High and Very High Frequency Power Supplies for Industrial Applications

IN RECENT years, high frequency has become a developing trend for power converters with the advantages of possible cost saving and high power density. However, the increase of switching frequency leads to potential loss increase from fast switching, magnetic components, and drive losses in the same time, which will directly reduce the system efficiency. Though the emergence of the third-generation semiconductor devices with low conduction resistance and low parasitic capacitance can reduce system loss to some extent, they have higher requirements for drive circuits such as narrower voltage range and are more sensitive to parasitic parameters. All these are the new challenges to high frequency systems. Therefore, advanced topologies and control strategies are suitable for high frequency as well as high-frequency magnetic design are becoming the critical topics. This "Special Section on High & Very High Frequency Power Supplies for Industrial Applications" in the IEEE Transactions on Industrial Electronics provides an insight into some of the newly emerging challenges and potential solutions to overcome those aforementioned issues. For this Special Section, 63 manuscripts were submitted for the peer review. With reviewers' hard work and considerations, 23 were finally accepted for publication in this Special Section. All the analyses and techniques proposed by the accepted articles are verified by experimental results. They cover the hot topics of high-frequency converters and represent a comprehensive reference for the researchers who are interested in this field. The complete list of articles is presented in the Appendix. All the 23 articles can be subdivided into four categories.

The first category focuses on the topologies of converters and drive circuits, which are favorable to high-frequency applications. The first article [item 1) in the Appendix] presents a multiresonant gate drive circuit, which can be applied to high/very high frequency (HF/VHF) applications. Compared with other VHF self-oscillating multiresonant gate drivers, the design procedure of the proposed gate driver is greatly simplified. This gate driver reduces the long start-up time and better utilizes the fast-transient capability of VHF converters. It produces trapezoidal quasi-square wave voltage and can drive a high-voltage SiC MOSFET at a frequency of 30 MHz. The second article [item 2) in the Appendix] proposes a two-phase bidirectional converter with high voltage-gain, and reduces switch stresses significantly. The operating principle of the proposed converter is similar to that of the conventional converter, so that the control techniques employed in the conventional converters can be used to lower design complexity. The third article [item 3) in the Appendix] proposes a 1-MHz half-bridge high-gain multi-CLLC bidirectional resonant converter. Gallium Nitride (GaN) FETs and integrated planar magnetics are adopted. Excellent gain characteristic and high power density are achieved, and it is suitable for distributed energy storage systems well. Besides the explanation of operation principles, topology features and parameter design, the improved winding method for planar magnetic integration is also elaborated in detail. The fourth article [item 4) in the Appendix] proposes a two-stage silicon carbide (SiC) bidirectional *LLC* charger architecture. In order to achieve unity power factor, an interleaved bridgeless totem pole PFC is used as the first stage, and the second stage is a 300-kHz *LLC* with the advantage of wide ZVS range. High efficiency and high power density are achieved. The charging efficiency is above 96% through the battery voltage from 240 to 420 V, and the peak discharging efficiency under 6.6 kW is 96%, both higher than the state-of-the-art efficiency. The power density is 3.42 kW/L with 3 kW/kg and increases 55.6% over the reference design. The fifth article [item 5) in the Appendix] proposes a GaN HEMTs half-bridge driver for high switching frequency automotive applications. The safety of high-side GaN HEMT is guaranteed by bandgap reference comparator clamping, which can adaptively clamp the bootstrap rail voltage at an appropriate level with acceptable voltage ripples. At the same time, a dual-level shifter scheme is applied in both the high-side and low-side driving paths to drive the GaN HEMTs with low propagation delay and high *dv/dt* immunity. The proposed driver can support a buck converter with GaN HEMT switches operating from 2 to 10 MHz and achieving the maximum efficiency of 91.58%. The sixth article [item 6) in the Appendix] presents a novel modified transformer-based SEPIC converter with GaN HEMTs and planar magnetic components. With the integration of some passive components, the proposed converter obtains such as high-voltage gain, low-voltage stress, and soft switching compared with conventional SEPIC converters. In the process of magnetic component optimization, parasitic capacitance as well as leakage inductance is considered and partially interleaved structure is adopted accordingly, and an integrated scheme is applied to improve the power density.

The second category concerns the control method, which aims at improving the performance of converters at high frequency. The first article [item 7) in the Appendix] presents a monolithic voltage-mode dc–dc buck converter with advanced burst mode (ABM) and pulsewidth modulation (PWM) to achieve high frequency and high efficiency over a wide load range. The proposed load current detector and counter-based scheme can be widely used in various wide-load high-frequency high-efficiency

Digital Object Identifier 10.1109/TIE.2019.2929900

application. The switching frequency is 3 MHz and this converter provides high efficiency over an ultrawide load range from 0.001 to 5 A. The second article [item 8) in the Appendix] proposes a closed-loop modulation scheme to compensate for the duty cycle distortion of PWM voltage based on one-cycle control or charge control. Compared to the traditional feedforward-type of compensation, the proposed scheme removes online calculation and instantaneous inductor current sampling, and it is suitable for variety of topologies and modulations. The proposed scheme was demonstrated by experiment and the output current total harmonic distortion (THD) is effectively reduced. The third article [item 9) in the Appendix] presents a 13.56-MHz Class-D full-bridge zero voltage switching (ZVS) inverter, applicable to wireless power transmission (WPT) systems with dynamic dead-time control (DDTC). DDTC is adopted to maintain soft switching of the inverter over the full range of output power and to regulate the input dc bus voltage at the same time. Experimental results show that the proposed control method reduces the switch-node voltage overshoot, increases the inverter efficiency, and reduces the steady-state temperature of the inverter during output power regulation. The fourth article [item 10) in the Appendix] presents a current sharing method for an interleaved high-frequency *LLC* converter with partial energy processing. The proposed method is simple to implement and easy to extend to multiple phases by transforming the current sharing of the resonant converter into PWM control of a dc–dc converter. Moreover, the frequency of the auxiliary converter is independent of the main *LLC* converter, so the switching frequency and duty cycle of the main *LLC* converter is fixed that makes the converter feasible for high-frequency applications. The fifth article [item 11) in the Appendix] deals with transient current imbalance of parallel connected SiC MOSFETs. In-depth mathematical models are derived to reveal the electrothermal mechanisms of the imbalance current in terms of device parameters, circuit parasitics, and junction temperatures. Moreover, an effective approach by using differential mode chokes (DMC) is proposed to suppress the imbalance current among paralleled SiC MOSFETs. The proposed method is proved to be effective to guarantee consistent and synchronous ON–OFF trajectories of paralleled SiC MOSFETs. The sixth article [item 12) in the Appendix] focuses on the implementation of a multiphase dc–dc power amplifier (PA) with high bandwidth and high power rate. A sensorless control method based on the injection of random sequence in the reference signal is proposed to solve the current imbalance problem induced by quasi-naturally sampled phase-shifted carrier modulation. Effectiveness of the proposed control method is verified by experimental results. The seventh article [item 13) in the Appendix] overcomes the drawback of ripple modulations (RM). In this article, it is demonstrated that the RM can be used to reproduce multicarrier modulation schemes by considering the envelope and the instantaneous phase of the communication signal. The control system of the power stage is described in detail in this article, explaining how to modulate both the width and the phase of the gate signals. The eighth article [item 14) in the Appendix] proposes a ZVS self-regulating control method for boundary conduction mode converters operating in the megahertz switching frequency range. The proposed model is verified and proves the feasibility of the presented control method to achieve ZVS under fast perturbations of the converter operating conditions. The improvement of using the proposed control method is proved by experimental efficiency measurements, especially under light-load conditions.

The articles in the third category mainly deal with magnetic component design. The characteristics of magnetic components will directly affect the performance of converters under high-frequency applications, therefore, the design of magnetic components is of great significance. The first article [item 15) in the Appendix] proposes a 20-MHz low-profile dc–dc converter with magnetic-free characteristics based on air-core planar inductors. Switching loss is significantly reduced due to soft switching of the switch and diode. The parasitic capacitances are taken as part of corresponding resonant capacitors. In the aspect of magnetic optimization, a high-performance air-core inductor with a variable width and an optimal connecting angle is analyzed, which reduces system the vertical dimension. The optimal parameters design method of achieving minimum winding resistance is derived in detail in this article. The second article [item 16) in the Appendix] proposes a sequential offline–online–offline (SO3) measurement method to obtain all the real transformer parasitic parameters in a low cost and simple implementation way. This method measures all the transformer parasitic parameters online and combines the advantages of both traditional offline and online measurement methods while removing their corresponding shortcomings. The proposed method is validated by the experiments. The third article [item 17) in the Appendix] proposes a quarter-turn planar transformer structure and implemented in an *LLC* resonant converter for server power supplies. Compared with traditional structures, a fractional-turn transformer structure can reduce core volume and winding loss. This optimized structure can also enable the fractional-turn ratio to achieve normal coupling of primary and secondary sides without generating flux imbalance. The effects of different fractional-turn windings on efficiency are examined in this article, and the structure and operation of the planar transformer are verified by Maxwell simulation results. The fourth article [item 18) in the Appendix] studies the effect of an outer fractional winding on the equivalent parallel capacitance (EPC) of a differential-mode (DM) inductor. A winding scheme that can reduce EPC and increase inductance is presented, achieving both high-frequency filtering performance and high power density. A comprehensive layer capacitance model based on energy equivalence principle is established, enabling impact evaluation of winding elements and schemes. Experimental results have demonstrated the accuracy of this EPC model and excellent performance of the proposed winding scheme. The fifth article [item 19) in the Appendix] presents a multiphysics optimal design framework for air-core planar transformers in high-frequency *LLC* resonant converters. The interaction among multiple physical models applies progressive bisection method and Bayesian optimization algorithm are all considered in the optimal design process. Accurate air-core transformer model together with loss model are built to calculate inductance and efficiency, respectively. Compared with traditional methods, this optimal design method does much fewer simulations with a similar optimal efficiency.

The articles of the fourth category propose optimization of existing technologies in high-frequency converters. The first article [item 20) in the Appendix] presents a complete and accurate switching analytical model of low-voltage eGaN HEMTs, which considers the effects of low-parasitic inductances, nonlinear junction capacitances, and nonlinear transconductances. The switching processes are described in detail and the resulting equations are solved by mathematical software to predict the switching waveforms during the switching periods. Based on the proposed model, an accurate loss calculation method is proposed including the reverse conduction loss. The second article [item 21) in the Appendix] proposes a design methodology for a switched-tank converter (STC). The power loss breakdown analysis is conducted to point out the directions and paths for component optimization. In the converter, the resonant capacitor is carefully designed to meet both current stress and ripple requirements. Besides, the resonant inductors and PCB layout are also optimized. In addition to the hardware-level optimization, an improved control method is also proposed, in which the conduction time of switching devices is tuned to mitigate the circulating power. The third article [item 22) in the Appendix] explores the design and digital control method for a rail grade dc–dc module. In order to satisfy the target application, the devices and the topologies are evaluated. The voltage regulation is analyzed for the buck converter when the inductors are negatively coupled, and then the ZVS extension is explored. Due to the limitation of the digital controller, a tradeoff is made between the dynamic response and the footprint. The compromise solution is to use a small and slow microcontroller for high-frequency control and various demands. The fourth article [item 23) in the Appendix] deals with the megahertz series resonant converter (SRC) dc transformer (DCX). As for 380 V-12 V DCX with such high switching frequency, GaN devices are necessary. By analyzing and modeling the conduction losses caused by the parasitic capacitance and turn-ON resistance of switches, this article points out that the series-connected low-voltage devices can reduce primary conduction losses at megahertz frequency. Therefore, using low-voltage Si MOSFETs is able to improve the efficiency at megahertz switching frequency. An input-series output-parallel prototype with multiple SRC DCX cells is built up to verify the analysis, where 60 V MOSFETs are adopted in each circuit cell.

The guest editors sincerely wish that the timely covered research topics in this special section can pave the way for new ideas and solutions in order to overcome/mitigate the challenges of high and very high frequency converters.

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ACKNOWLEDGMENT

The guest editors would like to thank the authors for sharing their contributions and the reviewers for their dedicated efforts in providing valuable comments and suggestions on each article. The Guest Editors would also like to thank Prof. E. Levi and Prof. L. Franquelo, Editor-in-Chief and Past Editor-in-Chief, respectively, of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS for their great support and Miss J. Samantha and Mr. R. Raul, Journal Administrators of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS for their highly supportive assistance throughout the process.

APPENDIX
RELATED WORK

1) L. Gu, Z. Tong, W. Liang, and J. Rivas-Davila, “A multi-resonant gate driver for high-frequency resonant converters,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1405–1414, Feb. 2020.
2) N. A. Dung, H.-J. Chiu, Y.-C. Liu, and P. J. Huang, “Analysis and implementation of a high voltage-gain 1 MHz bidirectional DC-DC converter,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1415–1424, Feb. 2020.
3) Y.-F. Wang, B. Chen, Y. Hou, Z. Meng, and Y. Yang, “Analysis and design of a 1 MHz bi-directional multi-CLLC resonant DC-DC converter with GaN devices,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1425–1434, Feb. 2020.
4) H. Li, Z. Zhang, S. Wang, J. Tang, X. Ren, and Q. Chen, “A 300-kHz 6.6-kW SiC bidirectional LLC onboard charger,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1435–1445, Feb. 2020.
5) R. Yan, J. Xi, and L. He, “A 2–10 MHz GaN HEMTs half-bridge driver with bandgap reference comparator clamping and dual level shifters for automotive applications,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1446–1454, Feb. 2020.
6) S. Gao, Y. Wang, Y. Guan, and D. Xu, “A high step up SEPIC-based converter based on partly interleaved transformer,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1455–1465, Feb. 2020.
7) B. Yuan, M.-X. Liu, W. T. Ng, and X.-Q. Lai, “A hybrid buck converter with constant mode changing point and smooth mode transition for high-frequency applications,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1466–1474, Feb. 2020.
8) R. Ren, F. Zhang, B. Liu, F. Wang, Z. Chen, and J. Wu, “A closed-loop modulation scheme for duty cycle compensation of PWM voltage distortion at high switching frequency inverter,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1475–1486, Feb. 2020.
9) H. Tebianian, Y. Salami, B. Jeyasurya, and J. E. Quaicoe, “A 13.56 MHz full-bridge class-D ZVS inverter with dynamic dead time control for wireless power transfer systems,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1487–1497, Feb. 2020.

10) H. Chen, X. Wu, and S. Shao, "A current-sharing method for interleaved high frequency LLC converter with partial energy processing," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1498–1507, Feb. 2020.
11) Z. Zeng, X. Zhang, and Z. Zhang, "Imbalance current analysis and its suppression methodology for parallel SiC MOSFETs with aid of a differential mode choke," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1508–1519, Feb. 2020.
12) C. Wang, K. Wang, Z. Zheng, K. Sun, and Y. Li, "Modulation induced current imbalance and its sensorless control of a GaN-based four-phase DC-DC power amplifier," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1520–1531, Feb. 2020.
13) J. R. Mendez, D. G. Lamar, D. G. Aller, P. F. Miaja, and J. Sebastian, "Reproducing multi-carrier modulation schemes for visible light communication with the ripple modulation technique," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1532–1543, Feb. 2020.
14) J. C. Hernandez, M. C. Mira, L. P. Petersen, M. A. E. Andersen, and N. H. Petersen, "Zero voltage switching control method for MHz boundary conduction mode converters," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1544–1554, Feb. 2020.
15) Y. Guan, Y. Wang, W. Wang, and D. Xu, "A 20 MHz low profile dc–dc converter with magnetic-free characteristics," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1555–1567, Feb. 2020.
16) B. Zhao, X. Zhang, and Z. Zhang, "Sequential offline-online-offline measurement approach for high frequency LCLC resonant converters in the TWTA applications," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1568–1579, Feb. 2020.
17) Y. Liu *et al.*, "Quarter-turn transformer design and optimization for high power density 1-MHz LLC resonant converter," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1580–1591, Feb. 2020.
18) B. Liu, R. Ren, F. Wang, D. Costinett, and Z. Zhang, "Winding scheme with fractional layer for differential-mode toroidal inductor," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1592–1604, Feb. 2020.
19) G. K. Y. Ho, Y. Fang, and B. M. H. Pong, "A multiphysics design and optimization method for air-core planar transformers in high-frequency LLC resonant converters," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1605–1614, Feb. 2020.
20) J. Chen, Q. Luo, J. Huang, Q. He, and X. Du, "A complete switching analytical model of low-voltage eGaN HEMTs and its application in loss analysis," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1615–1625, Feb. 2020.
21) X. Lyu, Y. Li, N. Ren, C. Nan, D. Cao, and S. Jiang, "Optimization of high-density and high-efficiency switched-tank converter for data center applications," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1626–1637, Feb. 2020.
22) M. Fu, C. Fei, Y. Yang, Q. Li, and F. C. Lee, "A GaN-Based DC/DC module for railway applications: Design consideration and high-frequency digital control," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1638–1647, Feb. 2020.
23) X. Wu and H. Shi, "High efficiency high density 1 MHz 380 V-12 V DCX with low FoM devices," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1648–1656, Feb. 2020.

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