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MINIMIZING HIGH-FREQUENCY SWITCHING LOSSES IN WIDEBAND GAN HEMTS FOR FLYBACK CONVERTERS

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Background. In the realm of pulse power supplies, flyback converters play a pivotal role in efficient voltage conversion and providing electrical isolation. Typically, these converters utilize silicon transistors. However, they encounter several issues that hinder their energy efficiency and operational stability. A primary concern is the increase in switching losses at high frequencies. This is attributed to the lower switching speed and higher on-state resistance characteristic of silicon transistors. Such inefficiency leads to substantial power dissipation, thereby reducing overall efficiency. Additionally, the heat generated from these losses necessitates complex temperature control systems, increasing operational burden and affecting the reliability and longevity of the converters. Furthermore, the operational frequency of these converters is limited. While operating at higher frequencies is beneficial for reducing the size of passive components, it exacerbates the problems of switching losses and heat dissipation in silicon transistors.

Objective. This article aims to conduct a comprehensive study and optimization of flyback converters based on High Electron Mobility Transistors (HEMT) made of Gallium Nitride (GaN), focusing on minimizing losses in high-frequency switching. The study delves into the intrinsic properties of GaN HEMTs, highlighting their superior characteristics compared to traditional silicon counterparts, and emphasizes the circuit design methods for minimizing losses and their features.

Method. The research involved a detailed analysis of the switching losses of GaN HEMTs under high-frequency switching conditions. Using computer simulation models, the study examines the impact of various parameters, such as currents and voltages on the GaN transistor, power dissipation, and the output characteristics of the device with different circuit topologies on the performance and efficiency of switching.

Results. The results provide insights into the optimization strategies of topology, particularly the use of transistor gate drivers and snubber circuits, which are crucial for enhancing the overall efficiency and reliability of flyback converters.

Conclusions. The article offers an in-depth analysis into optimizing high-frequency flyback converters using GaN HEMTs, providing valuable guidance for devices requiring compact power sources, such as in small aircraft systems and telecommunications networks.

Keywords: *flyback converters; AC-DC; SMPS; gallium nitride; GaN; wide bandgap semiconductors.*

Introduction

In recent years, the electrical and radio engineering landscape has witnessed significant advancements in power conversion technologies, with a particular focus on enhancing efficiency and reliability. Among the pivotal components in this domain are Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs), renowned for their superior performance in high-frequency applications. However, despite their growing popularity, GaN HEMTs in flyback converters, a mainstay in power supply design, encounter a fundamental challenge: high-frequency switching losses. These losses not only impede efficiency but also affect the longevity and reliability of the device.

This study delves into the realm of minimizing high-frequency switching losses in wideband GaN HEMTs, specifically within the context of flyback converters. Our research is driven by a dual objective: firstly, to enhance the understanding of the loss mechanisms inherent in GaN HEMTs during high-frequency operation, and secondly, to develop strategies and techniques aimed at mitigating these losses. By accomplishing these goals, we aim to unlock the full potential of GaN HEMTs in flyback converters, thereby contributing to the development of more efficient, reliable, and cost-effective power conversion solutions.

This paper aims to address the following key objectives:

- Conduct a detailed analysis of the mechanisms contributing to switching losses in GaN HEMTs within flyback converters. This includes examining the intrinsic properties of GaN HEMTs and their interaction with the high-frequency operational characteristics of flyback converters;
- Explore and develop effective strategies for minimizing switching losses. This involves investigating various circuit design modifications, gate drive techniques, and other electronic control methods that can reduce losses without compromising the performance and efficiency of GaN HEMTs;

- Validate the proposed strategies through theoretical analysis and provide a comprehensive guide that bridges the gap between theoretical research and practical application. The aim is to offer insights and actionable recommendations that can be directly applied by engineers and researchers in the field of power electronics.

Switching loss analysis of Gallium Nitride based transistors

Gallium Nitride (GaN) is a complex, wide bandgap semiconductor material, distinct from other group III semiconductors like gallium arsenide (GaAs) or gallium phosphate (GaP). Its crystalline structure, known as wurzite, is both chemically and mechanically stable, even at high temperatures [1]. The band gap of GaN is 3.4 eV, significantly higher than silicon's 1.1 eV, leading to lower intrinsic leakage currents and higher operating temperatures. This increased band gap results in a higher breakdown voltage and thermal stability for GaN-based devices compared to other Group III nitrides.

The critical electric field (E_{crit}) of GaN is notably higher than that of silicon and other similar semiconductors, leading to a smaller drift zone width (Wdrift) at the same breakdown voltage. For GaN, Ecrit is approximately 3.3 MV/cm, compared to silicon's 0.23 MV/cm and GaAs's 0.6 MV/cm. This property, along with the higher number of charge carriers in the drift region, significantly enhances the performance of GaN-based transistors.

GaN's wurtzite structure imparts unique piezoelectric properties, resulting in high conductivity. By adding a thin layer of aluminium gallium nitride (AlGaN) to GaN crystals, a two-dimensional electron gas (2DEG) heterostructure is formed, further increasing electron mobility up to 1500-2000 cm2/V·s in the 2DEG region. This structure is crucial for power converters, allowing for higher operating voltages, increased maximum allowable switching frequencies, and reduced switching losses.

Recent advancements in GaN technology have led to the development of high-performance light pulsers and power electronics devices, showcasing superior characteristics compared to traditional designs. High-electron-mobility transistors (HEMTs) based on GaN have been identified as key components in power electronics, offering advantages over silicon and silicon carbide Metal-Oxide-Semiconductor Field-Effect transistors (MOSFETs) in both high-voltage and low-voltage applications [2].

In power converters, these properties translate into the ability to operate at higher voltages and frequencies, reducing switching losses and enhancing the overall efficiency of high-frequency switching converters. This is particularly beneficial in applications requiring compact and efficient power conversion solutions, such as in electric vehicles and renewable energy systems. GaN transistors' ability to operate at higher voltages translates to increased maximum allowable switching frequencies and reduced switching losses. This enhances the applicability of high-frequency switching converters, even with relatively simple topologies. One of the primary losses in these converters is attributed to the switching process. Moreover, the enhanced structure of GaN transistors contributes to zero-recovery time, further reducing total transistor losses and improving the efficiency of power converters. This makes GaN transistors highly suitable for applications where efficiency and compactness are crucial.

Switching losses can be calculated through switching energy (E_{sw}) and switching frequency (f_{sw}):

$$P_{SW} = E_{SW} \cdot f_{sw} \tag{1}$$

When the transistor operates on a load, the switching energy is determined through the drain-source voltage (V_{DS}) and the drain current (i_d) [2]:

$$E_{SW} = 2\int_{0}^{t_{on}} V_{DS}(t) \cdot i_d(t)dt \tag{2}$$

If the value of V_{DS} and i_d change linearly, then the power losses during switching can be calculated as:

$$P_{SW} = V_{DS} \cdot I_d (t_{rise} + t_{fall}) f_{sw}, \tag{3}$$

Where t_{rise} , t_{fall} — switching times (current rise and fall times) of the transistor. The switching time of the transistor is determined using the characteristics of the total gate charge of the transistor (Q_{Gtot}) as well as the parasitic capacitance at the gate and depends on the circuit design and the operation mode of the converter.

The value of the gate current when the transistor is turned on and off is determined as:

$$\begin{gathered} I_G(ON) = \frac{V_{GS} - \left(\dfrac{V_{PL} + V_{th}}{2} \right)}{R_G(ON)} \\ I_G(OFF) = \frac{\dfrac{V_{PL} + V_{th}}{2}}{R_G(OFF)} \end{gathered} \tag{4}$$

Where V_{GS} — rated voltage at the gate of the transistor, V_{PL} — voltage at which the Miller effect begins to appear, increasing the gate capacitance, as a result of which a false opening of the transistor is possible, V_{th} — threshold voltage, R_G — gate resistance.

Switching losses of the transistor can be obtained by:

$$P_{sw}(ON)=\frac{V_{DS}I_DR_G(ON)f_{sw}}{2}\cdot\left[\frac{Q_{GD}}{V_{GS}-V_{PL}}+\frac{Q_{GS}}{V_{GS}-\left(\frac{V_{PL}+V_{th}}{2}\right)}\right]$$
$$P_{sw}(OFF)=\frac{V_{DS}I_DR_G(OFF)f_{sw}}{2}\cdot\left[\frac{Q_{GD}}{V_{PL}}+\frac{Q_{GS}}{\left(\frac{V_{PL}+V_{th}}{2}\right)}\right] \quad (5)$$

Where Q_{GS} — gate-source charge, Q_{GD} — gate-drain charge.

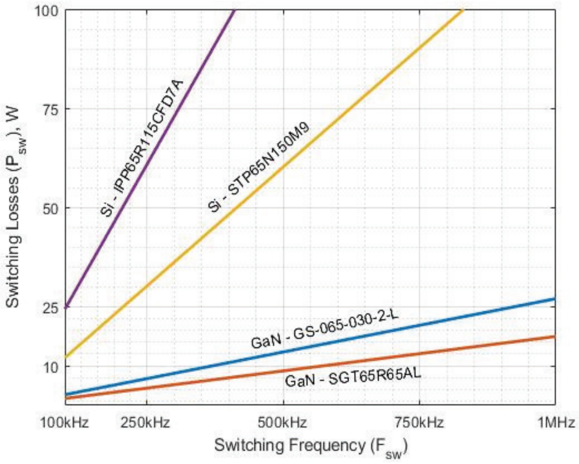

Fig. 1. Switching losses analysis of various Si and GaN transistors

In practical application, comparing transistors two transistors based on gallium nitride and two transistors based on silicon with similar electrical characteristics. According to datasheets of most popular models, gallium nitride-based transistors have lower charge values of Q_{GS} and Q_{GD}, therefore the total switching losses will be ten times less than that of silicon-based field-effect transistors. Fig. 1 presents the results of evaluating the values of switching losses of transistors based on gallium nitride and silicon of individual manufacturers used.

Considering also the lower conduction losses, as well as the zero-recovery time due to the enhanced structure of GaN transistors, it can be concluded that the total transistor losses will be less than that of standard field-effect transistors. This makes it possible to achieve greater efficiency of the power converters.

Analysis of Switching Losses in Flyback Converters performance

The flyback converter belongs to the type of isolated SMPS with galvanic isolation between input and output. The power transformer provides function of energy storage and transfer and a protective mechanism in case of a short circuit. The principle of operation of the converter is based on the accumulation of energy in the transformer and transferring it to the output of the device during the operation cycle, when the main transistor opens and closes, respectively [3].

The block diagram of the flyback converter with a GaN HEMT is shown in Fig. 2.

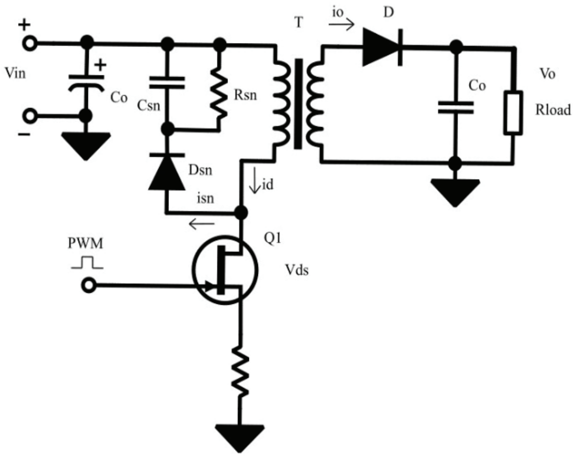

Fig. 2. Flyback converter

Operation modes. In flyback converters, the effect of switching losses significantly differs based on the operational mode, specifically whether in Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM).

In CCM, the inductor's current does not reach zero at any point during the switch cycle, leading to elevated average current levels and, consequently, increased conduction losses. Notably, CCM incurs substantial switching losses due to the elevated currents and voltages during transitions. Furthermore, the frequency of switching plays a pivotal role, with heightened frequencies escalating the switching losses.

Conversely, in DCM, the inductor current reduces to zero for a part of the cycle. A distinctive characteristic of DCM is the inductor's current dropping to zero before the commencement of the subsequent switching cycle. This phenomenon of zero current switching in DCM effectively diminishes switching losses, as the switch activation and deactivation occur at zero or near-zero current levels, leading to reduced energy dissipation during transitions. In DCM, the switching frequency is load-dependent, decreasing under lighter loads and extending the zero-current duration, thereby further mitigating switching losses in light-load scenarios [4]. Additionally, the peak current in DCM is lower than in CCM for equivalent output power, resulting in reduced voltage stress on the switch due to lower peak current and the operational nature of the flyback transformer in DCM. A notable drawback of DCM is the higher output voltage ripple, attributed to the more intermittent energy transfer to the output, as the inductor current zeroes in each cycle.

Switching losses in DCM primarily arise from two aspects: energy dissipation during the switch's ON and OFF states, and the diode's reverse recovery losses. However, these losses are typically lower in DCM compared to CCM. The exact magnitude of these losses also hinges on variables such as switching frequency, converter design, and load conditions.

Flyback transformer. In flyback converters, the primary magnetizing inductance stores energy when the switch is in ON state. This energy is transferred to the secondary side when the switch is turned off. When the switch turns off, the current through the inductance must rapidly decrease, leading to high dI/dt and associated losses.

The primary inductance (L_P) resonates with the total drain capacitance (C_{Drain}) when the transformer is discharged, leading to high frequency oscillations. This resonance is critical in determining the turn-on losses in the switch.

Osculation period is determined by:

$$T_{RES} \approx 2\pi\sqrt{L_P \cdot C_{Drain}} \tag{6}$$

Resonance can lead to additional losses, as energy is dissipated in the circuit elements during each oscillation. This can reduce the overall efficiency of the converter. The oscillatory behaviour can generate noise and electromagnetic interference (EMI), which can interfere with other components.

The small parasitic capacitance of the gallium nitride field-effect transistor, as well as the use of snubber circuit of a zener diode and a diode made it possible to reduce the load on the field-effect transistor, increasing the reliability of the circuit, as well as to eliminate the problem of electromagnetic interference caused by high-frequency vibrations.

Control. Among the disadvantages of high-speed GaN transistors, there are difficulties in controlling the device by applying a control signal to the gate of the transistor, as well as low threshold voltage and capacitance at the gate of the transistor, limiting the rate of rise of voltage and current dV/dt and dI/dt), leading to noise and oscillations [5].

Gate drive losses, related to the charge to be delivered to the gate each time when the switch is on ON state. This charge, supplied at oscillation frequency rate (f_{SB}), results in an equivalent gate drive current (I_{GD}). The parameter to be considered is:

$$I_{GD} = Q_G \cdot f_{SB} \tag{7}$$

Practical solution to these problems is the use of specialized integrated transistor gate drivers with using proper GaN HEMT with lower gate charge and parasitic capacitances.

Design and Simulation of GaN HEMT Flyback converter

The block diagram of the developed flyback converter, which incorporates a gallium nitride (GaN) transistor, is depicted in Fig. 3. The input filter and diode bridge maintain a consistent voltage at the converter's input. A circuit comprising Zener diode VD1 and diode VD2 limits inductive surges from the primary winding of transformer T1 which allows limiting voltage surges to protect the power transistor VT1 from breakdown. The Start-Up circuit, essential for regulating the input power of the PWM-controller LTC3803 and the specialized GaN transistor driver LMG1020, includes power switches and limiting resistors. Initially, it draws power from the supply voltage and after starting the converter from the additional winding of transformer T1. Capacitor C1 is instrumental in stabilizing the converter’s output voltage. The gate driver for the power GaN transistor generates the control signal and provides the required gate current for the transistor.

This converter operates from a 220 V power source, delivering an output power of 10 W. The transistor’s switching frequency is set at 350 kHz, and the converter functions in Discontinuous Conduction Mode (DCM), a common mode for low power consumption devices.

A GaN transistor, model GS-065-004-1-L, manufactured by GaN Systems, was selected for this device based on its suitable specific parameters.

The custom developed transformer has the following parameters:

- A ferritic core of type EE 30/15/7, using ferrite material 3F35;

By understanding the transformer’s parameters, one can simulate its behaviour, along with the entire converter, in a SPICE simulator, factoring in all these losses.

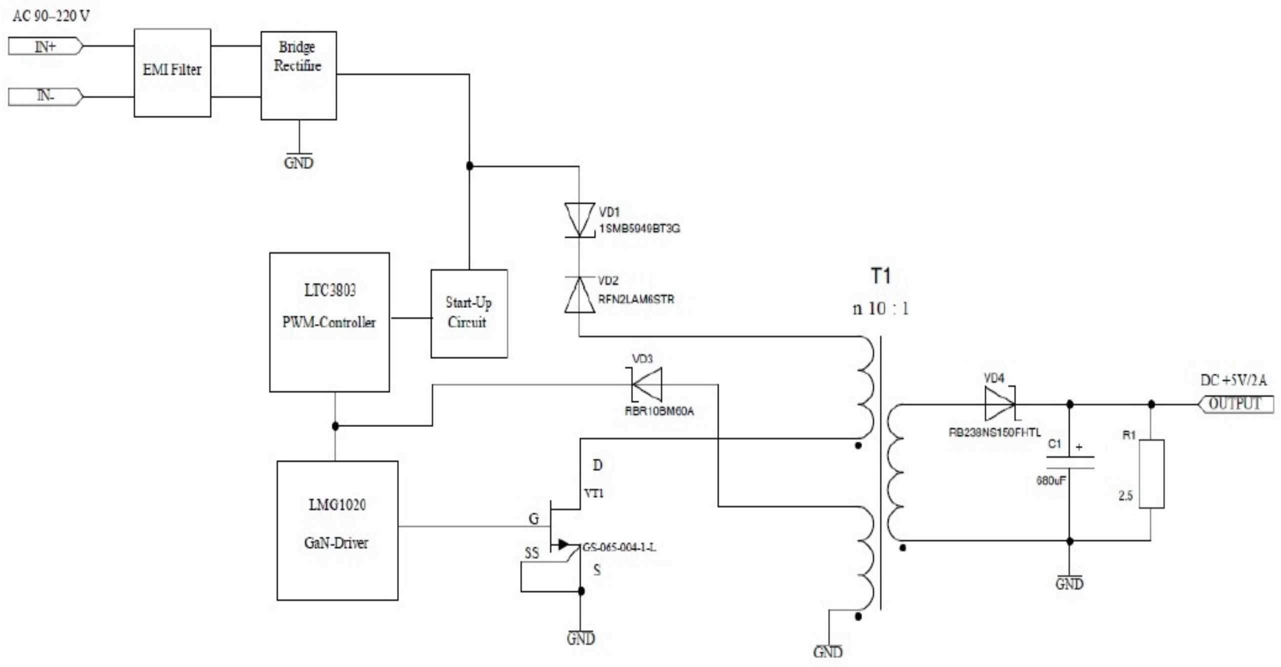

Fig. 3. Block diagram of the designed flyback converter

- Twenty turns in the primary winding and two in the secondary.
- Peak currents of 0.56 A in the primary and 5.66 A in the secondary winding.

To mitigate transistor breakdown risks due to high voltage surges from inductive surges in the transformer, a voltage suppressor circuit, consisting of a Zener diode and a diode is used.

The converter was modelled using SPICE (Simulation Program with Integrated Circuit Emphasis), a method ensuring accurate emulation of the electronic components' characteristics and the processes present in a real device. Special attention was given to simulating the power transformer, focusing on the ferrite core's behaviour, including static hysteresis, magnetizing inductance, core losses, and the parasitic parameters of windings. LTSpice facilitates transformer modelling with a hysteresis model of the magnetic core, leveraging the core’s basic hysteresis loop parameters and linear dimensions. [6].

Fig. 4 illustrates the transformer's core loss region within the hysteresis loop. In designing energy converters and switching power supplies, it's crucial to account for energy losses in power elements. These losses, such as ohmic, hysteresis, eddy current, and dielectric losses in insulators, dissipate in various forms of radiation through the converter's parasitic elements.

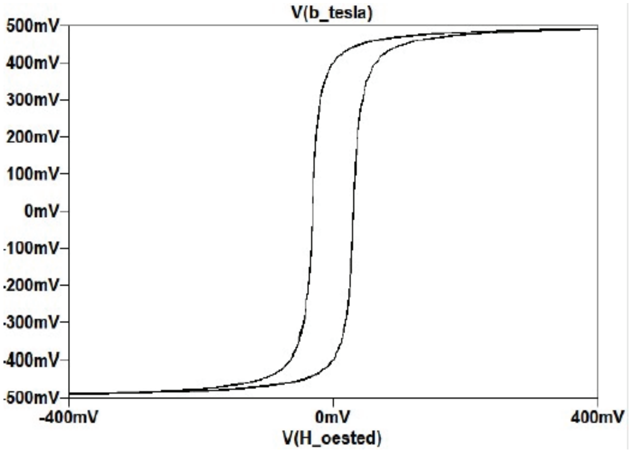

Fig. 4. The loop of the hysteresis of the simulated transformer

Fig. 5 and 6 display the drain current and drain-source voltage characteristics of the GaN transistor. The transistor’s switching disrupts the current through the transformer’s leakage inductance, causing a high voltage surge across the drain and source of the HEMT. Resonance, resulting from the leakage inductance of the transformer and the transistor's parasitic capacitance, induces high-frequency oscillations. The drain voltage value during turn-on in DCM operation is influenced by these oscillations. An increase in input voltage, despite elevating the oscillation's settling value, may lower the turn-on value due to specific combinations of T_{ON}, T_{OFF}.

The minimal parasitic capacitance of the GaN field-effect transistor, coupled with the snubber circuit comprising a Zener diode and a diode, has enabled a reduction in the load on the field-effect transistor. This improvement not only enhances circuit reliability but also addresses issues of electromagnetic interference caused by high-frequency oscillations.

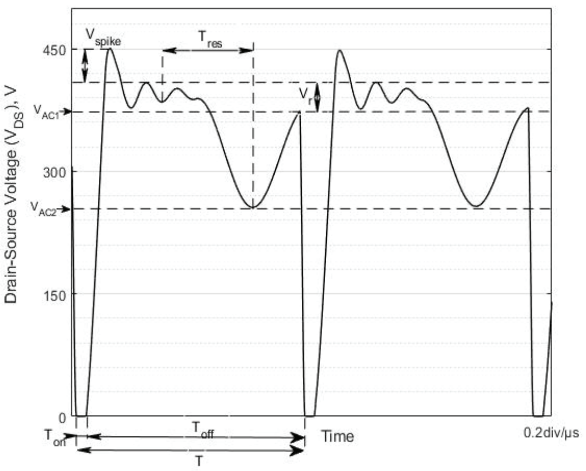

Fig. 5. Time characteristic drain-source voltage (V_{DS}) of the transistor

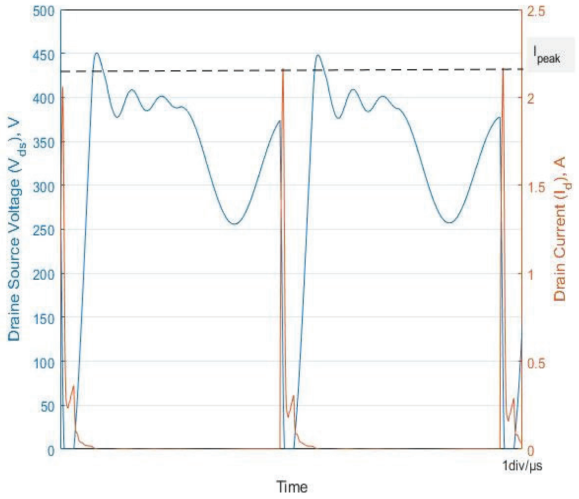

Fig. 6. Time characteristic of the current (I_D) and voltage (V_{DS}) of the drain-source of the transistor

Fig. 7 illustrates the detailed timing diagram of the Pulse Width Modulation (PWM) control, specifically highlighting the short pulse sequences in the Gate circuit. These pulses are characterized by their swift transition times between the ON and OFF states. The ability to achieve such short pulse widths is intricately linked to the condition of the capacitive load within the circuit. Moreover, the operating frequency of the gate driver plays a crucial role in determining these pulse widths. This figure effectively demonstrates how these two factors interact to influence the precise timing and duration of the PWM control pulses.

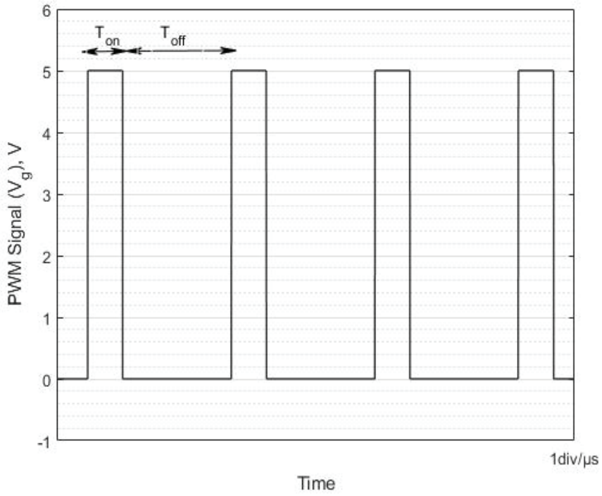

Fig. 6. Time characteristic of Gate Voltage (V_G) of the transistor

Fig. 8 illustrates the power dissipation in the utilized GaN HEMT. The observed power peaks are transient, resulting from the HEMT's switching losses. The average power dissipation approximates 5 W. GaN HEMTs are noted for their low ON-state resistance and thermal resistance, attributed to reduced resistive power losses. The absence of a built-in diode in GaN HEMTs further lowers switching and total power losses in the transistor, significantly enhancing the converter's efficiency.

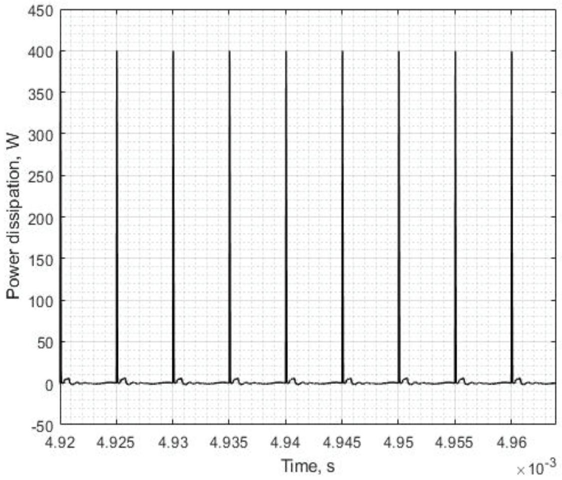

Fig. 7. Power dissipation of GaN HEMT

The enhanced efficiency of the converter is notably influenced by the omission of a built-in diode in the GaN HEMT. This design choice significantly lowers the transistor's switching losses. Additionally, it contributes to a reduction in the overall power losses of the transistor, a key factor that facilitates a marked improvement in the converter's efficiency.

Conclusions

In conclusion, the advantages of the designed flyback converter include a significant reduction of dynamic losses and pulsations on main transistor, with low heat dissipation. Considering the lower power losses, as well as the zero-recovery time it can be concluded that using gallium nitride transistors makes it possible to operate at higher switching frequencies.

Among the disadvantages of the device is the need for high-speed gate drivers for the GaN HEMT to compensate for unwanted effects such as oscillations and noise on the transistor's gate, which can lead to uncontrolled turning on of the transistor.

Article provides a thorough investigation into the optimization of GaN HEMTs for high-frequency flyback converters, offering valuable guidelines for applications requiring compact power sources, such as in small aircraft systems and telecommunication networks.

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Арсенюк Д.О., Зіньковський Ю.Ф.

Мінімізація комутаційних втрат на високих частотах у широкозонних нітрид галієвих транзисторів з високою рухливістю електронів для зворотноходових перетворювачів

Проблематика. У сфері імпульсних джерел живлення зворотні перетворювачі відіграють ключову роль для ефективного перетворення напруги та забезпечення електричної ізоляції. Зазвичай ці перетворювачі базуються на кремнієвих транзисторах, однак вони стикаються з проблемами, що перешкоджають їхній енергоефективності та стабільності роботи, зокрема зі збільшенням втрат на перемикання на високих частотах. Це пояснюється нижчою швидкістю перемикання та високим опором у відкритому стані, що є характерним для кремнієвих транзисторів. Така неефективність призводить до значного розсіювання потужності, знижуючи загальну ефективність. Тепло, що виділяється внаслідок цих втрат, вимагає складних систем контролю температури, що збільшує експлуатаційне навантаження та впливає на надійність і довговічність перетворювачів. Крім того, обмеження робочої частоти цих перетворювачів ускладнює роботу на вищих частотах, що було б вигідним для зменшення розміру пасивних компонентів, але погіршує проблеми втрат на комутацію та виділення тепла в кремнієвих транзисторах.

Мета дослідження. Ця стаття має на меті провести комплексне дослідження та оптимізацію зворотноходових перетворювачів на основі транзисторів з високою рухливістю електронів (HEMT) з нітриду галію (GaN), фокусуючись на мінімізації втрат при високочастотному перемиканні. Дослідження охоплює внутрішні властивості GaN HEMT, виокремлюючи їх переваги порівняно з традиційними кремнієвими аналогами, та акцентує увагу на схемотехнічних засобах мінімізації втрат і їх особливостях.

Метод. У дослідженні було проведено детальний аналіз комутаційних втрат GaN HEMT при високочастотному перемиканні. Використовуючи комп'ютерні імітаційні моделі, досліджено вплив різних параметрів, таких як струми та напруги на транзисторі GaN, розсіювана потужність і вихідні характеристики пристрою з різними топологіями схем на ефективність комутації.

Результати дослідження. Результати надають уявлення про стратегії оптимізації топології, включаючи використання драйверів затвору транзистора та ланцюгів демпфера, які мають ключове значення для підвищення загальної ефективності та надійності зворотноходових перетворювачів.

Висновки. Стаття пропонує глибоке дослідження оптимізації високочастотних зворотноходових перетворювачів, використовуючи GaN HEMT, і пропонує цінні вказівки для приладів, які потребують компактних джерел живлення, наприклад, у системах малих літаків та телекомунікаційних мережах.

Ключові слова: *зворотні перетворювачі; AC-DC; SMPS; нітрид галію; GaN; широкозонні напівпровідники.*