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Matrix Converter-Based Three-Phase Modular High-Power Wireless Charging Systems for Heavy-Duty Electric Vehicles

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***Abstract*—Due to the increasing requirement of charging power for electric vehicles, especially heavy-duty electric vehicles (HDEVs), this paper proposes novel matrix converter-based three-phase medium voltage AC (MVAC) grid-connected modular high-power wireless charging systems. The stiff DC-link absent power transfer from low-frequency AC to high-frequency AC is achieved by the full-bridge direct matrix converter (FBDMC). The cascaded FBDMC structure is proposed to achieve the MVAC grid connection. The three-phase coupler is used here to generate the rotating magnetic fields to achieve higher transfer capability and power density. The second and third grid harmonics can be cancelled due to the nature of the FBDMC and three-phase system, which results in significantly less DC-link current ripple compared to single-phase wireless charging systems. Several novel connections between FBDMCs and coils are proposed to provide more flexibility and multiplexity for WPT charging. The topology is verified by the simulation in PLECS and by a down-scale experiment setup.**

***Index Terms*—Wireless power transfer, matrix converter, single-stage AC-AC conversion, three-phase electric power, modular structure.**

I. Introduction

Heavy-duty vehicles (HDV) are responsible for over 6 % of total EU greenhouse gas (GhG) emissions [1]. Due to the irreplaceable position of HDVs in transport, electrifying HDVs is of great significance.

Many heavy-duty electric vehicle (HDEV) models are available on the market, but the charging time is still one of the main bottlenecks for deployment compared to fossil fuel-based HDVs. Compared to the conductive charging method, wireless power transfer (WPT) technology emerges as a more user-friendly alternative, delivering weather-proof, hands-free, safe, and autonomous charging solutions for EVs. A typical WPT system is shown in Fig. 1. However, the maximum charging power specified in all WPT standards is 500 kW, as defined by HD-WPT9 in SAE J2954/2, which still has a lot of space to improve in terms of power levels, especially for HDEV applications like mining trucks with over 500 kWh batteries.

For HDEVs to compete with HDVs, charging power must be at the MW level, so the modular design is indispensable. Some MW-level WPT charging infrastructures have been developed

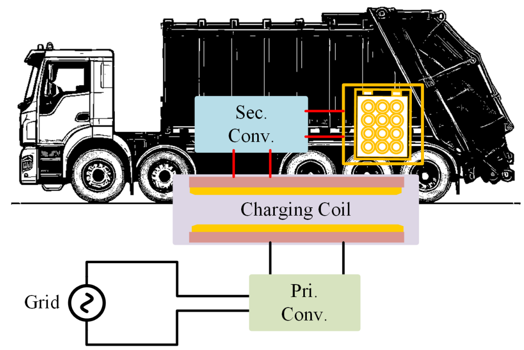

Fig. 1. Typical WPT system. Pri. Conv. means primary power conversion and Sec. Conv. means secondary power conversion.

[2], [3], but they are designed for dynamic charging for trains (∼100-m transmitter) and static charging for ships (2∼8 kHz), which is not suitable for charging HDEVs. Modular primary power converters have been investigated in [4]–[7] to increase the transfer power. Moreover, compared to the conventional two-stage power conversion with a bulky capacitor-based stiff DC link in between, one-stage AC-AC conversion can have a capacitor-less structure which increases not only the overall efficiency [8] but also the power density and reliability of the system. A few researchers have also studied the grid-connected direct AC-AC converter-based WPT systems to increase the power density [9]–[11]. However, no one has studied the one-stage medium voltage AC (MVAC) grid-connected three-phase modular power converters for wireless charging. Regarding the coil part, the three-phase coil has been proven to generate a more uniform magnetic field and have a higher power transfer and power density compared to a single-phase coil [12], but the modularity and the multiplexity have not been studied yet.

This paper proposes novel MVAC grid-connected matrix converter-based three-phase modular systems to improve the power transfer, power density, flexibility, and modularity of the WPT charging systems for HDEVs. Modular full-bridge direct matrix converters (FBDMCs) are used as the grid interface between the MVAC grid and the transfer coils. Several novel

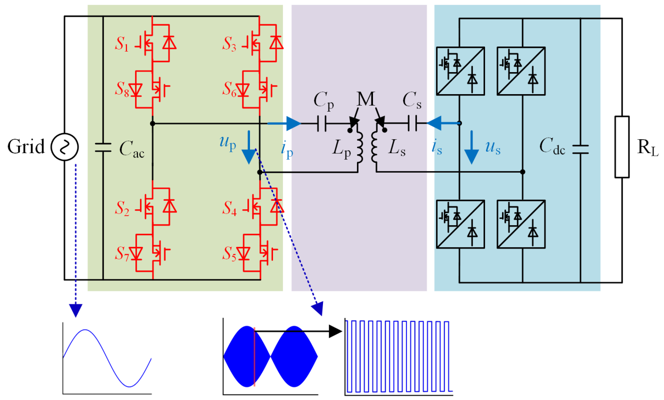

Fig. 2. Proposed FBDMC-based single-phase single-stage WPT system.

connections between the primary converter and the three-phase coil have been proposed to not only increase the power transfer capability but also enhance the compatibility with light-duty vehicles with single-phase coils.

II. Proposed Modular System

Hereby, we will first present the single FBDMC-based single-phase WPT system, then illustrate the single FBDMC-based three-phase WPT system. Finally, the modular FBDMC-based three-phase WPT system is proposed.

A. Single FBDMC-based single-phase WPT system

Fig. 2 illustrates the circuit topology of the proposed single FBDMC-based single-phase WPT system, where the FBDMC is also one cell of the following subsections.

In order to have an intuitive comparison between traditional two-stage power conversion and proposed matrix converter-based single-stage power conversion, assume that the RMS value of the grid is 800 V, the load current is 25 A, and the ripple is 1%, then the DC-link filter capacitance required for the three-phase two-stage conversion is around 5mF. However, considering the maximum voltage and capacitance of the commercial electrolytic capacitor, they need to be connected in parallel and in series. For example, 2500μF/400V capacitors are used here. The DC output of the three-phase rectifier is around 1080 V. Capacitors should be connected 4 in series to achieve a 1600 V withstand voltage level. According to the commercial dimensions, the volume of the DC-link capacitor is about 8000 cm^3, and it should be noted that heat dissipation and placement are not taken into consideration. This DC-link is not needed in the proposed topology. Thus, the proposed matrix converter-based single-stage WPT system can have much higher power density.

Compared to the half-bridge and T-type converters, the full-bridge (FB) matrix converter has the most degrees of freedom in control, the lowest current stress and conduction loss according to [13]. But one thing that should be noted is that the other two structures also have their own advantages, so it is also possible to choose them in a particular application scenario. Four pairs of common-source back-to-back MOSFETs are used as four-quadrant switches to convert the LFAC to HFAC. The series-series (SS) compensation is used here only as an illustration, dual-side LCC (DLCC) and other methods can also be used. The secondary side can be a diode-based rectifier to obtain the simplest system or an active rectifier to increase efficiency and the control degrees of freedom in control, as well as to achieve bi-directional power flow to realise V2G or V2X.

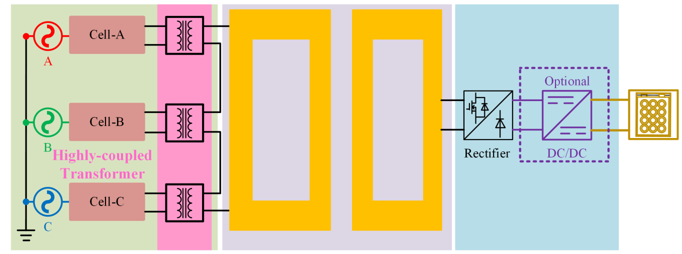

Fig. 3. Proposed FBDMC-based single-stage three-phase WPT system with single-phase coil.

In this paper, the simplest control method, i.e., fixed nearly 50% duty cycle, is used for the control, and advanced control methods will be investigated in the future paper.

B. Single FBDMC-based three-phase WPT system

As extracted power from a one-phase grid goes much higher, the grid imbalance becomes a serious issue. To solve this problem, the three-phase matrix converter-based WPT system is proposed in this section. Unlike the normal three-phase converter used in [9], [12], separated converters and coils are used here to provide the system more modularity and flexibility.

1) Single-phase coil: The single-phase coils, especially rectangular coils, are widely used in high-power wireless charging due to their simple structure and good anti-misalignment performance, as shown in the 1-2 MW WPT electric ship charging system presented in [3]. Inspired by [13], a novel single FBDMC-based three-phase topology is proposed to convert three-phase LFAC into single-phase HFAC as shown in Fig. 3, where the colour of the background is consistent with Fig. 1, and each cell is an FBDMC shown in Fig. 2.

The highly-coupled transformer is used here to connect the output of the three-phase matrix converter in series, which can eliminate the third harmonic from the grid. Except for the three two-winding transformers shown in Fig. 3, a four-winding transformer can also be used here to increase the power density [13].

2) Three-phase coil: Compared to the simple single-phase coils, three-phase coils suffer from the complicated structure and non-zero inter-phase mutual inductance. However, according to [12], the non-zero inter-phase mutual inductance can enhance the power transfer if the coil is excited by three-phase AC voltage. Moreover, the generated rotated magnetic field allows better utilization of the allocated space and suits

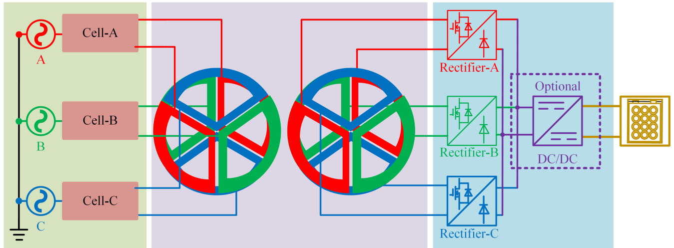

Fig. 4. Proposed FBDMC-based single-stage three-phase WPT system with three-phase coil.

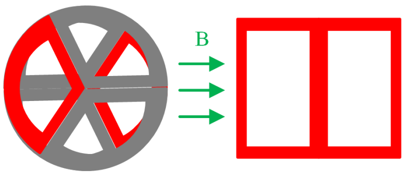

Fig. 5. Compatibility between a three-phase coil and a DD coil.

for high-power application. The proposed system is shown in Fig. 4.

From Fig. 4, we can see that a bipolar three-phase coil is used as the transfer pad. Unlike in [12] where the three-phase coils need to be connected in Star or Delta, which only provide 3 ports to the converter, we split the coils so that each phase of a bipolar coil has its own converter, or we can even split each phase of a bipolar coil into two separately reverse powered coils to provide more flexibility, the detailed analysis of the flexibility and multiplexing of the proposed topology is in another paper. As shown in Fig. 5, each bipolar coil in each phase has its own converter, which can give the system more compatibility for charging vehicles other than HDEVs. For example, if there is a car with a bipolar charging coil like DD, we can only operate a one-phase converter to excite a magnetic field similar to a DD coil, as shown in Fig. 5, to provide the system more compatibility with the vehicles having single-phase coils. The situations of meeting with other single-phase coils are analyzed in another paper.

According to [12], the third harmonics can be eliminated by the three-phase WPT system. Moreover, using three-phase grid-connected matrix converters can eliminate the second harmonics from the grid at the DC side [14], so the filter would be much smaller compared to the traditional two-stage conversion.

C. Modular FBDMC-based three-phase WPT system

For simplicity, only the modular FBDMC-based three-phase system with the three-phase coil is analyzed here. The analyses of the single-phase coils are similar.

Like the connection in the cascaded H-bridge, multiple cascaded cells are here to make a high-voltage grid interface to extract MW-level power from the MVAC. However, the output of each cascaded cell can have two different connections with the three-phase coils as shown in Fig. 6. The '/*'means for the single three-phase coil on the right, the cell* here is

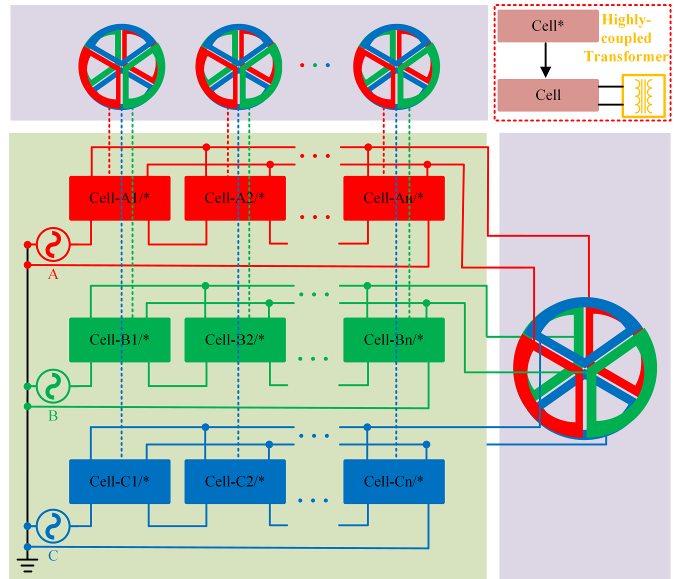

Fig. 6. Matrix converter-based modular three-phase WPT system.

the combination of a matrix converter and a highly-coupled transformer to achieve output-parallel connection.

It is clear from Fig. 6 that the proposed matrix converter-based three-phase modular WPT system can be connected to either an array of small three-phase coils or one large three-phase coil. The coil array shown in the upper part of Fig. 6 provides the advantage of full system modularity, thereby facilitating the maintenance and scaling of power transfer capabilities. The typical heavy-duty truck chassis dimension is around 10 m $\times$ 2.5 m. According to [15], a 75-cm diameter coil can transfer up to 300 kW, so it is theoretically possible to achieve MW-level charging in large trucks using the coil array. The modular converter and coil structure are also very easy to maintain, repair, and replace. In addition to charging HDEVs, a separate three-phase coil can also be used as a charger for other small vehicles. However, the inter-coil mutual inductance, the synchronisation of the control system, and the power balance between stages are the key challenges and need further study.

If the charging power level is settled, one single three-phase coil is preferable since in general, the simpler the system, the more reliable it is. So did in [3] with a single huge rectangular coil. The schematic is the connection on the right side of Fig. 6.

III. Simulation Results

Since the cascaded structure in Section II-C is similar to the modular multilevel converter (MMC) and cascaded H-bridge (CHB), only the simulation of Section II-B compared with Section II-A is shown here. The inductance matrix of the single-phase coil comes from our previous work, and the three-phase coil comes from [12], respectively. The grid voltage is set as 800 VAC, and the switching frequency is set as 88.5 kHz to obtain the ZVS. One thing should be noted that the grid voltage in the simulation can be changed into any voltage level in realistic. For example, if the transferred power is not

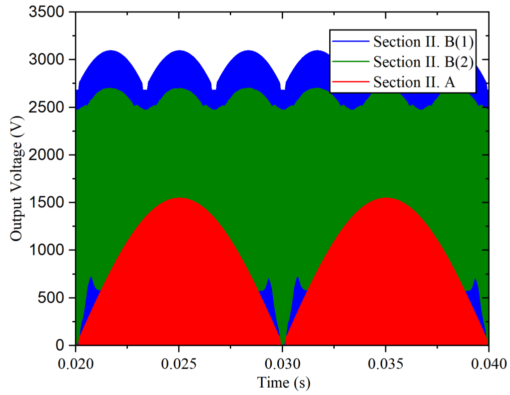

Fig. 7. Output voltage of the simulation results for Section II-A and Section II-B.

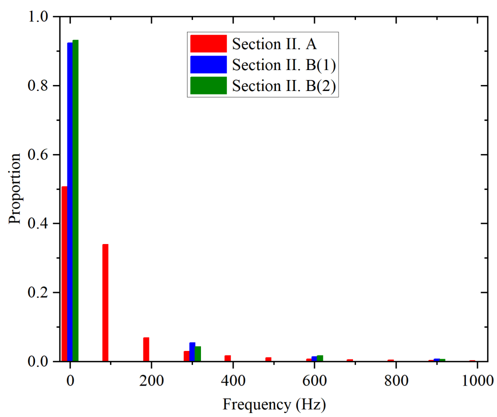

Fig. 8. FFT analysis of the output current from the simulation results for Section II-A and Section II-B.

high, 3-phase 400 VAC is preferred in this situation. The load is set as a 32-Ω resistor in both simulations, and the impedance matching is not considered here since the simulation is only to prove the feasibility of the proposed topologies. The ideal MOSFET model is used to speed up the simulation. The output voltage and the DC side current FFT analysis are shown in Fig. 7 and Fig. 8, respectively.

As can be seen from the figures, the three-phase matrix converter-based WPT system has significantly fewer DC-link current harmonics and ripple compared to the single-phase system, which will result in a much smaller DC-side filter system. Besides, the power transfer is more uniform.

IV. Experiment Results

The proposed topology is validated in experiments step-by-step from Section II-A to Section II-C, and due to time constraints, only a half-bridge direct matrix converter (HB-DMC) is finished and tested. Consistent with the main idea of FBDMC, HBDMC also has no bulky capacitor-based stiff DC link. So HBDMC-based single-phase single-stage WPT system is also suitable to verify the feasibility of the proposed topology. The schematic and the setup are shown in Fig. 9 and Fig. 10, respectively. The air gap is fixed at 150 mm. The values of the components are shown in Table I.

TABLE I. Parameters of the components.

Parameters	Value	Units
U_{grid}	0-50	V
L_{ac}	25	μH
C_{ac1}&C_{ac2}	10	μF
L_p	292.3	μH
L_s	199.6	μH
M	52	μH
C_p	11.99	nF
C_s	17.57	nF
$V_{pos,limit}$	23.5	V
$V_{neg,limit}$	23.5	V
R_L	44	Ω
f_s	85500	Hz

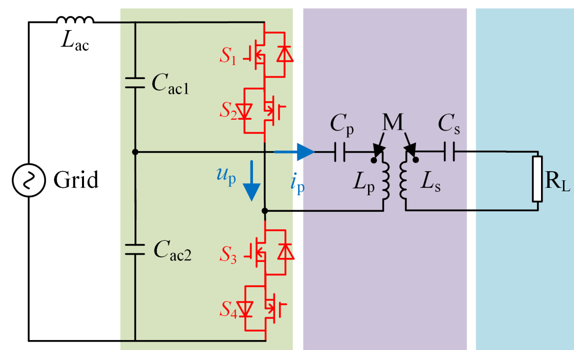

Fig. 9. HBDMC-based single-phase single-stage WPT system.

The input AC voltage comes from a variable transformer shown in Fig. 10. Impedance matching is not considered in the experiments as we do not have a variable transformer with suitable power and current, and the amplitude of the input AC voltage was limited to 50 V to avoid the overcurrent damage to the transformer (maximum 1.5 A).

Due to parasitic inductance, the inductive requirements for soft-switching of the MOSFETs, and the variations in real grid frequency and waveform, determining the grid zero-crossing point for switching the MOSFETs' operating states is challenging. Besides, sometimes, there will be multiple zero-crossing points around zero due to problems like harmonics, noise, and EMI issues, which is a challenge for matrix converters. The Phase-locked loop (PLL) is a good solution, but it needs a high dynamic response. Otherwise, there may be a short circuit problem. So, a simple deadband method shown in Fig. 11 is adopted here to ensure the commutation and freewheeling of the current during the commutation process. The large positive limit and negative limit are used here for a clearer understanding.

It is clear from Fig. 11 that the corresponding MOSFETs operate at 85.5 kHz only when the grid voltage is larger than the positive limit or smaller than the negative limit. And at the period in between, where the cross-zero point exists, a deadband is set. During this time period, S_1 and S_2 are always open, providing a freewheeling path for the inductive current.

The output voltage on the load resistor is shown in Fig. 12. The yellow line is the input grid voltage, and the blue line is the voltage on the load resistor. It is clear from Fig. 12 that

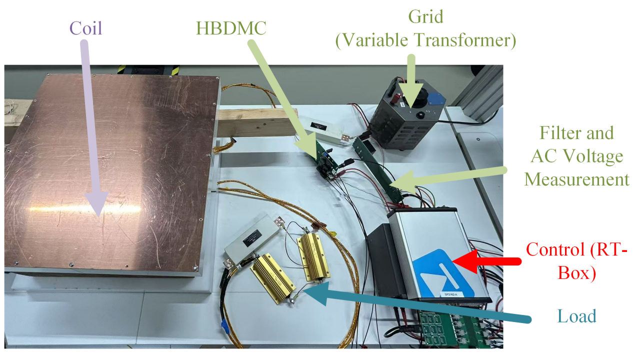

Fig. 10. Experimental platform.

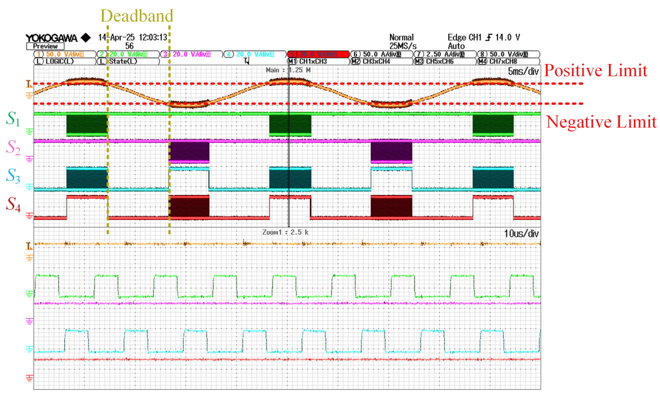

Fig. 11. Gate signal.

50 Hz AC is directly converted to 85.5 kHz AC without a stiff DC-link in the primary stage, which verifies the feasibility of the proposed topology in Section II. A.

The topology in Section II. B and Section II. C are verified by the simulation. The experimental results and the comparison to the existing solutions will be studied and published in future papers.

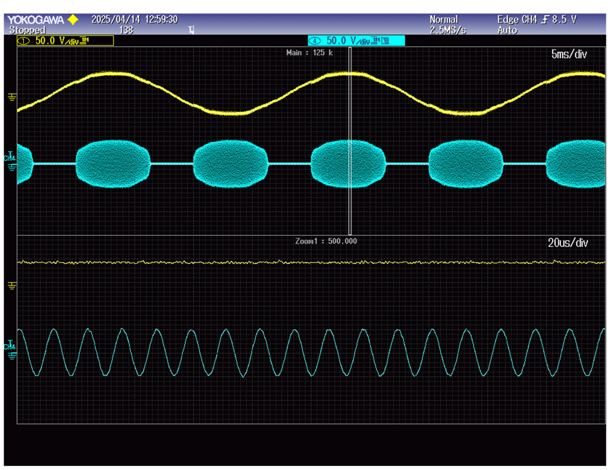

Fig. 12. Output voltage

V. Conclusion

This paper proposes novel matrix converter-based three-phase modular high-power wireless charging systems for HDEVs. The bulky DC-link capacitors are eliminated by the use of the matrix converter. The system structures based on the single-phase coil and three-phase coil are proposed, respectively. The modular cascaded structure is used to achieve the connection to the MVAC grid for the MW-level charging power. The coil array or a single large coil are two options, and converter structures for excitation are also proposed. The feasibility of the proposed topology is validated through simulation and experiment.

References

[1] E. Commission, "Reducing co2 emissions from heavy-duty vehicles." https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles, 2024. Accessed: Nov. 19, 2024.

[2] J. H. Kim, B.-S. Lee, J.-H. Lee, S.-H. Lee, C.-B. Park, S.-M. Jung, S.-G. Lee, K.-P. Yi, and J. Baek, "Development of 1-mw inductive power transfer system for a high-speed train," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 10, pp. 6242–6250, 2015.

[3] G. Guidi, J. A. Suul, F. Jenset, and I. Sorfonn, "Wireless charging for ships: High-power inductive charging for battery electric and plug-in hybrid vessels," *IEEE Electrification Magazine*, vol. 5, no. 3, pp. 22–32, 2017.

[4] W. V. Wang, D. J. Thrimawithana, F. Lin, and G. A. Covic, "An mmc-based ipt system with integrated magnetics and zvs operations," *IEEE Transactions on Power Electronics*, vol. 37, no. 2, pp. 2425–2436, 2021.

[5] X. Liu, F. Gao, Y. Zhang, M. M. Khan, Y. Zhang, T. Wang, and D. J. Rogers, "A multi-inverter high-power wireless power transfer system with wide zvs operation range," *IEEE Transactions on Power Electronics*, vol. 37, no. 12, pp. 14082–14095, 2022.

[6] H. Hu, J. Su, F. Chen, and Y. Sun, "Modularized inductive power transfer systems with inherent impedance decoupling for high-power applications," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 2, pp. 1492–1502, 2023.

[7] X. Li, D. Zhou, S. Jia, X. Liu, and J. Zou, "A wpt system with wide-range voltage gains and soft switching via primary-side hybrid modulation," *IEEE Transactions on Power Electronics*, 2024.

[8] D. B. Yelaverthi, R. Hatch, M. Mansour, H. Wang, and R. Zane, "3-level asymmetric full-bridge soft-switched pwm converter for 3-phase unfolding based battery charger topology," in *2019 IEEE energy conversion congress and exposition (ECCE)*, pp. 2737–2743, IEEE, 2019.

[9] A. Zade, C. R. Teeneti, M. Mansour, S. Gurudiwan, B. Hesterman, H. Wang, and R. Zane, "A 21 kw unfolding-based single-stage ac-dc converter for wireless charging applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2023.

[10] E. Asa, O. C. Onar, V. P. Galigekere, G.-J. Su, and B. Ozpineci, "A novel three-phase oak ridge ac/dc converter for wireless ev charger applications," in *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 437–443, IEEE, 2021.

[11] P. S. Huynh, D. Ronanki, D. Vincent, and S. S. Williamson, "Direct ac–ac active-clamped half-bridge converter for inductive charging applications," *IEEE Transactions on Power Electronics*, vol. 36, no. 2, pp. 1356–1365, 2020.

[12] J. Pries, V. P. N. Galigekere, O. C. Onar, and G.-J. Su, "A 50-kw three-phase wireless power transfer system using bipolar windings and series resonant networks for rotating magnetic fields," *IEEE Transactions on Power Electronics*, vol. 35, no. 5, pp. 4500–4517, 2019.

[13] F. T. Jauch, *Medium voltage AC-DC converter systems for ultra-fast charging stations for electric vehicles*. PhD thesis, ETH Zurich, 2016.

[14] J. Saha, *Analysis, Optimization and Control of Grid-Interfaced Matrix-Based Isolated AC-DC Converters*. Springer Nature, 2022.

[15] O. C. Onar, G.-J. Su, M. Mohammad, V. P. Galigekere, L. Seiber, C. White, J. Wilkins, and R. Wiles, "A 100-kw wireless power transfer system development using polyphase electromagnetic couplers," in *2022 IEEE Transportation Electrification Conference & Expo (ITEC)*, pp. 273–278, IEEE, 2022.