Topologies and Control Strategies of Very High Frequency Converters: A Survey

Dianguo Xu, Yueshi Guan, Yijie Wang, and Wei Wang

Abstract—**with the fast development of power electronics, very high frequency (VHF) power converters (30–300 MHz) gradually become research focus, which can greatly reduce the value, volume of passive components and help to improve the system power density. However, at such high operating frequency, many challenges have been proposed, such as switching characteristics, topologies characteristics and control methods. This paper starts from the development background of VHF power converters, and an overview of VHF development is described. Different topologies adopted in VHF condition are introduced and compared. At the same time, the resonant driving strategies and control methods for very high frequency converters are discussed and analyzed, which can provide guidance for further research of VHF converters.**

Index Terms—**Very high frequency power converters, topologies, resonant driving, control strategies.**

I. Introduction

WITH the development of power electronics technique, very high frequency (VHF, 30~300 MHz) power converters have gradually become a hot field of research directions. By increasing the working frequency of the system, the VHF power converters can effectively reduce the volume of the passive components, and improve the power density. Meanwhile, the transmitted and stored energy of components during each operating period can be significantly decreased due to the increase of the frequency. Thus the speed of the transient response can be accelerated. The decrease of the value and volume of passive components is beneficial to the integration and manufacture of the system.

The topologies of VHF converters are proposed through a combination of RF power amplifier technology and power electronic technology [1]-[8]. The power amplifier can transform DC components into high frequency AC components, which is similar to the inverter stage of Switching Mode Power Supplies (SMPS). Nowadays, many researchers have focused on the research of VHF power converters based on the existing topologies. Combining the inverters with the corresponding rectifiers, different topologies of the VHF power converter have been proposed [9]-[64], which own excellent characteristics, such as small volume, high power density and fast response speed. Although the VHF system has such merits, the high switching frequency puts forward strict requirements on the selection of semiconductor devices [21]-[28], the utilization of parasitic parameters [29]-[36], the design of the circuit [37]-[42] and the design of passive components [43]-[49].

In the VHF power converters, with the increasement of system switching frequency, switching losses also increase rapidly. Thus, the losses of the switch and the driving circuit must be reduced to ensure a high system efficiency. In the existing VHF power converters, scholars mainly adopt zero voltage switching (ZVS) technology to reduce the power losses caused by the overlap of voltage and current at the instant of switching. Besides, to reduce the driving circuit losses, the resonant driving circuit is also proposed which can utilize the energy stored in the switch input capacitor.

Apart from the topologies and the driving methods, another important aspect of VHF converters is the control method. For traditional converters, pulse width modulation (PWM) or pulse frequency modulation (PFM) is used to adjust the drive signal of the system in close-loop control. However, both methods are not available to be adopted in VHF situations. Because in such a high frequency condition, it is difficult to sample and adjust the duty cycle or the operating frequency of driving signals. At the same time, the change of period or duty cycle will affect the operating modes of switches. Thus some suitable control methods have been researched to regulate the output voltage and keep the switch operating in soft-switching modes when the input voltage or load change.

In this paper, introduction and detailed analysis of advanced technologies in VHF power converters are presented. Based on existing VHF power converter topologies, the design principle of VHF topology is introduced. The characteristics of different inverter stages, rectifier stages and matching networks are analyzed in Section II. The driving methods of the VHF system are explored in Section III. An overall analysis and comparison of the self-resonant driving circuit and multi-resonant driving circuit are given. The control strategies of VHF power converter are discussed in Section IV. Section V elaborates the opportunities and chal-

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lenges in the field of VHF power converters.

II. Topologies of VHF Power Converters

A. Overview of Topologies

As shown in Fig. 1, the circuit topology of VHF DC-DC converter is usually composed of three parts: inverter stage, matching network and rectifier stage. The inverter stage transforms DC voltage into AC voltage. The rectifier stage regulates AC voltage into constant DC output voltage. Resonant and soft-switching technologies are adopted in the inverter and rectifier in order to reduce the system switching losses. Between inverter and rectifier stage, the matching network is used to adjust the equivalent load of the rectifier, so that the converter can achieve the required output power.

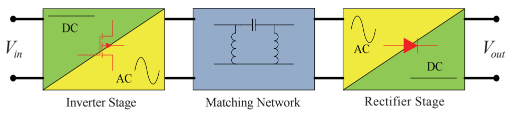

Fig. 1. The diagram of VHF power converters.

In the VHF conditions, the switching losses of the switch and diode increase rapidly. To ensure the efficiency of the system, the switch and diode should achieve soft-switching to decrease losses. In the present researches, most of the VHF circuits are based on the single switch structure to avoid floating drive. Combining with different structures of VHF power amplifiers, Class E topology [50], [51] and Class Φ_2 topology [52]-[55] are used to constitute the inverter and rectifier stage. The following sections will introduce these three parts in detail.

B. The Analysis of Inverter Stage

Fig. 2 shows the diagram of Class E resonant inverter circuit. The inductor L_F, capacitor C_F and the corresponding resonant tank constitute Class E inverter network. It should be noted that C_F is the sum of the output parasitic capacitor of the switch and the parallel discrete capacitor. When the switch is off, inductor L_F and capacitor C_F resonate. To reduce the switching losses under VHF conditions, the switch should operate at ZVS state. Through comprehensive design of the resonant frequency, operating frequency and duty cycle, the voltage across the switch can exactly be zero when the drive signal comes, therefore the soft switching characteristic is achieved. In ideal situations, the parasitic capacitor

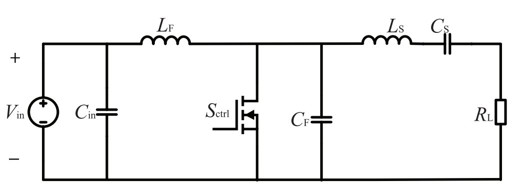

Fig. 2. Circuit of Class E type resonant inverter stage.

of the switch can exactly act as the resonant capacitor in the inverter stage, so there is no need to add extra capacitor. However, the parasitic output capacitance of the switch varies with its type, and the value of the parasitic capacitor changes nonlinearly while the drain-source voltage changes. So a parallel discrete capacitor is generally necessary.

Although the topology of the Class E inverter stage is simple, and the switch can work in soft-switching state, the major defect is that the switch's drain-source voltage stress is very high. When the duty ratio of the switch is 50%, the drain-source voltage stress is about 3.6 times of the input voltage, which means that the switch with high rated voltage has to be adopted. Also the cost of this system increases. With high voltage stress, the application area of this topology is greatly restricted.

According to these problems, scholars expect the introduction of higher harmonics to reduce the peak voltage across the switch. Fig. 3 shows the peak voltage across the switch is effectively reduced by superimposing the fundamental and third harmonic voltages. Based on above method, the Class Φ_2 inverter, as shown in Fig. 4, is proposed and is widely used in VHF power converters [52]-[57]. The topology can meet the soft switch requirement and effectively reduce the voltage stress across the switch.

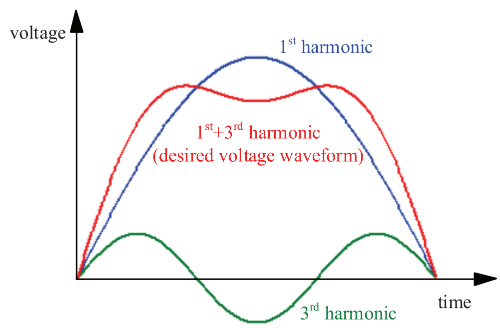

Fig. 3. The desired voltage waveform with the addition of third harmonic.

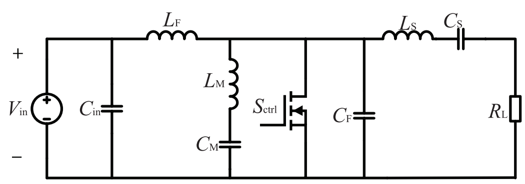

Fig. 4. The circuit of Class Φ_2 type resonant inverter stage.

The Class Φ_2 inverter is derived from Class E circuit. The input resonant network consists of L_F, C_F, L_M and C_M. In parameter design process, to make the switch drain-source waveform presenting a low impedance at the second harmonic frequency, the resonant frequency of L_M and C_M is set to be close to twice of the switching frequency. Then the resonant tank should be adjust to exhibit high impedance at the fundamental and three harmonic frequency with proper L_F and C_F. Since the superposition of one and third harmonic, the voltage waveform across switch is in approximately trapezoidal form. The voltage stress of switch can be reduced to twice of the input voltage, thus the topology can be adopted in wide application fields. Meanwhile the switch is still able to maintain an excellent ZVS characteristic. However compared with Class E resonant rectifier topology, the introduction of L_M and C_M increases the size and cost of the system, also improves the complexity of circuit design. Therefore, the inverter topologies of VHF power converters should be selected considering different system requirements.

C. The Analysis of Rectifier Stage

In VHF DC-DC power converters, the inverter stage converts the DC signal into a high frequency AC component, and the rectifier converts the AC signal into a DC output signal with the desired amplitude. Meanwhile in VHF power converter the rectifier circuit also decides the impedance across the switch. For the design of the resonant rectifier circuit, the ideal working state is that the input fundamental voltage and current are in the same phase. Thus it can reduce the circulating current and improve the rectifier efficiency. In this condition, the rectifier can be replaced with a resistor. In very high frequency conditions, the ZCS characteristic of the diode can also be realized by the resonance of the inductor and capacitor, which can reduce the switching losses of the diode.

Fig. 5 and Fig. 6 show two commonly used resonant rectifier circuits respectively, they can be deduced from the Class E inverter according to duality characteristics [58], [59]. Each resonant rectifier circuit consists of a resonant inductor L_R, a resonant capacitance C_R and a diode D_1, C_R includes the parasitic capacitance of the diode. When the diode is turned on, the diode anode voltage is clamped by the output voltage. In contrast, when the diode is turned off, the inductor and capacitor begin to resonate in order to achieve the ZCS characteristic of diode. According to the different types of input source, the circuit shown in Fig. 5 is called the voltage-driven rectifier circuit and the circuit shown in Fig. 6 is called the current-driven rectifier. They all provide a DC path from the input side to the output side. The advantage is that the DC component can be used to deliver part of the required energy, reduce system losses and improve efficiency. However the disadvantage is that the output voltage must be higher than the input voltage, it means the converter can only be used in step-up condition. A DC blocking capacitor is necessary when to achieve step-down conversion.

Although the diode operating in ZCS state can effectively reduce the switching losses. In the resonant rectifier, the

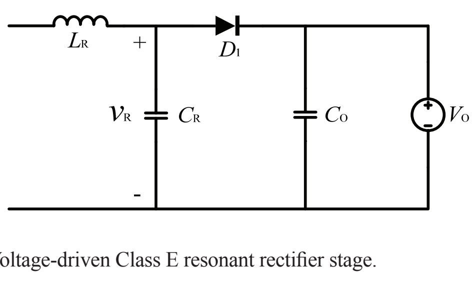

Fig. 5. Voltage-driven Class E resonant rectifier stage.

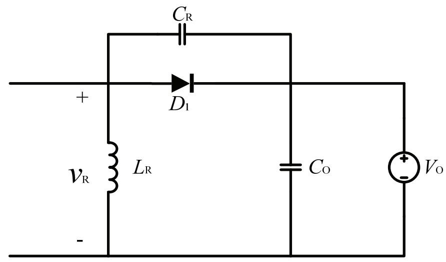

Fig. 6. Current-driven Class E resonant rectifier stage.

diode conduction voltage drop will also cause great losses. Especially in the low output voltage conditions, the system efficiency will be greatly compromised. To solve above problems, a new method based on synchronous rectification is put forward, in which the diode is replaced by a switch. The switch is driven by proper signal to achieve the required rectifier characteristics. With low conduction voltage drop, the method can effectively reduce the conduction losses. However an extra driving circuit must be added which increases the driving losses. Besides, the driving signal of synchronous rectifier switch and inverter switch need to meet a specific time relationship which is very difficult in VHF situation. Therefore, the proper rectifier stage of the VHF power converter should be decided according to the specific requirements of the system.

D.The Analysis of Matching Network

As the diagram of VHF DC-DC power converter shown, a matching network is usually added between the inverter and the rectifier, which can play the role of impedance conversion. As mentioned above, the input voltage and current of rectifier are usually designed to be in the same phase. Then the rectifier circuit can be represented by an equivalent impedance, which can be transformed by the matching network to meet the requirement of the impedance value under the required output power. There are two kinds of matching networks: isolated type [11], [24], [60] and non-isolated type [56]. The isolated type matching network adopts the transformer as the impedance conversion element which can realize the electrical isolation between the system input and output side. In a wide frequency variation range, the transformer owns a constant impedance conversion characteristic. However, in VHF condition, the transformer will introduce more non-ideal parameters, such as parasitic capacitance, leakage inductance, magnetizing inductance. Based on optimization design, the transformer leakage inductance and magnetizing inductance can be effectively absorbed and utilized. However, the parasitic capacitance cannot be eliminated because of the facing area between adjacent windings, which affects the performance and operating mode of the system. So in the applications without the requirement of electrical isolation, the non-isolated matching networks are widely adopted.

Fig. 7 shows the topologies of some commonly used non-isolated matching networks. From the point of frequency domain characteristics, these matching networks can be divided into low-pass matching network and high-pass matching network. In VHF power converters, the high-pass matching network is more suitable because it can transfer the energy of the fundamental waveform and other high harmonics to the load. It means the energy of the inverter can be fully utilized compared with low-pass ones. Fig. 7(b) is the simplest structure of high-pass matching network, which is called L type. It contains only one inductor L_S and a capacitor C_S. Meanwhile the capacitor C_S is connected in series with the load which can play a role of DC blocking capacitor. With this matching network, the converter can achieve step-up and down conversion. At the same time, combining the L type matching network with the current-driven rectifier, the inductor L_S of matching network and the inductor L_R of rectifier can be merged to one inductor, which effectively reduces the component number and the corresponding losses. Fig. 7(d) and Fig. 7(f) show the π type and T type matching network. With optimal design, these two circuits can ensure constant impedance angle conversion under load variation conditions, which is conductive to ensure the soft switching characteristics of the switch at different output power. The non-isolated matching network can only achieve the required impedance transferring ratio at a certain frequency. When the operating frequency of the matching network changes, the impedance transferring ratio will change, which affects the switch operating mode. Therefore considering the advantages and disadvantages of different matching networks, the topology of matching network should be selected according to the system specific requirement.

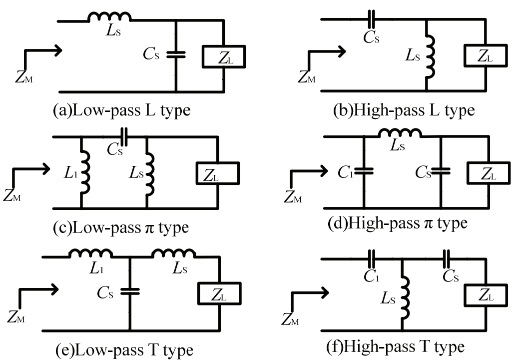

Fig. 7. The diagrams of different non-isolated matching networks.

E. Typical Topologies of VHF Converters

Based on the different types of the inverter stage, the rectifier stage and the matching network, many VHF power converters with different characteristics are gradually proposed. Fig. 8 shows the circuit of the SEPIC VHF power converter proposed in article [56], the inverter stage is Class E topology, the rectifier stage is current-driven resonant topology, and the matching network is L type high-pass network. As mentioned above, the inductance L_R is the equivalent inductance of the matching network and the rectifier stage. Here C_T also plays the role of DC blocking capacitor, thus this converter owns both step-up or down voltage transferring ability.

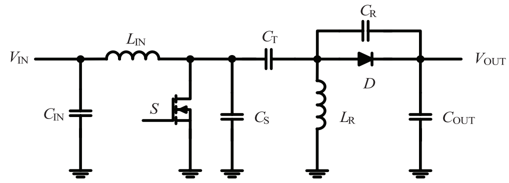

Fig. 8. Schematic diagram of a SEPIC VHF converter proposed in [56].

Fig. 9 shows the circuit diagram of the Boost VHF power converter proposed in article [54], [57]. The inverter stage is ClassΦ_2 topology; the rectifier stage is voltage-driven resonant topology. In this prototype, the equivalent impedance of the rectifier meets the inverter requirement. Thus the matching network is not added in this circuit. As can be noticed from the schematic, because of the absence of the DC blocking capacitor, this converter can only provide stet-up power conversion. Fig. 10 shows the circuit diagram of the isolated VHF power converter proposed in [11]. The inverter stage is still ClassΦ_2 topology. Here the rectifier stage adopts synchronous rectifier resonant topology, which can reduce the conduction losses. Meanwhile, a transformer is adopted here to be the matching network, so the electrical isolation between the input side and output side is achieved. The leakage inductances in primary side and secondary side are both absorbed by the resonant inductor of rectifier stage, which can reduce the magnetic components in the high frequency converter. Meanwhile, the effect of parasitic inductances can be reduced by the optimal design.

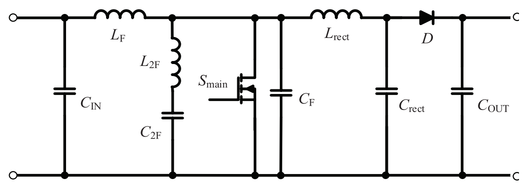

Fig. 9. Schematic diagram of a Class Φ_2 based Boost VHF converter.

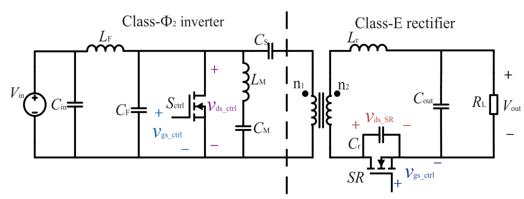

Fig. 10. Isolated Class Φ_2 resonant converter.

F. Novel Topologies of VHF Converters

Based on the aforementioned typical topologies, some scholars begin to propose some new topologies, such as the interleaved VHF converters, the bidirectional VHF converters and the half-bridge VHF converters.

Similar to the application of the interleaved technology in low frequency condition, the input current ripple of VHF power converter can be reduced when two complementary signals are applied to drive the two interleaved circuit modules. The schematic of the interleaved VHF converter based on Class E topology is shown in Fig. 11. In article [61], this prototype is used as the LED driver operating at 120 MHz. The output power is 3-9 W, and the efficiency is 80%~89%. The application of the interleaved technology can effectively reduce the input and output ripple, so that this converter can be applied in high power fields. However, the tiny deviations of the two circuit modules may result in the offset of the system's optimal operating point. In such high frequency condition, the differences of two modules will greatly affect the system nominal operating mode.

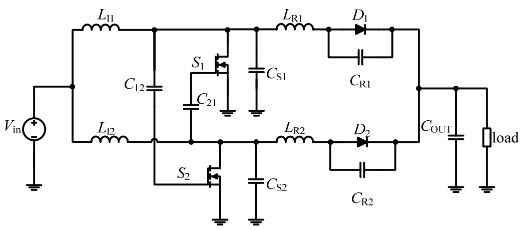

Fig. 11. Schematic view of the interleaved class E converter from [61].

As seen in Fig. 12, the diode in the rectifier stage is replaced by a switch, then a bidirectional VHF converter is obtained [62]. This converter is composed of Class E inverter and Class E synchronous rectifier. When the circuit operates in forward transferring mode, S_1 acts as the power switch, S_2 acts as the synchronous rectifier diode. When the circuit runs in reverse transferring mode, the roles of the switches are opposite to the former. Besides having the ability to conduct bi-directionally, this converter can also effectively reduce the conduction losses of the rectifier stage by introducing the synchronous rectifier switch. However, as mentioned above, this topology requires an extra driving circuit, and the two driving signals must satisfy a specific logical relationship at high frequency, which is a great challenge for the design of driving circuits. As mentioned in the former section, the

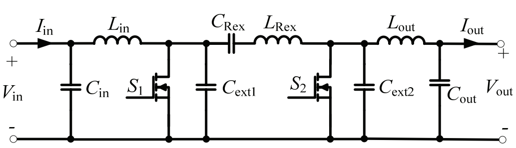

Fig. 12. Schematic diagram of a VHF converter with class-E inverter and synchronous class-E rectifier.

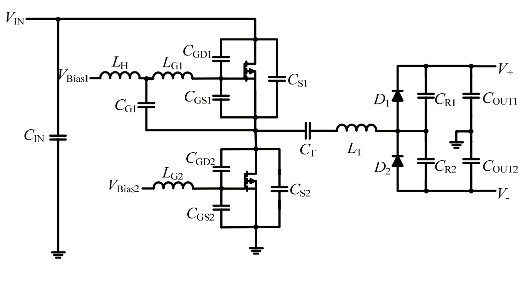

Fig. 13. Schematic diagram of a VHF converter with class-DE inverter and rectifier.

scholars try to avoiding the applications of half-bridge topology in VHF converters. The floating driving method of the top switch is difficult to solve in half-bridge structure. But a natural advantage of this topology is that the voltage stress across the switch is very low, for the switch is directly connected with the input voltage, the stress is equal to input voltage. Based on Class DE half-bridge inverter topology [64] and Class DE rectifier topology, a VHF converter is presented in [63], as shown in Fig. 13. Self-resonant driving method is proposed in this paper. The half bridge circuit is very suitable for the applications where high input voltage or output voltage is required. In addition, compared with the other topologies mentioned above, the power circuit of the converter presented in Fig. 13 only contains one inductor, which is beneficial to improving the power density of the system.

III. Driving Methods of VHF Power Converters

In VHF power converters, with the increasement of operating frequency, the losses of the driving circuit also increase rapidly. In the low frequency power converters, the most commonly used driving circuit is square wave driving circuit in which the switch driving signals are square waveforms. In this case, the driving losses are caused by the charging and discharging energy dissipation of the parasitic capacitance C_{gs}. The losses of the driving method can be calculated by $C_{gs}V_g^2f$, where V_g is the amplitude of driving voltage and f is the driving frequency. As can be seen, the power losses are proportional to the operating frequency, the high driving losses in VHF converter greatly restricts the improvement of high frequency system efficiency.

A. Analysis of VHF Resonant Driving Circuit

In order to solve the above problems, the concept of resonant driving circuit has been proposed in recent years [65]-[70]. Compared with the square wave driving circuit, the most obvious difference of the resonant driving circuit is that the driving voltage is in sinusoidal or approximately sinusoidal form, which can use the energy of switch parasitic capacitance. Thus, the driving losses can be reduced. Fig. 14 shows diagram of the simplest resonant driving circuit. A series resonant inductor L_{res} is added in the circuit. In Fig. 14, R_g is the gate resistance of switch, R_I is the equivalent resistance introduced by other components in the driving circuit.

In the traditional square wave driving circuit, the energy

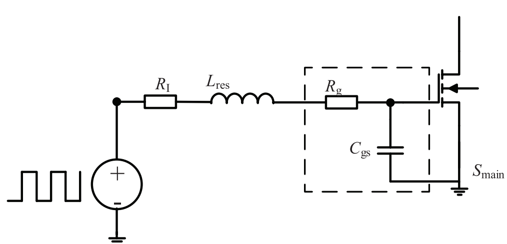

Fig. 14. Schematic diagram of resonant circuit.

stored in the input capacitor C_{gs} is completely consumed during each switching cycle. However in the resonant driving circuit, the energy is converted between the capacitor and the series resonant inductor in the form of electromagnetic energy. Ignoring the small equivalent resistance R_l in the driving circuit, the losses are only caused by the gate parasitic resistance R_g. The losses can be calculated by $2R_g\pi^2 f^2 C_{gs}^2 V_{g,ac}^2$, where V_{gac} is sinusoidal driving voltage amplitude. For the switch of MRF6S9060, comparing the power losses of the above two driving methods, the losses of the resonant driving circuit are much less than that of the square wave driving circuit [70].

Fig. 15 shows a typical VHF sinusoidal resonant drive circuit based on the external oscillator signal, in which the control method will be introduced in the next section. This circuit reduces the current flowing through the equivalent resistance R_l by introducing a parallel branch which consists of an resonant inductor L_p and a resonant capacitor C_B. So the losses of equivalent resistance R_l can be reduced and the efficiency of the resonant driving circuit can be further improved. In the driving circuit, U_3 is a CMOS inverter and S_1 is an auxiliary switch. When the control signal is in low level, the output signal of U_3 is high, and the auxiliary switch turns on. The additional circuit can accelerate the shutdown process.

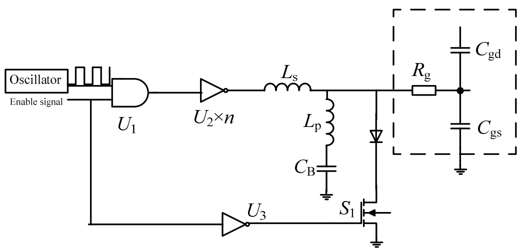

Fig. 15. The typical VHF resonant circuit based on external oscillating signal.

The aforementioned resonant driving circuit owns many advantages, such as simple structure, high reliability, and high efficiency. However, the rising and falling edge slopes of the sinusoidal driving signals are slow which increases the average on-resistance of the switch during the switching period. To solve the above problems, some scholars have proposed trapezoidal wave driving method which can speed up the rise and fall edge of driving signal. Also there is no negative voltage in this trapezoidal driving signal. But the structure of trapezoidal wave driving circuit is complex. There are many components in the circuit which is not conducive to the improvement of power density.

B. Analysis of Self-Resonant Driving Circuit

The above mentioned resonant driving circuits have been widely used in VHF power converters. However, these methods require many components, such as oscillator, AND gate, CMOS inverter, auxiliary switch, etc. These components will increase system cost and reduce system reliability. To solve above problems, the self-resonant driving circuits have been adopted in VHF condition.

Within the above mentioned VHF power converters, the switch drain-source voltage waveform is always in approximate half-wave sine form. When the switch is turned on, the drain-source voltage is in low level, and the driving voltage is in high level. When the switch is turned off, the situation is just the opposite. From the perspective of phase, there is an almost 180 degree phase difference between the driving voltage and the drain-source voltage. According to above analysis, a passive network is expected to be designed, which can feed back the drain-source voltage to the gate with an almost 180 degree phase difference. Meanwhile with the adjustment of the feed-back voltage amplitude, a self-resonant driving system can be built with a proper feed-back network.

Fig. 16 shows a VHF self-resonant driving circuit based on series resonant inductor [71]. In the circuit, L_G is the resonant inductor and V_{bias} represents the bias DC voltage. Based on the inductor and the switch parasitic capacitors, a high-pass filter with the capacitive load is formed. The transfer function V_{ds}/V_{gs} needs to be carefully designed to satisfy the requirements. Fig. 17 shows the Bode diagram of the feedback network with different series inductance parameters. As can be seen from the figure, the network can achieve about 180 degree phase difference within certain frequency range. By changing the value of inductances, the voltage gain at the operating frequency can be adjusted to meet the amplitude

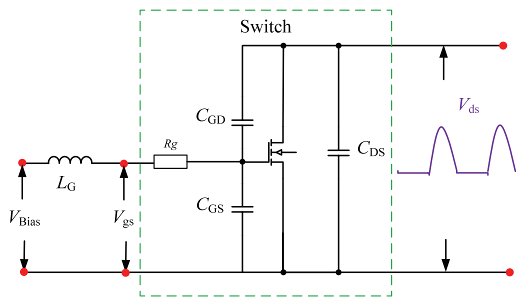

Fig. 16. Circuit of a self-resonant VHF driving circuit.

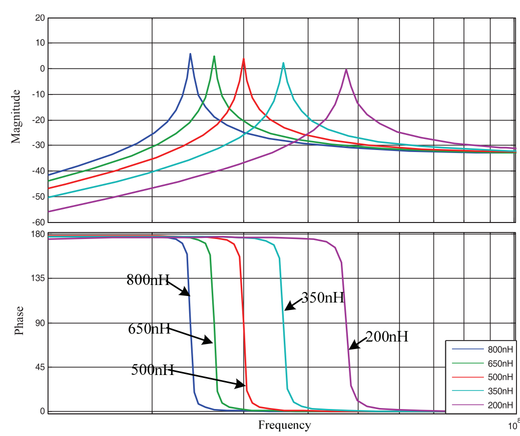

Fig. 17. The bode plots of self-resonant circuit with different inductor values.

requirement of different switches. The bias voltage V_{bias} can be adjusted to change the switch duty cycle with different threshold voltages.

Although the above mentioned self-resonant driving circuit has a simple structure, the network performance mainly depends on the parasitic parameters of the selected switch. For many switches, the feed-back network cannot achieve 180 degree phase difference. Meanwhile the amplitude of the driving voltage is proportional to the input voltage. With the increasement of input voltage, the driving voltage may exceed the switch allowable voltage, which restricts the application fields of the self-resonant circuit.

To solve the above problems, paper [72] proposes a VHF self-resonant driving circuit based on the auxiliary switch as shown in Fig. 18. The driving circuit adopts Class E resonant circuit. Based on the proper feed-back network, the auxiliary switch is driven by the self-resonant signal. Then the drain-source voltage of the auxiliary switch is used as the driving voltage of the main switch. With proper DC bias voltage, the driving signal is independent of the input voltage of the power circuit. Meanwhile an inductor L_{start} is added between the gate of the auxiliary switch and the DC voltage source, which can fasten the switch transition. Although the structure solves the problem of self-resonant driving circuit based on series inductor, the driving method is more complicated and needs many components.

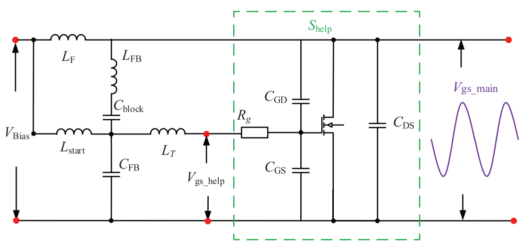

Fig. 18. The VHF self-resonant circuit based on an auxiliary switch.

IV. Control Strategies of VHF Power Converters

Apart from the topology structures and the driving methods, another important factor of VHF converters is the control method. For traditional converters, pulse width modulation (PWM) or pulse frequency modulation (PFM) is used to adjust the system driving signal, and finally the system's closed-loop control can be achieved. However, both methods are difficult to realize in VHF situations. As for PWM, the ZVS characteristic of the switch in the VHF system is realized at a certain duty ratio. Once the duty ratio changes, the switch will lose the ZVS characteristic, thus the system losses will greatly increase. And if PFM is utilized in the VHF topology, the frequency range of the system will be too wide, the elements and control system will be difficult to design and operate. Of course, PWM and PFM can be combined to control the system collectively, but this will increase the complexity of the control circuit and still cause the system to withstand a wide frequency range.

In VHF converters, on-off control method is widely used, Fig. 19 shows the control block diagram [56], [60], [72]-[75]. The driving signal is obtained after the low frequency control signal and high frequency oscillator signal passing the AND gate. The final driving signal is shown in Fig. 20. With this method, the output voltage can be regulated. The advantage of this control method is that the switch keeps working at its optimal operating point once it turns on. Thus with a constant output voltage, this control method can also ensure high efficiency in a wide input range. However the drawback of this approach is that it causes low-frequency harmonic interference, so it is necessary to increase the values of the filter elements. Besides, as the switch state constantly converting between working and non-working, this method puts forward higher requirements for the transition speed of the power circuit. On the basis of on-off control method, the improved hysteresis control method and the phase-shift control method also have been used in VHF converters.

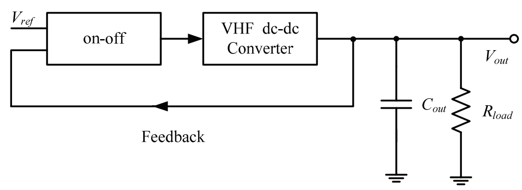

Fig. 19. The diagram of VHF DC-DC converter controlled by on-off method.

In [76], the outphasing control technology is applied to VHF power converters, Fig. 21 is the schematic diagram of this control method. This method is to adjust the phase difference between the two or more inverters to control the output voltage amplitude of the rectifier. Fig. 22 is a VHF power converter based on outphasing control, it has fast response speed, wide adjustment range and small input output filters. However the system losses are roughly the same

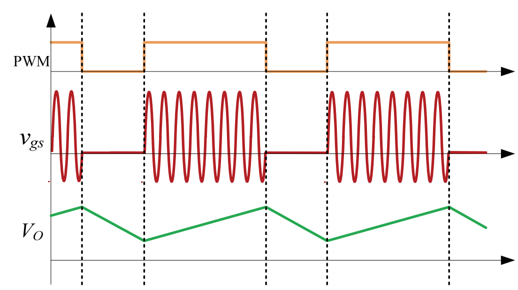

Fig. 20. The waveforms of control signal and gate voltage.

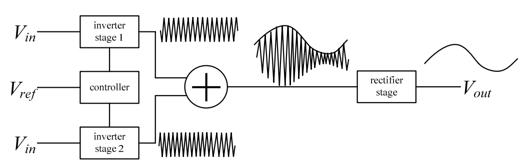

Fig. 21. System diagram of VHF converters based on outphasing modulation.

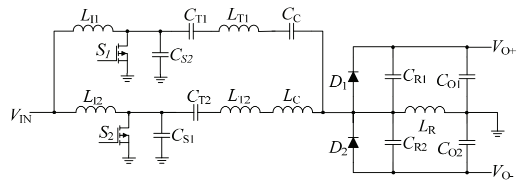

Fig. 22. The circuit of VHF resonant circuit based on outphasing control method.

when the circuit is under light load and full load conditions, which will cause lower efficiency in the light load situation. Another defect is that the control circuit is complex and not easy to design.

V. Opportunities and Challenges of VHF Power Converters

With the continuous improvement of the working frequency, the VHF converters can effectively reduce the value and volume of passive components and increase the power density [77]-[82]. In the future, the integrated VHF converters will become the development trend of the VHF converters. In order to achieve the integrated system, the design and integration method of the magnetic components, such as inductors and transformers, becomes one of the hottest and most difficult subjects. In VHF situations, planar magnetic components can effectively reduce the volume of the inductors and transformers, especially their height in the vertical direction. Generally speaking, air core structure can be adopted to design magnetic components when the frequency is tens of megahertz. The copper tracks in the PCB board can act as the windings of the inductors and transformers. However, the ac resistance, parasitic capacitance, the primary and secondary leakage inductances under high frequency conditions are all needed to be studed thoroughly and designed optimally.

At the same time, with the rapid development of the wide band gap semiconductors, such as GaN, the development of VHF power converters is correspondingly promoted. GaN FETs own lower on-resistance and smaller parasitic capacitance, and can effectively reduce the conduction losses and the driving losses. Although GaN FETs have many advantages when applied in VHF converters, there are many problems that need to be addressed. Compared with Si switch, the threshold voltage of GaN FET is lower, so GaN FET is more sensitive to the driving voltage amplitude, the spikes contained in the driving signal may cause malfunctions or even damage to the GaN FETs. In addition, the reverse conduction voltage of this switch is relatively high, in order to reduce the losses caused by this aspect, the opening time of the switch is required to be calculated and designed precisely.

Nowadays, most of the available VHF converters are only suitable for the applications where the input and output voltage are low. This is mainly constrained by the high voltage stress of the switches and diodes in the inverter stage and rectifier stage. Even if the Class Φ_2 topology is used, the stress is twice of the input voltage. Thus, investigating new inverter and rectifier topologies with low voltage stress can widen the input and output voltage range of the VHF converters. For the application of high power conditions, the design of optimal system structure is another urgent problem to study and settle.

The non-ideal parasitic parameters created by the pins of the components and the layout of the PCB board will also greatly affect the performance of the VHF power converters. In the further study, the characteristics of parasitic parameters and the suppression methods need to be studied deeply under the VHF conditions. And the optimal layout of elements in VHF converters should be proposed with the help of 3D simulation software. Meanwhile, the sensitivity of the system to parasitic parameters can be restrained by exploring the new topologies. Also the compensation method of non-ideal parasitic parameters should be deeply researched.

VI. Conclusion

High frequency and high power density have become the developing trend of power electronics technology, the VHF converter can effectively reduce the system volume, improve the system power density and other performance. However, it also brings many challenging problems. In this paper, from the perspective of the topology, the inverter stage, rectifier stage and matching network are introduced respectively, and their merits and demerits are analyzed in detail. Then in the respect of driving technology, the resonant and self-resonant driving mode have taken place of the traditional hard drive mode, which can take advantage of the energy stored in parasitic capacitance. Besides, the control methods of VHF converters are described and compared in this paper. In the end, the development trends and challenges of VHF converters are introduced, and the promotion in components and topologies is expected.

References

[1] A. Grebennikov, and N. Sokal, *Switchmode RF* Power Amplifiers, Amsterdam: Elsevier, 2007.

[2] M. K. Kazimierczuk, *RF Power Amplifiers*, New York: Wiley, 2008.

[3] N. O. Sokal, and A.D. Sokal, "Class E-a new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE Journal of Solid-State Circuits*, vol.10, no.3, pp.168-176, 1975.

[4] N. O. Sokal, *Class-E High-efficiency RF/microwave Power Amplifiers: Principles of Operation, Design Procedures, and Experimental verification,* New York: Springer, 2003.

[5] F. H. Raab, "Maximum efficiency and output of class-F power amplifiers," *IEEE Trans. Microwave Theory Technology*, vol. 49, no. 6, pp. 1162-1166, Jun. 2001.

[6] F. H. Raab, "Class-F power amplifiers with maximally flat waveforms," *IEEE Trans. Microwave Theory Technology,* vol. 45, no. 11, pp. 2007-2012, Nov. 1997.

[7] H. Krauss, C. Bostian, and F. Raab, *Solid State Radio Engineering,* New York: Wiley, 1980.

[8] P. J. Baxandall, "Transistor sine-wave LC oscillators. Some general considerations and new developments," *IEEE Electronic Communicating Engineering,* vol. 106, no. 16, pp. 748-758, May 1959.

[9] D. A. Jackson, "Design and characterization of a radio-frequency DC/DC power converter," Massachusetts Institute of Technology,

Cambridge, 2005.

[10] J. R. Warren, "Cell modulated DC/DC converter," Massachusetts Institute of Technology, Cambridge, 2005.

[11] Z. Zhang, X. W. Zou, Z. Dong, Y. Zhou and X. Ren, "A 10-MHz eGaN isolated Class-Φ2 DCX," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2029-2040, Mar. 2017.

[12] A. Sagneri, "Design of a very high frequency dc-dc boost converter," Massachusetts Institute of Technology, Cambridge, 2007.

[13] O. Leitermann, "Radio frequency DC-DC converters: device characterization, topology evaluation, and design," Massachusetts Institute of Technology, Cambridge, 2008.

[14] J. W. Phinney, "Multi-resonant passive components for power conversion," Massachusetts Institute of Technology, Cambridge, 2005.

[15] J. Rivas, "Radio frequency DC-DC power conversion," Massachusetts Institute of Technology, Cambridge, 2006.

[16] Y. Han, "Circuits and passive components for radio-frequency power conversion," Massachusetts Institute of Technology, Cambridge, 2010.

[17] D. J. Perreault, J. Hu, J. M. Rivas, and et al, "Opportunities and challenges in very high frequency power conversion," in *24th Annual IEEE Application Power Electronics Conference and Exposition,* Washington, 2009, pp.1-14.

[18] J. M. Rivas, R. S. Wahby, J. S. Shafran, and et al, "New architectures for radio-frequency DC/DC power conversion," *IEEE Trans. Power Electron.*, vol.21, no.2, pp. 380-393, Feb. 2006.

[19] A. Toke, "Radio frequency switch-mode power supply," Technology University of Denmark, Lyngby, 2010.

[20] P. Kamby, "High efficiency radio frequency switch-mode power supply for LED applications," Technology University of Denmark, Lyngby, 2011.

[21] Z. Zhang, J. Lin, Y. Zhou and X. Ren, "Analysis and decoupling design of a 30 MHz resonant SEPIC converter," *IEEE Trans. Power Electron.,* vol. 31, no. 6, pp. 4536-4548, Jun. 2016.

[22] J. Spreen, "Electrical terminal representation of conductor loss in transformers," *IEEE Trans. Power Electron.,* vol.5, no.4, pp. 424-429, Oct. 1990.

[23] W. Hurley, E. Gath, and J. Breslin, "Optimizing the ac resistance of multilayer transformer windings with arbitrary current waveforms," *IEEE Trans. Power Electron.*, vol.15, no.2, pp. 369-376, Feb. 2000.

[24] Z. L. Zhang, Z. Dong, X. Zhou, and X. Ren, "A digital adaptive driving scheme for eGaN HEMTs in VHF converters," *IEEE Trans. Power Electron.*, to be published.

[25] W. Odendaal, and J. Ferreira, "Effects of scaling high-frequency transformer parameters," *IEEE Trans. Ind. Appl.,* vol.35, no.4, pp. 932-940, Jul./Aug. 1999.

[26] J. Reinert, A. Brockmeyer, and R.W. De Doncker, "Calculation of losses in ferro-and ferrimagnetic materials based on the modified steinmetz equation," *IEEE Trans. Ind. Appl.*, vol.37, no.4, pp. 1055-1061, Jul./Aug. 2001.

[27] J. Li, T. Abdallah, and C. R. Sullivan, "Improved calculation of core loss with nonsinusoidal waveforms," in *36th IAS Annual Meeting,* Chicago, 2001, pp.2203-2210.

[28] K. Venkatachalam, C. R. Sullivan, T. Abdallah, and et al, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only steinmetz parameters," in *IEEE Workshop on Computers in Power Electronics,* Chicago, 2002, pp. 36-41.

[29] W. Shen, F. Wang, D. Boroyevich, and et al, "Loss characterization and calculation of nanocrystalline cores for high-frequency magnetics applications," *IEEE Trans. Power Electron.,* vol.23, no.1, pp. 475-484, Jan. 2008.

[30] T. Nakamura, "Snoek's limit in high-frequency permeability of polycrystalline Ni-Zn, Mg-Zn, and Ni-Zn-Cu spinel ferrites," *Journal of Applied Physics,* vol.88, no.4, pp. 348-353, 2000.

[31] C. Xiao, "An investigation of fundamental frequency limitations for HF/VHF power conversion," Virginia Polytechnic Institute and State University, Blacksburg, 2006.

[32] D. Choi, M. Choi, and J. Kim, "Effect of organic fuel on high-frequency magnetic properties of Fe–Al2O3 composite powders synthesized by a combustion method," *IEEE Trans. Magnetics,* vol.51, no.11, pp. 11-14, Nov. 2015.

[33] G. D. Lu, X. S. Miao, W. M. Cheng, and et al, "Influence of Cu underlayer on the high-frequency magnetic properties of FeCoSiO thin films," *IEEE Trans. Magnetics,* vol.51, no.11, pp. 1-4, Nov. 2015.

[34] R. Erickson, and D. Maksimovic, *Fundamentals of Power Eectronics,* Norwell: Kluwer Academic Publishers, 2000.

[35] M. Praglin, L. Raymond, and J.R. Davila, "Inductance cancellation in RF resonant power converters," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE),* Milwaukee, WI, 2016, pp. 1-7.

[36] A. Bossche, and V. Valchev, *Inductors and Transformers for Power Electronics,* Abingdon: Taylor and Francis Group, 2005.

[37] J. Hu, and C.R. Sullivan, "AC resistance of planar power inductors and the quasi-distributed gap technique," *IEEE Trans. Power Electron.*, vol.16, no.4, pp. 558-567, Jul. 2001.

[38] D. Monster, P. Madsen, A. Pedersen, and et al, "Investigation, development and verification of printed circuit board embedded air-core solenoid transformers," in *IEEE Applied Power Electronics Conference and Exposition*, Charlotte, 2015, pp. 133-139.

[39] Y. Han, G. Cheung, A. Li, and et al, "Evaluation of magnetic materials for very high frequency power applications," in *IEEE Power Electronics Specialists Conference*, Rhodes, 2008, pp. 4270-4276.

[40] W. Wang, S. Haan, A. Ferreira, and et al, "A novel and simple method to distinguish winding loss from inductor loss under practical excitations," in *39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, 2013, pp. 252-257.

[41] K.V. Iyer, W.P. Robbins, and N. Mohan, "Design and comparison of high frequency transformers using foil and round windings," in *International Power Electronics Conference*, Hiroshima, 2014, pp. 3037-3043.

[42] A. Z. Amanci, H. E. Ruda, and F. P. Dawson, "Load–source matching with dielectric isolation in high-frequency switch-mode power supplies," *IEEE Trans. Power Electron.,* vol.31, no.10, pp. 7123-7130, Oct. 2016.

[43] C.Y. Ku, K. L. Yeh, and J. C. Guo, "The impact of layout dependent stress and gate resistance on high frequency performance and noise in multifinger and donut MOSFETs," in *IEEE MTT-S International Microwave Symposium Digest*, Seattle, 2013, pp. 1-3.

[44] W. Liang, L. Raymond, M. Praglin, D. Biggs, F. Righetti, M. Cappelli, B. Holman, and J. Rivas Davila, "Low mass RF power inverter for CubeSat applications using 3D printed inductors," *IEEE Journal of Emerging and Selected Topics in Power Electron.*, to be published

[45] C. R. Sullivan, W. Li, S. Prabhakaran, and et al, "Design and fabrication of los-loss toroidal air-core inductors," in *IEEE Power Electronics Specialists Conference,* Orlando, 2007, pp. 1754-1759.

[46] M. Nigam, and C. R. Sullivan, "Multi-layer folded high frequency toroidal inductor windings," in *Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition,* Austin, 2008, pp. 682-688.

[47] J. R. Warren, A. Rosowski, and D.J. Perreault, "Transistor selection and design of a VHF DC-DC power converter," *IEEE Trans. Power Electron.*, vol.27, no.1, pp. 27-37, Jan. 2008.

[48] A. Huang, "New unipolar switching power device figures of merit," *IEEE Electron. Device Letters,* vol.25, no.4, pp. 298-301, 2004.

[49] A. D. Sagneri, "Design of miniaturized radio frequency dc-dc power converters," Massachusetts Institute of Technology, Cambridge, 2008.

[50] N. O. Sokal, *Class-E RF Power Amplifiers,* New York: Qex Commun Quart, 2001.

[51] M. J. Chudobiak, "The use of parasitic nonlinear capacitors in Class E amplifiers," *IEEE Trans. Circuits and Systems I: Fundamental Theory and Applications*, vol.41, no.5, pp. 941-944, 1994.

[52] J. W. Phinney, D. J. Perreault, and J. H. Lang, "Radio-frequency inverters with transmission-line input networks," *IEEE Trans. Power Electron.,* vol.22, no.4, pp. 1154-1161, Apr. 2007.

[53] J. W. Phinney, D. J. Perreault, and J. H. Lang, "Synthesis of lumped transmission-line analogs," *IEEE Trans. Power Electron.*, vol.22, no.4, pp. 1531-1542, Apr. 2007.

[54] R. Pilawa-Podgurski, A. Sagneri, J. M. Rivas, and et al, "High-frequency resonant boost converters," in *IEEE Power Electronics Specialists Conference,* Orlando, 2007, pp. 2718-2724.

[55] J. M. Rivas, Y. Han, O. Leitermann, and et al, "A high-frequency resonant inverter topology with low voltage stress," in *IEEE Power Electronics Specialist Conference*, Orlando, 2007, pp. 56-76.

[56] J. Hu, A.D. Sagneri, J.M. Rivas, and et al, "High-frequency resonant SEPIC converter with wide input and output voltage ranges," *IEEE Trans. Power Electron.,* vol.27, no.1, pp. 189-200, Jan. 2012.
[57] R. Pilawa-Podgurski, "Design and evaluation of a very high frequency dc/dc converter," Massachusetts Institute of Technology, Cambridge, 2007.
[58] W. Nitz, W. Bowman, F. Dickens, and et al, "A new family of resonant rectifier circuits for high frequency DC-DC converter applications," in *Third Annual IEEE Applied Power Electronics Conference and Exposition*, New Orleans, 1988, pp. 12-22.
[59] S. Birca-Galateanu, and J.L. Cocquerelle, "Class e half-wave low dv/dt rectifier operating in a range of frequencies around resonance," *IEEE Trans. Circuits and Systems I: Fundamental Theory and Applications,* vol.42, no.2, pp. 103-113, 1995.
[60] J. Rivas, O. Leitermann, Y. Han, and et al, "A very high frequency dc-dc converter based on a class Φ_2 resonant inverter," in *IEEE Power Electronics Specialists Conference,* Rhodes, 2008, pp. 1657-1666.
[61] M. Kovacevic, A. Knott, and M. A. E. Andersen, "Interleaved selfoscillating class E derived resonant DC/DC converters," in *International Conference Electrical Computer System*, Lyngby, 2012, pp. 1-8.
[62] J. A. Pedersen, "Bidirectional very high frequency converter," Technology University of Denmark, Lyngby, 2013.
[63] M. P. Madsen, A. Knott, and M. A. E. Andersen, "Very high frequency half bridge DC/DC converter," in *2014 IEEE Applied Power Electronics Conference and Exposition,* Fort Worth, 2014, pp. 1409-1414.
[64] D. C. Hamill, "Half bridge class DE rectifier," *Electronics Letters,* vol.31, no.22, pp. 1885-1886, 1995.
[65] D. Maksimovid, "A MOS gate drive with resonant transitions," in *22nd Annual IEEE Power Electronics Specialists Conference,* Cambridge, 1991, pp. 527-532.
[66] D. M. Sype, A. P. M. Bossche, J. Maes, and et al, "Gate drive circuit for zero-voltage-switching half- and full-bridge converters," *IEEE Trans. Ind. Appl.*, vol.38, no.5, pp. 1380-1388, 2002.
[67] I. D. Vries, "A resonant power MOSFET/IGBT gate driver," in *17th Annual IEEE Applied Power Electronics Conference,* Dallas, 2002, pp. 179-185.
[68] K. Yao, and F. C. Lee, "A novel resonant gate driver for high frequency synchronous buck converters," *IEEE Trans. Power Electron.*, vol.17, no.2, pp. 180-186, 2002.
[69] A. D. Sagneri, "The design of a very high frequency dc-dc boost converter," Massachusetts Institute of Technology, Cambridge, 2007.
[70] J. Hu, "Design of a low-voltage low-power dc-dc HF converter," Massachusetts Institute of Technology, Cambridge, 2008.
[71] M. P. Madsen, J. A. Pedersen, A. Knott, and et al, "Self-oscillating resonant gate drive for resonant inverters and rectifiers composed solely of passive components," in *2014 IEEE Applied Power Electronics Conference and Exposition,* Fort Worth, 2014, pp. 2029-2035.
[72] R. Pilawa-Podgurski, A. D. Sagneri, J. M. Rivas, and et al, "Very high frequency resonant boost converters," *IEEE Trans. Power Electron.,* vol.24, no.6, pp. 1654-1665, Jun. 2009.
[73] S. Hamamura, T. Ninomiya, M. Yamamoto, and et al, "Combined PWM and PFM control for universal line voltage of a piezoelectric transformer off-line converter," *IEEE Trans. Power Electron.*, vol.18, no.1, pp. 270-277, Jan. 2003.
[74] J. M. Rivas, D. Jackson, O. Leitermann, and et al, "Design considerations for very high frequency DC-DC converters," in *37th IEEE Power Electronics Specialists Conference,* Jeju, 2006, pp. 1-11.
[75] M. Kovacevic, A. Knott, and M. A. E. Andersen, "A VHF interleaved self oscillating resonant SEPIC converter with phase-shift burst-mode control," in *2014 IEEE Applied Power Electronics Conference and Exposition,* Fort Worth, 2014, pp. 1402-1408.
[76] M. P. Madsen, A. Knott, M. A. E. Andersen, and et al, "Outphasing control of gallium nitride based very high frequency resonant converters," in *2015 IEEE Workshop on Control and Modeling for Power Electronics*, Vancouver, 2015, pp. 1-7.
[77] K. H. Lee, E. Chung, Y. Han, and J. I. Ha, "A family of high-frequency single-switch DC–DC converters with low switch voltage stress based on impedance networks," *IEEE Trans. Power Electron.,* vol. 32, no. 4, pp. 2913-2924, Apr. 2017.
[78] J. Choi, D. Tsukiyama, and J. Rivas, "Comparison of SiC and eGaN devices in a 6.78 MHz 2.2 kW resonant inverter for wireless power transfer," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE),* Milwaukee, WI, 2016, pp. 1-6.
[79] S. Park, and J. Rivas-Davila, "A design methodology for class-D resonant rectifier with parallel LC tank," in *2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL),* Trondheim, 2016, pp. 1-6.
[80] L. C. Raymond, W. Liang, and J. M. Rivas, "Performance evaluation of diodes in 27.12 MHz Class-D resonant rectifiers under high voltage and high slew rate conditions," in *2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL),* Santander, 2014, pp. 1-9.
[81] Z. L. Zhang, Z. Dong, D. D. Hu, X. W. Zou, and X. Ren, "Three-level gate drivers for eGaN HEMTs in resonant converters," *IEEE Trans. Power Electron.,* vol. 32, no. 7, pp. 5527-5538, Jul. 2017.
[82] E. Chung, K. H. Lee, Y. Han and J. I. Ha, "Single-switch high-frequency DC–DC converter using parasitic components," *IEEE Trans. Power Electron.,* vol. 32, no. 5, pp. 3651-3661, May 2017.

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