A Review on VHF Power Electronics Converter and Design Issues

N. Z. Yahaya, *Member, IAENG*, K. M. Begam, and M. Awan

***Abstract*—A high output power density VHF converter has become important in recent years. This output power density of the converter is experiencing an adverse effect resulted from the applied switching frequency. In addition, the frequency which is higher than 20 MHz will no longer be applicable on the discreet SMT technology hence lowers the output power density. Thus, further improvement on circuit analysis and PCB layout design could help in the improvement of higher operating frequency. Even though it is suggested that power density and efficiency do not necessarily require a high switching frequency to achieve, the resonant network topology still has to be considered. In spite of issues resulted from the VHF converter design, power device selection and PCB layout circuit design are among the critical factors to consider, to maximize the capability of frequency-output power product in the VHF converter applications.**

***Index Terms*—GaN HEMT Device, MOSFET, PWM Technique, Resonant Network, VHF Converter Design.**

I. Introduction

Switching speed or transient response is the key factor in introducing very high frequency (VHF) to the power electronic converter systems. Theoretically, having higher switching speed, the average load current and voltage of the converters could be made consistent with minimal ripple fluctuation. There have been lots of studies with regards to high frequency converter design in recent years. This leads to a driving demand with fast transient response circuits which require an integrated system and consideration in the trade off between the dimension of the converter and also the cost. Increasing switching frequency enables elimination of magnetic materials. This is the energy storage of passive components that limits achievable transient response. However, converter circuit designers encounter tremendous challenges to derive the best approach in minimizing the influential factors and optimizing the components' types and values. This paper will look at the review of VHF converters and the related design issues in search of the maximum capability of silicon based power switches and the newly developed Gallium Nitride (GaN) high-electron mobility transistor (HEMT) switch in the VHF converter design.

As frequency increases, it is expected that the switching loss and power dissipation of the switch to increase. In operating at VHF, the switching loss of the switch has to be minimized. Power switches play the important role in making the pulsating waveforms work effectively in high frequency environment. There are two types of basic pulse width modulation (PWM) switching modes. One is the hard switching, where most of the energy loss comes from the commutation of the switch and this is proportional to the switching speed. The other is the soft switching which can be categorized into two; zero-voltage-switching (ZVS) and zero-current-switching (ZCS). Particularly in ZVS where mostly used in VHF power converters, it can reduce the switching loss by maintaining the low or zero voltage across the switch during switching transitions. This draws to the benefits of reduction in electromagnetic interference (EMI). However, ZVS normally incurs losses that do not scale back with the output load.

On the other hand, operating in ZCS can minimize the switching loss. However there is a greater concern in choosing this mode as it inhibits greater limitations in designing VHF converter circuits. The upper limit of 2 MHz switching frequency is one of the limitations in ZCS mode [1] when operating off-line where slower transient response is reported especially in half mode condition [2]. Even though full mode operation can solve this limitation, it is difficult to implement at VHF due to the switch's body diode [3]. Thus this leads to ZVS preference in the VHF converter design.

Conventional PWM technique is a process of interrupting power flow and controlling duty cycle of the converter. Here, the generated waveforms will be in the form of pulsating current and voltage. The technique is simple and easy to control. This technique is preferred and used predominantly in today's power electronics industries particularly in low-power applications. However, it is quickly becoming a mature technology at a certain range of switching frequency. The use of PWM structure operating at a switching frequency more than 500 kHz normally can cause considerably losses due to the switching on the semiconductor device [4]. At megahertz range of frequency, the semiconductor switch will experience high switching stress hence high switching loss. In addition, there is presence of leakage inductance in the transformer and leakage junction capacitance of the switch. The gate drive circuit that drives the switch will also be affected by the Miller's effect which leads to significant noise and instability of the converter.

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II. CONCEPTS OF RESONANT NETWORK IN VHF CONVERTERS

Auxiliary *LC* configurations are applied in the resonant network to shape the switching device's current and voltage waveforms in order to successfully turn-on and turn-off exactly at zero condition. This will ensure the reduction of device's switching stress hence the switching losses imposed during the transition cycle. In ZCS, the switch's current waveform at on-time is shaped to create zero-current condition for the switch to turn off. While in ZVS, the switch's voltage is set to zero-voltage condition for the switch to turn-on during the off-time of the switching cycle.

A. Comparison between Current-mode and Voltage-mode Resonant Switches

An inductor, *L* and a capacitor, *C* are the auxiliary components to make up the resonant network and normally they are connected in series or parallel with a switching device. There are many types of *LC* configurations that have been applied in the circuits. The basic configurations are current-mode and voltage-mode resonant types. In current-mode as shown in Fig. 1, an inductor L_r is in series with the switch S_1. This ensures the ZCS. The resonant interaction between L_r and C_r is initiated by turn-on of S_1.

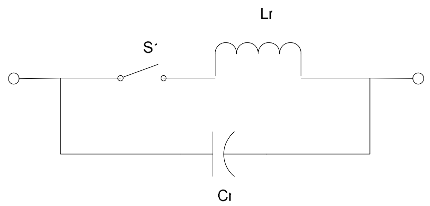

Fig. 1: Current-mode resonant switch

On the other hand, in voltage-mode resonant switch as shown in Fig. 2, the capacitor C_r is connected in parallel with the switch S_1 thus result in ZVS. The S_1 switch is turned off in the voltage-mode resonant switch operation. As higher frequency is expected to operate in converter system especially in higher megahertz range, ZVS mode is preferred than ZCS.

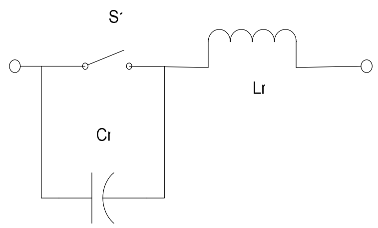

Fig. 2: Voltage-mode resonant switch

Referring to Fig. 2, if S_1 is implemented by a MOSFET transistor switch, Q_1, and there is an additional diode which connected in parallel to the switch, then the voltage across the capacitor C_r will be clamped by the diode resulting to a minimum voltage value. At this instant, the switch is operating in a half-wave mode as shown in Fig. 3.

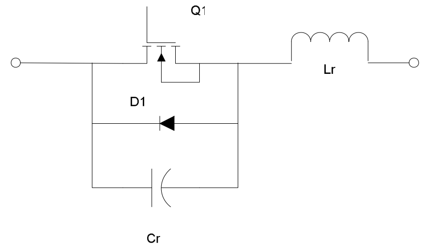

Fig. 3: Half-wave mode resonant switch

While in full-mode, the MOSFET transistor switch Q_1 is connected in series with D_1 as shown in Fig. 4, resulting in free oscillation of voltage on C_r which makes an easy adjustment on zero voltage implementation during the switch's turning-off. Due to the difficulties in capacitive turn-on loss, however, full-wave mode is not practical at high frequency operation.

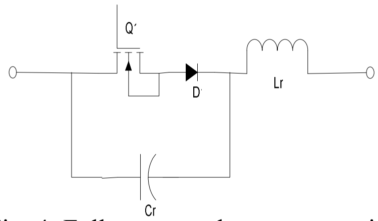

Fig. 4: Full-wave mode resonant switch

Quasi-resonant converter (QRC) which was proposed by [5], [6] and many more, is the condition where transistor switch is formed as S_1-*Lr*-*Cr*. ZVS turn-on is achieved when the resonant switch is applied in parallel with the resonant capacitor. Theoretically, when the switch is conducting, the resonant capacitor is shorted where no resonant action occurs. However, the resonant takes place when the switch is in off-mode.

There are many types of QRC configurations developed in past years mainly in QRC-ZCS and QRC-ZVS. QRC-ZVS is mostly chosen compared to QRC-ZCS due to its capability in the operations of VHF converter systems. Even though QRC-ZCS have design difficulties, in lower megahertz range, it can still be used mainly in the current-mode Buck converter QRC-ZCS topology. However, in order to operate in much higher megahertz frequency range, the voltage-mode QRC-ZVS Boost converter is still preferred [7].

In QRC-ZVS, the undesired parasitic oscillation occurs at the output voltage stage where this is due to the interaction between resonant inductor and junction capacitance of rectifier [8]. Consequently, this limits the converter's load range and affects the DC voltage-conversion-ratio characteristics [9]. The oscillation requires suppression to stabilize the circuit but in the cost of reduced efficiency. Multi-resonant converter (MRC) is another version of QRC. MRC-ZVS was then proposed [10] to solve the problems where an additional external capacitance is added with the rectifier to allow junction capacitance to resonate with resonant inductor. This suppresses the oscillation however this eventually leads to higher switching loss in the device.

B. Comparison between voltage-mode QRC-ZVS Boost and Class E converters

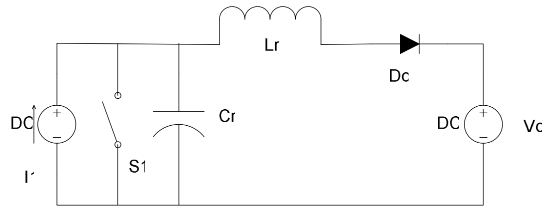

Fig. 5: Voltage-mode QRC-ZVS Boost Converter

In Fig. 5, the circuit behavior is determined by the values of L_r and C_r. There are four parameters as described in (1)-(4) below that make the resonant operation. They are the characteristics impedance,

$$Z_n = \sqrt{Lr}\Big/Cr \qquad (1)$$

resonant angular frequency,

$$\omega = 1\Big/\sqrt{LrCr} \ , \qquad (2)$$

resonant frequency,

$$f_n = \left(\frac{\omega}{2}\right)\pi \qquad (3)$$

and normalized load resistance

$$r = \frac{Ro}{Zn} \qquad (4)$$

In addition, there are also four stages: capacitor charging stage, resonant stage, inductor discharging stage and free-wheeling stage. The details of circuit operations can be found from [10]. The output waveforms are shown in Fig. 6(a).

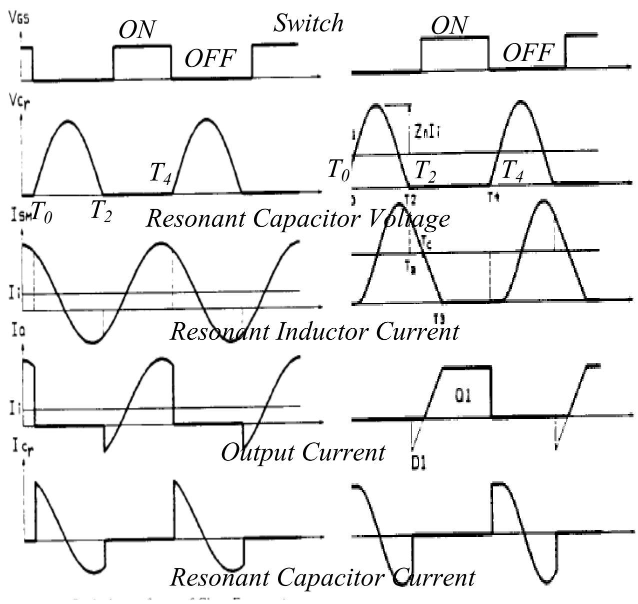

Fig. 6(a) Fig. 6(b)

Fig. 6(a) is the waveforms of all 4-stage of the voltage-mode QRC-ZVS boost converter from T_0 to T_4. It can be seen that the output voltage is zero when the switch is turned-off at T_2. This is the time of the resonant stage. Fig. 6(b) shows the waveform of the equivalent Class-E converter. Both circuits give same output results but only with different topologies. This concept can be applied to Class-E converter as shown in Fig. 7, proposed by [11].

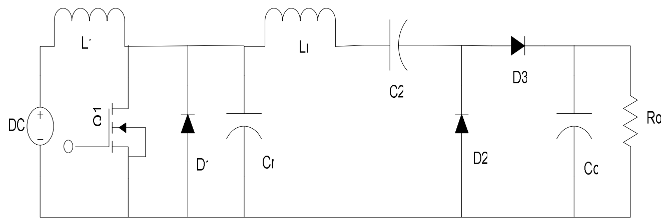

Fig. 7: Class-E converter

Class-E converter is a tuned power amplifier circuit to generate a sinusoidal output current waveform with a band-pass filter. This circuit usually imposes a limitation to support a wide range of load variation. In Class-E converter, an impedance matching network is required. This will add complications to the circuit. In addition, the tuned network may hinder the performance of the converter which can give higher conduction loss [12].

On the other hand, the voltage-mode ZVS-QRC boost converter circuit does not require a tuned network. This will enable the converter to support a wide range of load variation. Most importantly, unlike in Class-E converter, it can achieve ZVS without affecting much the original switch current waveform. Thus, the degradation of the input signals can be minimized and thus improves the output signals.

III. VHF CONVERTER USING CONVENTIONAL LOW ON-RESISTANCE MOSFET

The studies on the VHF converters had been started as early in 1970's where researchers looked for designs of having high power density and fast transient response system. There are several types of circuit topologies which have been used to realize the VHF converters. The type of topology used is based mainly on the applications. For an example, for microprocessor power supply, the circuit topology used is the voltage regulator module (VRM). The VRM was implemented using the resonant technique to achieve highest possible switching frequency. Others were selected based upon the reasons of solving or improving issues within the present circuit designs.

Without the use of resonant techniques, the converters cannot operate well in VHF mode. As for MOSFET switch, it can only achieve as high as 20 MHz. Beyond that, the converter circuits have to be implemented using different design scheme via Monolithic and Class-E. Fig. 8 below shows an example of basic circuit diagram of buck ZVS-QRC [13]. The experimental result showed that at 6.6 MHz, with low load condition, the output power is 8 W (efficiency of 91%) and with full load condition, output power is 30 W (efficiency of 78%).

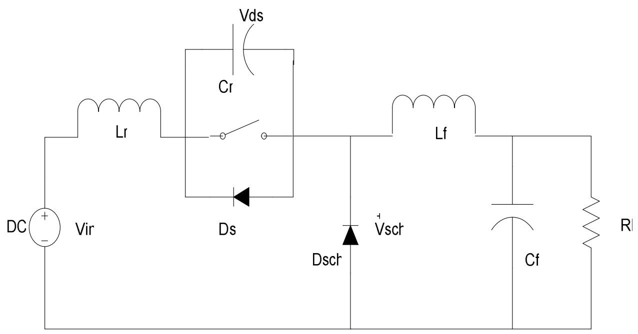

Fig. 8: Buck ZVS-QRC converter

In 1989, the conventional MOSFET based switch has reached its maximum capability in operating switching frequency. Any further increase in frequency will require a new switch that is suitable for the purpose. Table I below shows the summary of the VHF MOSFET-based on-board low-power converters with respect to the achievable operating frequency.

Table I: Discreet SMT (on-board) Implementation On selected VHF converters

Frequency	Circuit Topology	Resonant Type	Output Power	Efficiency
1 MHz	Half-bridge	ZVS	500 W	90%
1 MHz	Forward	ZVS Clamped mode	33 W	83%
2 MHz	Forward	MRC ZVS	50 W	80%
2 MHz	Forward	MRC ZVS	50 W	80.5%
5 MHz	Flyback	ZVS	25 W	83%
6.6 MHz	Buck	QRC-ZVS	30 W	78%
8 MHz	Half-bridge	MRC ZVS	75 W	80%
10 MHz	Forward	MRC ZVS	50 W	83%
15 MHz	Buck	MRC ZVS	50 W	83%
20 MHz	Half-bridge	MRC ZVS	32.3 W	85.2%
> 50 MHz	Monolithic and Class-E Power Amplifier Implementation Output power is expected to reduce			

From Table I, it clearly shows that ZVS technique is the best choice in giving the converters to operate at VHF using the conventional MOSFET device via discrete and SMT implementation on printed circuit board (PCB). Below the 20 MHz frequency mark, any type of circuit topologies can be utilized but the selection depends on the applications. There are still some switching losses present in the VHF converter as the efficiency range is only between 80% and 90%. A frequency higher than 20 MHz will need special attention in the use of integrated CMOS device in order to achieve highly efficient converter. It is expected that as the switching frequency increases, less output power will be generated. This is the main trade-off in VHF converter design. Hence the efficiency will be further reduced. New switching devices that have the capability to operate at VHF should be employed. Among the suitable candidates are the non-MOSFET based switches such as Gallium Arsenide (GaAs) and GaN HEMT which are from the group III-V element.

IV. Low power VHF Converters Using Other Types of High Frequency Switches

Different types of power semiconductor switches have been used in the attempt to operate VHF converters. The most concern is to achieve the maximum switching frequency in the case where the gate drive circuit design limits the efficiency. The new trend now is to use the devices for the group III-V, such as GaAs, Silicon Carbide and GaN.

In 2000, the converter operated in 100 MHz had been realized [14]. The Cuk converter was used as the test circuit. Another is the GaAs device, which was applied and by using the MESFET gate drive circuit with appropriate passive components, the 1-watt converter showed remarkable efficiency higher than 65%. In other experiment done by [15], an optimized 3-watt on-board boost converter prototype produced efficiency of 74% at 100 MHz as shown in Fig. 9. The optimizations of passive and active devices have been carried out in order to achieve high converter performance in terms of power and efficiency. However, the new design of ferrite inductor should be considered in VHF converter design since its cutoff frequency depends upon switching frequency.

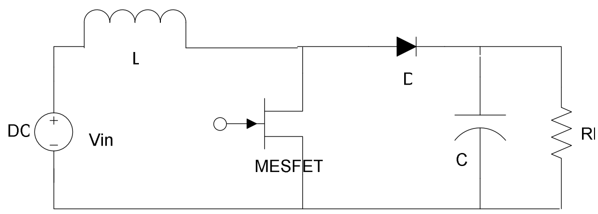

Fig. 9: Boost converter

CoolMOS device, developed by Infineon in 1999, also had been tested in VHF converters. One of the applications was in electronic ballast [16] where the circuit implementations were done on both resonant SEPIC converter as shown in Fig. 10 and on the resonant flyback converter. The results showed that both circuits were able to demonstrate a tuned frequency up to 2.5 MHz using the CoolMOS device. The studies were extended in order to further increase the switching frequency. It is summarized that switching loss of the switch is the key role and it could not be neglected.

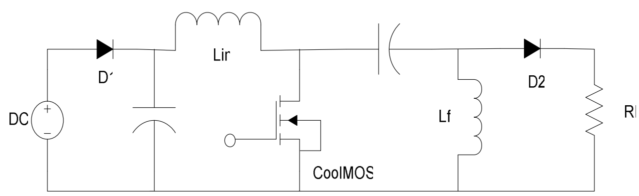

Fig. 10: Resonant SEPIC

V. Application of GaN HEMT in VHF RF Converter Circuits

The GaN HEMT device structure inhibits better characteristics compared to silicon-based devices. GaN HEMT device has been tested on VHF converter operations especially in RF Class-E applications. In a study done by Wataru Saito et al., a 13.5 MHz Class-E amplifier using GaN HEMT has been demonstrated [17]. The implementation of the circuit is considered to be the same as if it is in the single-ended resonant inverter. The circuit is shown in Fig. 11. The fabricated GaN HEMT results in output power of 13.4 W and efficiency of 91%.

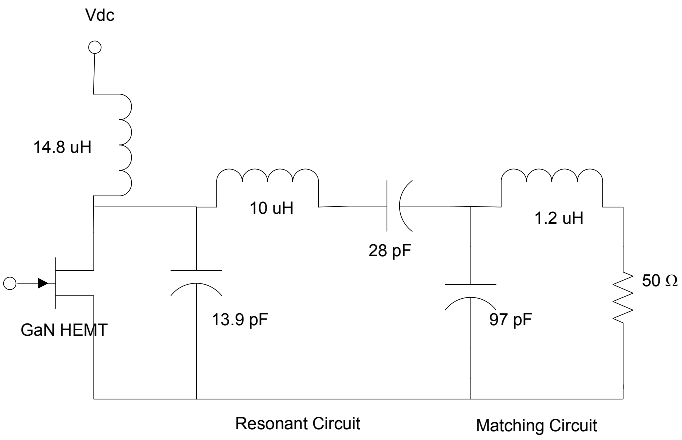

Fig. 11: 13.5 MHz Class-E Amplifier

Then Wataru has made some further improvement by studying the effect of parasitic influence of the VHF converter. As a result, 27.1 MHz Class-E amplifier has been achieved [18] as shown in Fig. 12. The output power of the circuit is achieved at 10.8 W with the efficiency of 80% considering the effect of parasitic resistance and capacitance. However, the power efficiency depends on the Field-Plate (FP) structure of the GaN HEMT. With further improvement in removing the parasitic influence in the VHF circuit gives better power efficiency to 89.9% at maximum output power of 13.8 W.

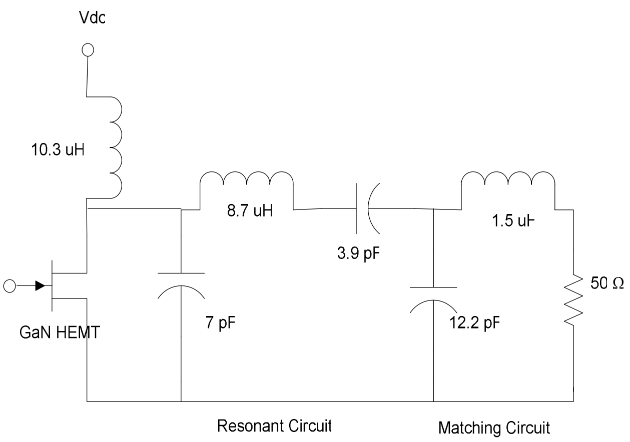

Fig. 12: 27.1 MHz Class-E Amplifier

A. *Design Parameters/Considerations*

In the design of VHF converter circuit, obviously the switching speed will be high. The increase in frequency will result in high switching loss and conduction loss of the device. Hence this lowers the efficiency. All components have to be carefully chosen and designed in order to operate in VHF environment, especially in RF applications. The influence of parasitic elements, thermal analysis and on-board PCB layout design are important to achieve compact, higher power density and high efficient converters.

B. *Design Issues*

One of the most challenging factors is to design the gate drive circuit so that the GaN HEMT can operate at its maximum switching capability. The gate drive design is complex where the internal parasitic capacitances of the devices need to be considered comprehensively. In addition, the proportional relationship between switching frequency and switching loss is another factor. Increasing switching frequency will increase power loss. Thus, this gives more challenges in the design of VHF converter. The optimization technique using all of the design parameters is required to produce better converter results.

C. *Discreet / SMT (on-board) design approach*

From the literature, it shows that the implementation of on-board approach for the low-power VHF converter is only up to 20-22 MHz operating frequency. This is due to the limitation on the components design and their capability in reducing switching loss hence lower efficiency due to the parasitic influence. Other important considerations are the effect on the circuit design layout, gate drive circuit design as well as optimization technique are still due for further investigation.

D. *Numerical Relationship between GaN HEMT output power-frequency product*

As switching frequency is pushed higher in the VHF converter design, the output power generated at the load will be reduced. Here, it shows that there is a limitation of applied frequency to the converter in order to achieve certain output power range. In other words, the output power cannot be maintained at high value if the switching frequency reduces. The circuit design and good choice of new components must be carefully considered or possibly designed to drive higher switching frequency and at the same time manage to maintain higher output power level.

According to the derivation from the semiconductor junction device electrical characteristics and its intrinsic material property, the power frequency product is given by [19],

$$P_{max} f_T = \frac{\varepsilon}{32\pi} \frac{d}{L_g} \left(E_{bk} * v_s\right)^2 \quad (5)$$

where d/L_g is the form factor of the device, typically in the range of 3-5. The power-frequency product shows the dependence of semiconductor properties in the device. Thus the power density would be reduced because of reduced power when the frequency is pushed to a higher range value up to its maximum limit. So this gives a need to better converter designs which could realize higher power density in higher switching frequency operation.

VI. Conclusion

The design of high density output VHF power converter requires new technique not only to produce better efficiency but also reliability. There are limitations in the design where designers have to consider trade-offs between frequency and output power. The power-frequency product in semiconductor property is inversely proportional to each other, so a frequency which is higher than 20 MHz will no longer be applicable on the discreet SMT technology hence lowers the output power density. Further development on circuit analysis and PCB layout implementation may increase in operating frequency. An improved power density and efficiency do not necessarily require a high switching frequency. However, higher switching frequency requires correct use of the resonant network circuit implementation. In fact, new components design and circuit design layouts techniques are required to maximize the capability of the frequency-output power product in the design of VHF power converters. This is one of the requirements of GaN HEMT device to be used in high frequency applications.

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