]. The only way to shorten charging durations is to use high-power input [4]. Thus, there has been an uptick in the need for high-power WPT technology [3, 5, 6]. Raising the power capacity of WPT systems is quite difficult because of the voltage and current constraints of power electronic components. In order to avoid employing wide-band gap devices like Silicon-Carbide (SiC), some academic and commercial organisations have suggested 50 kW or more WPT systems [7-9]. However, gadgets will continue to inhibit the advancement of system power capabilities. Also, the insulation of resonant parts and voltage stress are the obstacles to high-power wireless charging in the real world of electric vehicles with limited interior space. Many other ways to get beyond the restrictions of the device and the resonant element have been suggested as solutions to the aforementioned difficulty, with the goal of increasing the power capacity of the WPT system. A cascaded multilevel inverter has been suggested as a means to enhance the power level in the WPT system [10-13]. Due to the inverters' series connection, however, the cascaded structure of the multilayer converter has poor dependability. To boost the transmitter current and enhance the WPT system's dependability, it is suggested to use several inverters that are linked in parallel using low-current semiconductor devices [14]. Insulation design is made more challenging by the high voltage stress on the resonant parts caused by the high transmitter current. Due to the fact that both the cascade and parallel connection techniques only use a single transmitting coil, the system only has one outlet for power transmission. Because of their shared issue with unreliability and malfunction, they are all vulnerable to failure. In [15] [19], the authors suggest WPT systems that use several transmitters and receivers to send and receive power. A decrease in voltage stress on resonant parts and an improvement in the system's power capabilities make this possible. But there's not insignificant cross-coupling between different power transfer channels, which leads to uneven power distribution and circulation across channels and drastically reduces the efficiency and capacity of power transfer [15]. Coupling two magnetic couplers is achieved in [17] by combining polarized and non-polarized coils. Still, the two-channel system can only broadcast 4.73 kW, and because the technology isn't expandable, there's no way to increase the transmission power capabilities via modularization. To solve the problem of magnetic coupling between couplers, the authors of [18] and [19] use a technique that involves moving the polarized coils of the two couplers apart. The transmitting power of the two channel systems is 44 kW and 7 kW, respectively. This approach can be scaled up or down, but there will be a limit to how much space each module can take up. On top of that, electric vehicle parking becomes more complicated in real-world scenarios because of the polarised coils' properties, which cause the multi-channel systems discussed before to have an uneven system misalignment tolerance in the horizontal and vertical directions. To facilitate rapid electric vehicle charging, this study proposes a modular four-channel WPT system using a decoupled coil architecture. The four WPT modules that make up the modular system's four parallel power transfer channels are similar in every respect. Each module has a main PFC rectifier, an inverter, a set of coils for the transmitter and receiver, and a secondary rectifier. Because all four modules have the same power capacity, the total transmitted power is equal to four times that amount. The primary challenge is the short range of electric vehicles caused by the finite power of batteries. Driving range is directly proportional to battery size and capacity; increasing the battery rating is one apparent way to accomplish this, but doing so would raise the vehicle's weight and the expense of electric vehicles in general [20]. The whole driving cycle, including acceleration, coasting, and de-acceleration, puts an electric motor used in a vehicle under varied dynamics. The motor is turned on with a positive peak torque while the driving cycle is in acceleration mode and a negative peak torque when the cycle is in de-acceleration [21]. When in acceleration mode, power is drawn out of the power supply. When the car is in de-acceleration mode, the energy comes from the battery. To slow down, the brakes are applied, which is represented by the negative torque. In this case, the vehicle's kinetic energy is redirected to the battery, causing the battery's state of charge to escalate. This energy regeneration is a great way to increase the electric vehicle's range [22-23]. As the motor decelerates, its stored kinetic energy is directed by the current-controlled VSI, which in turn powers the permanent-magnet synchronous motor [24]. Our primary goal in this project is to design a system for LEVs that use batteries to power the engine. Permanent magnet synchronous motors are highly regarded for their many advantageous features, including their simple and sturdy design, lack of a permanent magnet rotor, lossless rotor, almost nil cogging torque, affordable price, and dependable operation [25-26]. Thus, it offers great promise as an alternative to induction motors (IMs) in EVs and other vehicles with variable speed control drives. Compared to IM and PMSM, the energy conversion efficiency of permanent magnet synchronous motors is greater [27-28]. There are a few drawbacks to consider, such as a poor power factor, significant core loss, and strong torque ripple. An electric vehicle (EV) is one of the major uses of a permanent magnet synchronous motor gaining prominence. A permanent magnet synchronous motor is indicated for use in a propulsion system [29]. This paper proposes on the design and study of several PMSM machines. The concept of electric vehicle system modeling, which encompasses modeling the vehicle's acceleration, range, and analysis of various driving cycles, is carried out. The contributions of this paper are summarized as follows:

1) The study introduces a novel approach to address the challenges of high-power wireless charging in electric vehicles by proposing a modular four-channel WPT system with a decoupled coil design. This system comprises four parallel power transfer channels, each consisting of a complete WPT module. By leveraging this modular architecture, the system achieves faster charging while mitigating issues related to power transfer imbalance and coil misalignment tolerance.
2) The research emphasizes the importance of extending the operating range of electric vehicles without significantly increasing battery size and weight. It discusses how energy regeneration during deceleration, controlled by a current-controlled Voltage Source Inverter (VSI) powering a Permanent Magnet Synchronous Motor (PMSM), can augment the driving range of EVs. This focus on enhancing EV driving range contributes to the overall sustainability and practicality of electric transportation.
3) The study highlights the significance of PMSMs in electric vehicle propulsion systems, noting their advantages such as simplicity, efficiency, and reliability. It discusses the use of bi-directional buck-boost converters to enhance the performance of battery-powered PMSMs during regenerative braking. Additionally, it underscores the ongoing research and development efforts aimed at optimizing PMSM design and control strategies for EV applications.

2. SYSTEM CONFIGURATION

The proposed synergistic integration comprises a modular four-channel 50 kW Wireless Power Transfer (WPT) system for fast Electric Vehicle (EV) charging and Permanent Magnet Synchronous Motor (PMSM) drive integration. The WPT system features four parallel power transfer channels, each capable of delivering 50 kW of power. Each channel consists of a Primary Power Factor Correction (PFC) rectifier, an inverter, transmitter and receiver coils, and a secondary rectifier, facilitating efficient wireless power transmission. The modularity of the system ensures scalability and ease of maintenance. Concurrently, the PMSM drive system, seamlessly integrated into the EV's propulsion system, includes the PMSM itself, providing high-efficiency propulsion power with superior torque density. This integration streamlines EV operation while maximizing energy efficiency and facilitating rapid charging, enhancing the overall performance and sustainability of electric vehicles.

3. MODULAR CIRCUIT DESIGN

The four-channel WPT system that is being suggested uses identical circuit modules for each channel, as can be seen in Figure 1. Equipped with compensation networks, a main side high-frequency inverter, a grid-side PFC rectifier, and a secondary side high-frequency rectifier make up the circuit module. Figure 10 shows the schematic design of the circuit module, using Channel 1 as an example. The proposed four-channel magnetic coupler's inter-channel decoupling is tested by simulations utilising the 3-D Finite Element Method

(FEM). There are a total of 28 coupling coefficients in the coupler, which is caused by the 8 inductive coils (Lp1~ Lp4 and Ls1 Ls4). Out of these, four are for power transmission (kp1_s1, kp2_s2, kp3_s3, and kp4_s4), and there are 24 for interference (kpi_sj, kpi_pj, and ksi_sj, where i j). In a simulated setup with a 200 mm air gap between the main and secondary sides, the coupling coefficient kp1_s1 for power transmission is 0.261 and the interference coefficients across channels are close to zero, according to the data. Under aligned circumstances, inter-channel decoupling is therefore accomplished. Analysing the misalignment performance further, we find that the suggested four-channel magnetic coupler outperforms conventional single-channel systems in terms of balanced lateral (X-axis) and vertical (Y-axis) misalignment tolerance.

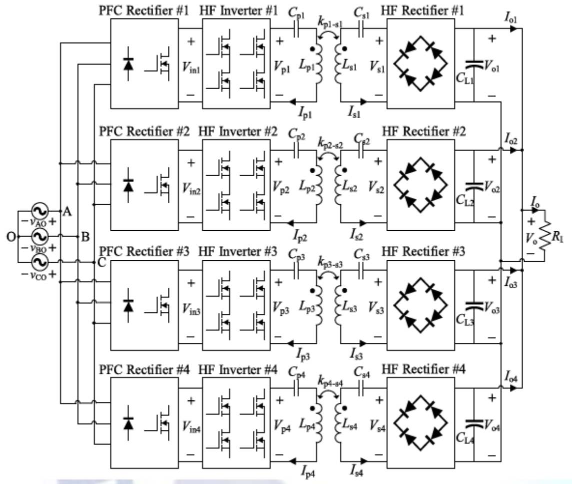


Figure 1. Block diagram of modular four-channel WPT system.

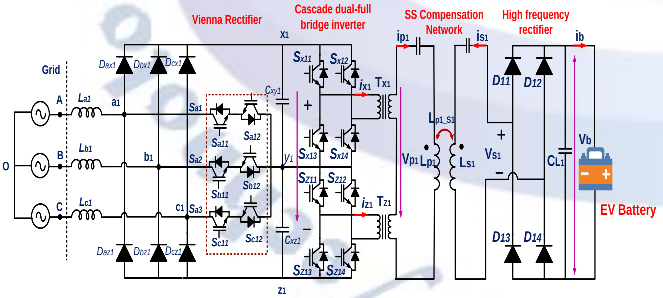


Figure 2. Schematic diagram of the circuit module for EV battery charging.

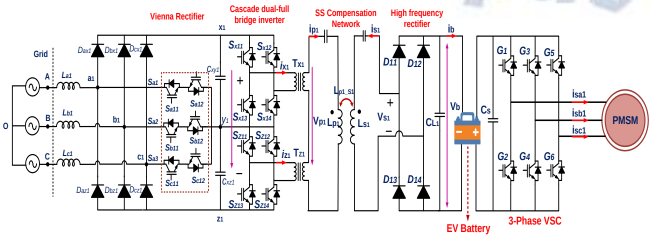


Figure 3. Schematic diagram of the circuit module for PMSM drive from EV battery system.

3. MODULAR FOUR-CHANNEL 50 KW WPT SYSTEM FOR FAST EV CHARGING AND PMSM DRIVE INTEGRATION WORKS.

The modular four-channel 50 kW Wireless Power Transfer (WPT) system and the Permanent Magnet Synchronous Motor (PMSM) drive are a revolutionary approach to electric vehicle (EV) charging and propulsion systems. The WPT system ensures precise positioning for optimal power transfer efficiency, while the PMSM drive provides optimal propulsion performance during subsequent journeys. The main PFC rectifiers in the WPT system change the AC power that comes in from the grid into high-quality DC power. Inverters then efficiently change the DC power into high-frequency AC signals that can be sent wirelessly. The transmitter coils embedded within the charging pad emit these AC signals, generating a magnetic field that induces a voltage in the receiver coils mounted on the underside of the EV. The secondary rectifiers in the EV's charging system convert the received AC signals back into DC power, directed to the vehicle's onboard battery pack. The modular design of the WPT system enhances reliability and fault tolerance, as it can dynamically adapt to changes in environmental conditions or charging requirements. During acceleration, the PMSM delivers precise torque output, providing a dynamic driving experience that rivals conventional internal combustion engine vehicles. The sophisticated control algorithms optimize energy consumption and driving dynamics, maximizing both range and performance. Crucially, the PMSM drive system transitions into regenerative braking mode during deceleration or braking maneuvers, harnessing kinetic energy from the vehicle's motion and converting it back into electrical power. This process extends the EV's driving range, improves overall energy efficiency, reduces brake wear, and enhances environmental sustainability and operational cost-effectiveness. Through the synergistic integration of the modular WPT system and the PMSM drive, this integrated solution offers numerous benefits to EV owners, operators, and society as a whole. These benefits include:

1. Convenience: The wireless charging capability of the WPT system eliminates the need for physical cables and connectors, simplifying the charging process and enhancing user convenience. The modular design allows for flexible deployment in various

locations, including residential garages, public parking lots, and commercial charging stations.

2. Efficiency: The high efficiency of both the WPT system and the PMSM drive minimizes energy losses during charging and propulsion, reducing overall electricity consumption and carbon emissions. The regenerative braking capability further enhances energy efficiency by recapturing kinetic energy that would otherwise be lost as heat.

3. Reliability: The robust design and fault-tolerant operation of the integrated system ensure reliable performance under diverse operating conditions, including extreme temperatures, weather conditions, and terrain. The modular architecture allows for easy maintenance and scalability, minimizing downtime and optimizing system longevity.

4. Performance: The seamless integration of the PMSM drive system delivers responsive and exhilarating driving dynamics, with instant torque delivery and smooth acceleration. The regenerative braking system enhances vehicle control and stability while maximizing driving range, resulting in an engaging and enjoyable driving experience for EV enthusiasts.

IV. GIRD-SIDE PFC RECTIFIER

A three-phase power factor enhancement is provided by the Vienna rectifier, which also offers several other benefits, such as sinusoidal input current, a power factor that is almost one, and minimal harmonic distortion [30–31]. A number of benefits are also associated with it, including a high efficiency rate, low voltage stress, and a low power loss rate [30]. Customers' electricity bills and air pollution are both helped by the Vienna rectifier. Very high switching frequencies (around 100 kHz) are used in Vienna rectifiers [32]. When the switching frequency is high, switching losses are significant and the sustainability of the switches is poor. While the Vienna rectifier makes use of two output capacitors, our suggested architecture makes use of a single one [30–32]. The Vienna control architecture is intricate, and there are severe limitations on reactive power production. For reaching the unity power factor, it is very appealing. Due to its reduced number of diodes and ease of implementation, our suggested modified Vienna rectifier is ideal. To contrast with the Vienna rectifier, we used a switching frequency of 21 kHz here, which is quite low. Since the switching losses are reduced at this lower switching frequency, the efficiency is increased. Included in our straightforward and dependable controller design are a handful of logic gates, linear components, and a proportional integral (PI) controller. The power factor and output DC voltage may be adjusted. The rectifier placed on the grid side is a Vienna rectifier. The rectification efficiency, power density, and size of the passive components are all quite modest in a Vienna rectifier [33]. Since the rectifier's voltage stress is only half of its DC output voltage (Vin1 in Fig. 4), it is able to produce a greater DC voltage. Using a high-voltage DC bus to reduce power coil current is helpful for the circuit's later stages. Lower power coil loss and more efficient energy transfer are the results of setting the power coil's quality factor. Discussion of the Vienna rectifier's operating principle and control approach is beyond the scope of this publication. The voltage relationship is shown in Fig. 2, and it may be used to explain the post-stage circuit. Essentially, the output of the Vienna rectifier is the same as two equal-amplitude series DC voltage sources.

$$V_{xy1} = V_{yz1} = \frac{1}{2} V_{in1} \qquad (1)$$

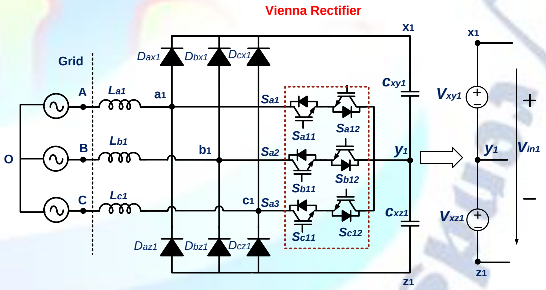


FIGURE 4. Output equivalent model of Vienna rectifier.

The Vienna rectifier is a three-phase AC-to-DC power conversion topology that is widely used for its high power factor correction (PFC) and low harmonic distortion characteristics. The operation of the Vienna rectifier involves several important formulas related to its performance and control.

1. Input Voltage and Current

For a balanced three-phase system, the phase voltages can be represented as:

$$V_{an}(t) = V_m \sin(\omega t) \qquad (2)$$

$$V_{bn}(t) = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \qquad (3)$$

$$V_{cn}(t) = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \qquad (4)$$

Where V_m is the peak phase voltage, ω is the angular frequency, and t is time. The corresponding line currents (assuming unity power factor) can be represented as:

$$I_a(t) = I_m \sin(\omega t) \qquad (5)$$

$$I_b(t) = I_m \sin\left(\omega t - \frac{2\pi}{3}\right) \qquad (6)$$

$$I_c(t) = I_m \sin\left(\omega t - \frac{2\pi}{3}\right) \qquad (7)$$

where I_m is the peak phase current.

2. DC Output Voltage

The average DC output voltage Vdc of the Vienna rectifier can be approximated by:

$$V_{dC} = \frac{3\sqrt{3}}{\pi} V_{LL} \cos(\phi) \qquad (8)$$

Where V_{LL} is the RMS line-to-line input voltage, and ϕ is the phase angle between the input voltage and current (ideally zero for unity power factor).

3. Power Factor Correction

The power factor $PFPF$ is given by the ratio of real power P to apparent power S:

$$PF = \frac{P}{S} = cos(\phi) \qquad (9)$$

For a unity power factor, ϕ=0 and PF=1.

4. Input Current Harmonic Distortion

Total harmonic distortion (THD) of the input current is a measure of the harmonic content and is given by:

$$THD = \sqrt{\Sigma_{n=2}^{\infty} \left(\frac{I_n}{I_1}\right)^2} \qquad (10)$$

Where In is the RMS value of the nth harmonic component of the input current, and $I1$ is the RMS value of the fundamental component of the input current.

5. Inductor Design

The inductance L required for the boost inductor in each phase can be estimated based on the desired ripple current ΔIL and switching frequency :

$$L = \frac{V_{dC} \cdot D \cdot (1-D)}{f_S \cdot \Delta I_L} \qquad (11)$$

where D is the duty cycle of the PWM signal.

6. Capacitor Design

The DC bus capacitor C is designed to smooth the output voltage and can be estimated by:

$$C = \frac{I_{dC}}{2 \cdot f_{ripple} \cdot \Delta V_{dc}} \qquad (12)$$

Where I_{dC} is the DC output current, f_{ripple} is the ripple frequency (typically twice the line frequency for a three-phase rectifier), and ΔV_{dc} is the allowable voltage ripple on the DC bus.

7. RMS Current in Components

The RMS current through the diodes and switches can be estimated as follows:

For diodes in each phase leg:

$$I_{DRMS} = \sqrt{\frac{1}{T} \int_0^T i_D^2(t)\, \mathrm{d}t} \qquad (13)$$

For switches in each phase leg:

$$I_{S_{RMS}} = \sqrt{\frac{1}{T} \int_0^T i_S^2(t)\, \mathrm{d}t} \qquad (14)$$

Where (t) and $i_S^2(t)$ are the instantaneous currents through the diodes and switches, respectively, and T is the period of the switching cycle.

5. PRIMARY SIDE HIGH-FREQUENCY INVERTER

The inverter's current capacity is 25% of the single-channel systems at the same power level in the proposed modular four-channel system. A cascaded dual-full bridge inverter is used to simultaneously lower the devices' voltage stress, as seen in Figure 10. The two full-bridge inverters in Figure 2 take half of the DC bus voltage Vin1 from the DC sources Vxy1 and Vyz1. The voltage stress on power components is reduced by half compared to a conventional full-bridge inverter by virtue of the cascaded architecture. A silicon-based MOSFET with a 650 V withstand voltage is a cost-effective choice for the 800 V DC bus voltage and may be used in both the Vienna rectifier and the inverter. A single inverter typically needs SiC devices to reach an 800 V input and output voltage level. This research demonstrates that by combining a Vienna rectifier with a cascaded inverter, Si devices may attain the same voltage level. Furthermore, by combining the Vienna PFC rectifier with cascaded dual full-bridge inverters, we can achieve balanced input voltages for each inverter. This is because the Vienna rectifier has a natural midpoint for its output, and unlike previous approaches that relied on cascade inverters to generate high power, our method eliminates the issue of device damage caused by inconsistent voltage stress on the inverter's switching devices. The cascaded dual-full bridge inverter uses high-frequency transformers Tx1 and Tz1 (turn ratio 1:1) to cascade the output of the upper and lower inverters instead of two separate sources of input voltage Vxy1 and Vyz1, which share a common point y1. Otherwise, Vxy1 and Vyz1, which are DC voltage sources, might be short-circuited in certain switching states. The inverter and post-stage circuit are electrically isolated, which is another advantage of using high-frequency transformers. Both full-bridge inverters have their switch driving signals configured to be identical. As a result, the cascaded dual-full bridge inverter's output voltage vp1 is double that of a single full-bridge inverter's output voltage vx1 or vz1.

$$v_{P1} = 2v_{x1} = 2v_{z1} \quad (15)$$

$$i_{P1} = i_{x1} = i_{Z1} \quad (16)$$

Both the Vienna rectifier and the cascaded dual-full bridge inverter use Infineon silicon-based MOSFETs. The 650 V rating of the device is more than enough for half of the 400 V maximum DC bus voltages. For each switch of the dual-full bridge inverter, two devices with an ON-state resistance of 80 mΩ in TO-247 housings are used in parallel to attain reduced conduction losses.

VI. Working operation PMSM drive system

The integration of a Permanent Magnet Synchronous Motor (PMSM) drive with an electric vehicle (EV) battery involves a seamless combination of several key components to achieve efficient propulsion. The EV battery pack, typically composed of lithium-ion cells, serves as the primary energy source, providing DC power to the system as shown in figure .5. This DC power is converted into three-phase AC power by an inverter, which is a crucial component in the drive train. The inverter uses pulse-width modulation (PWM) to precisely control the frequency and amplitude of the AC power supplied to the PMSM, enabling accurate control of the motor's speed and torque. The PMSM itself is known for its high efficiency, high power density, and excellent torque characteristics, making it ideal for EV applications. During vehicle operation, the PMSM converts the electrical energy from the inverter into mechanical energy, propelling the vehicle. The motor's rotor, embedded with permanent magnets, interacts with the rotating magnetic field produced by the stator windings, generating torque. The motor's performance is continuously monitored and adjusted by the vehicle's control system to optimize efficiency and response to driving conditions. Additionally, the system incorporates regenerative braking, where the PMSM acts as a generator during deceleration, converting kinetic energy back into electrical energy, which is then fed back to recharge the EV battery. This process not only enhances the vehicle's range but also improves overall energy efficiency. The combined operation of the EV battery, inverter, and PMSM provides a robust and efficient drive train solution, ensuring smooth, responsive, and energy-efficient propulsion for electric vehicles.

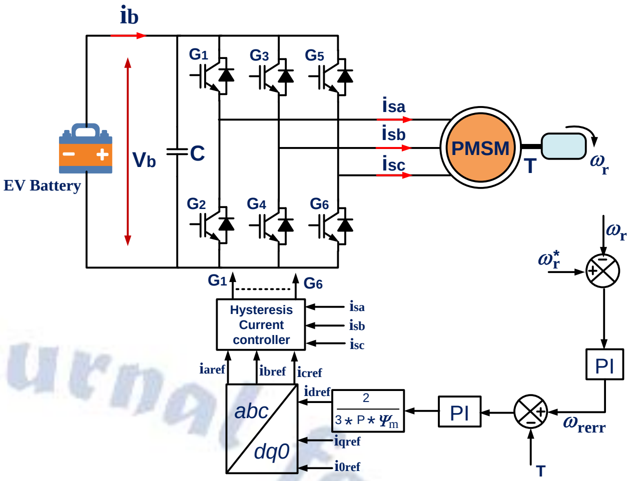


Fig.5 Layout of Battery fed for PMSM drive system

1. DC-DC Converter Efficiency (η_{DC-DC}): $\eta_{DC-DC} = \frac{P_{out,DC}}{P_{in,DC}} \times 100\%$ (17)

   Where: $P_{out,AC}$ is the output power of the DC-DC converter. $P_{in,DC}$ is the input power to the DC-DC converter.

2. Inverter Efficiency ($\eta_{inverter}$): $\eta_{inverter} = \frac{P_{out,AC}}{P_{in,DC}} \times 100\%$ (18)

   Where: $P_{out,AC}$ is the output power of the inverter. $P_{in,DC}$ is the input power to the inverter.
3. Motor Efficiency (η_{Motor}): $\eta_{Motor} = \frac{P_{out,Mechanical}}{P_{in,Electrical}} \times 100\%$ (19)

   Where: $P_{out,Mechanical}$ is the mechanical output power of the motor. $P_{in,Electrical}$ is the electrical input power to the motor.
4. Torque (T) - Current (I) Relationship for PMSM: $T = k_{torue} \times I$ (20)

   Where: k_{torue} is the torque constant of the PMSM.
5. Mechanical Power ($P_{Mechanical}$): $P_{Mechanical} = T \times \omega$ (21)

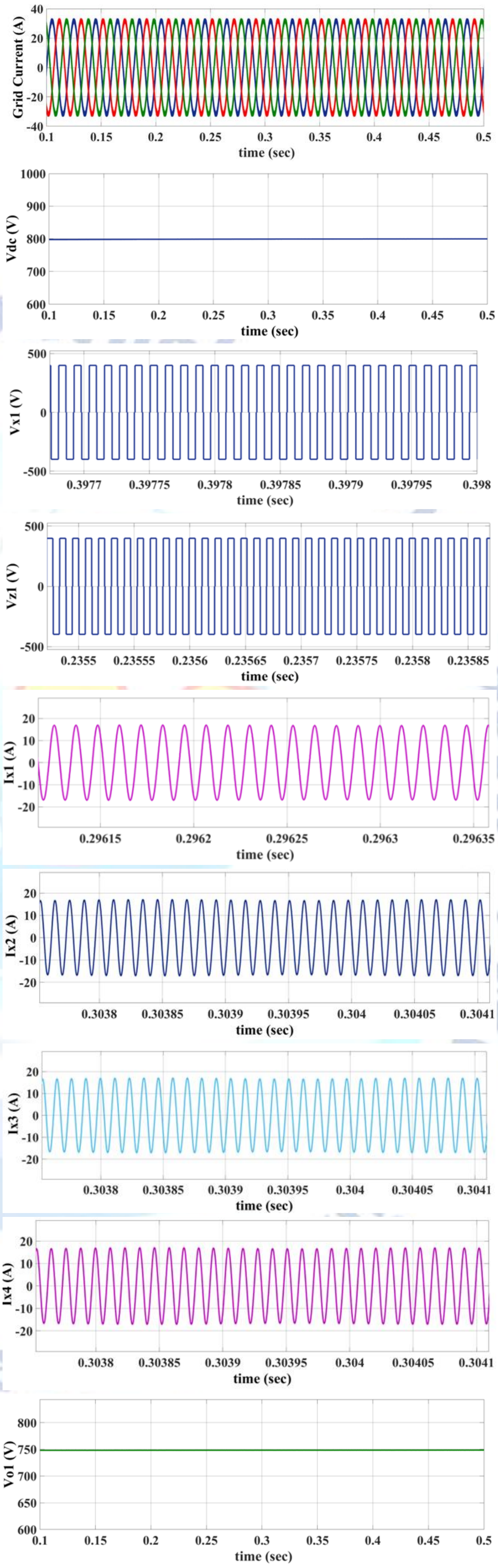
   Where: ω is the angular velocity of the motor.
6. DC-AC Conversion Power Losses: $P_{Loss,DC-AC} = P_{in,DC} - P_{out,AC}$ (22)

7. DC-DC Conversion Power Losses: $P_{Loss,DC-DC} = P_{in,Battery} - P_{out,DC}$ (23)

7. RESULTS AND DISCUSSION

A. EV charging used with modular four-channel 50 kW WPT system uses a Vienna rectifier

The modular four-channel 50 kW WPT system uses a Vienna rectifier to convert grid AC power to DC power while maintaining power factor. Vienna rectifiers, noted for their efficiency and harmonic distortion reduction, can handle 230 V grid power and 30 A current. MATLAB/Simulink showed that the Vienna rectifier converted three-phase AC input to steady DC output as shown in figure 6. The system was configured to handle typical power supply circumstances for rapid EV charging stations with input grid voltage (230 V) and current (30 A). The Vienna rectifier maintained a high power factor near to unity in simulations, which is essential for power system efficiency and loss reduction. The Vienna rectifier's DC output voltage was stabilised at a higher voltage for the WPT system's inverter and transformer stages to ensure smooth power transmission. Vienna rectifier DC output voltage was about 800 V, meeting cascade full-bridge inverter and WPT system operating requirements. The high DC voltage allows the inverter to effectively work at 86 kHz, boosting the voltage for wireless power transmission. The Vienna rectifier's input current has minimal total harmonic distortion (THD), indicating its efficacy in boosting grid power. This is essential for regulatory compliance and power conversion process reliability and efficiency. The simulation showed that the rectifier can manage rapid EV charging power levels with a steady-state output current that meets the system's design. The rectifier's excellent power conversion and stabilisation helps the WPT system supply high power to the load. Finally, the Vienna rectifier's integration with the modular four-channel 50 kW WPT system is crucial to converting grid AC power to DC efficiently and with power factor adjustment. It can provide a steady 800 V DC output voltage, 230 V input grid voltage, and 30 A current, according to simulations. This increases WPT system efficiency and reliability, allowing rapid and efficient EV charging.



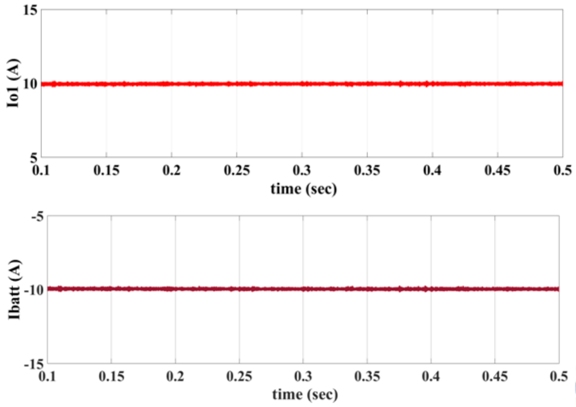


Figure 6. Waveform when four channels are fully loaded.

The integration and simulation of the modular four-channel 50 kW wireless power transfer (WPT) system were meticulously carried out using MATLAB/Simulink, emphasizing the system's performance and reliability. The design includes a cascade full-bridge inverter operating at a frequency of 86 kHz, and the simulation results underscore the system's efficacy in high-power transfer applications. The primary voltage (Vx1) of the transformer was recorded at 400 V, while the primary current (Ix1) measured 20 A. These values indicate that the transformer is efficiently stepping up the voltage to the required level while maintaining a manageable current. This efficient voltage transformation is critical for ensuring that the WPT system can deliver high power without incurring excessive losses or encountering thermal issues. The four-channel design of the WPT system demonstrated consistent performance, with each channel (Ix2, Ix3, Ix4) carrying a current of 20 A. This uniform current distribution across all channels is a testament to the system's balanced power handling capabilities. Such uniformity is essential for the stability and reliability of the system, as it prevents overloading of individual channels and ensures even power distribution as shown in figure 6. At the load end, the system successfully delivered a voltage (Vo1) of 750 V and a current (Io1) of 10 A. These load conditions confirm that the WPT system can effectively transfer power to the load with high efficiency. The high load voltage and current are indicative of the system's ability to meet the demands of fast EV charging, providing sufficient power to quickly recharge EV batteries. The results from the simulation validate the modular four-channel design's capability to manage high power levels efficiently. The decoupled coil design within the WPT system minimizes cross-coupling effects, leading to more efficient power transfer and reducing potential interference between channels. The system's high-frequency operation at 86 kHz further enhances power transfer efficiency, making it well-suited for practical implementation in fast EV charging infrastructure. The successful simulation outcomes demonstrate that the proposed system not only meets but exceeds the necessary performance metrics for modern EV charging. It offers a robust solution capable of delivering high power in a stable, efficient manner, addressing key challenges such as voltage stress, insulation requirements, and cross-channel interference. These results provide a strong foundation for the future development and deployment of high-power WPT systems in the EV industry, highlighting the potential for significant advancements in charging technology and efficiency.

B. Different speed variation of PMSM drive application

Electric vehicle (EV) battery systems include a sophisticated system called the Permanent Magnet Synchronous Motor (PMSM) drive, which relies on power electronics to transform the DC current from the battery into the AC current needed, as seen in figure 7. This transformation is made possible by an inverter, which transforms the direct current (DC) electricity from the battery into alternating current (AC) in three phases. Through the use of sensors, the PMSM drive's control system keeps tabs on critical parameters such as motor speed, position, and current, feeding this information back into the control algorithm in real-time. Motor speed, torque, and rotational direction may be precisely controlled by the control algorithm, which modulates the alternating current (AC) power supply's frequency, voltage, and phase angle. In response to input from the PMSM drive, which provides both power and control signals, the motor spins, which causes the vehicle's wheels to turn. Optimal performance, efficiency, and dependability are guaranteed by the PMSM drive, which continually modifies its control signals depending on data from the motor sensors. Ensuring smooth acceleration, deceleration, and overall vehicle functioning is this closed-loop control system. Figure 7 displays the results of the simulation, which showcase the control system's ability to maintain constant performance by showing how the speed of the PMSM drive varies under different load circumstances. To top it all off, the PMSM drive is perfect for electric cars that need accurate and dynamic control of motor functions because of how fast it can react to changes in operating circumstances.

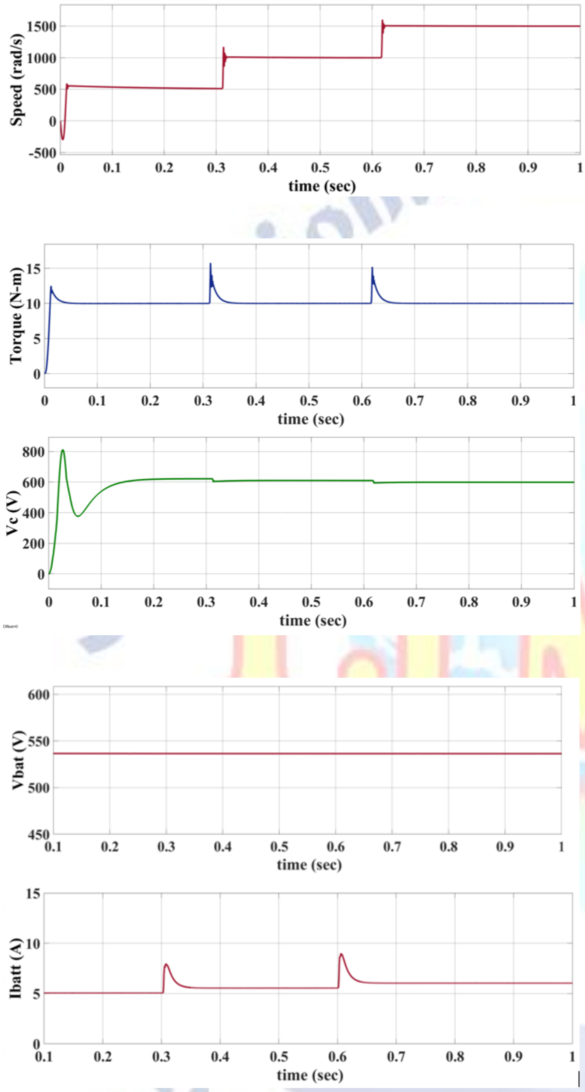


Figure.7 simulation results of different speed variation PMSM drive

8. CONCLUSION

The modular four-channel 50 kW wireless power transfer (WPT) system is a significant advancement in fast electric vehicle (EV) charging. It uses a decoupled coil design to enhance power transfer capabilities and address challenges like voltage stress, insulation issues, and cross-coupling effects. The modular system ensures a balanced misalignment tolerance, making it suitable for real-world EV parking scenarios. This innovative approach to WPT mitigates the limitations of traditional multi-channel systems, offering a robust solution that combines high power transfer with operational reliability. The symmetry and rotational design of the four-channel magnetic coupler improve the practicality and user-friendliness of wireless EV charging. The integration of Permanent Magnet Synchronous Motor (PMSM) drives with the EV battery system further enhances the vehicle's efficiency and performance. PMSM drives' regenerative braking capability allows for the recapture of kinetic energy during deceleration, extending the driving range and optimizing energy usage. This integrated system contributes to energy efficiency and sustainability in the automotive industry, with future developments expected to refine these technologies.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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