ЕЛЕКТРОНІКА

UDC 621.373
DOI https://doi.org/10.32782/2663-5941/2024.4/56

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SIMPLIFIED SHUNT BANDWIDTH CHARACTERIZATION GENERATOR FOR WIDE BANDGAP POWER CONVERTERS

Modern wide bandgap devices based on gallium nitride (GaN) and silicon carbide (SiC) can achieve switching transients within a few nanoseconds or even faster. To thoroughly measure and analyze these fast-switching transients processes, high bandwidth sensors are required. These sensors must introduce minimal additional parasitic inductance to the switching power loop. As switching times decrease, non-ideal effects become increasingly significant, potentially obscuring useful signal measurements. In miniature circuits, current probes and certain other methods require looping a high-current wire to accommodate the current measurement device. This loop adds detrimental inductance to the circuit, altering its operating characteristics at short response times. Therefore, current probes and magnetic field-based current measurement methods (for example, Hall-effect devices and Rogowski coils) are less suitable for high-frequency, wide-bandwidth current measurements.

Shunt resistors are a primary technique for high-frequency current measurements. A common way to characterize a shunt resistor or other resistive current measurement device/method is by applying a well-defined, sharp rise time (in the order of nanoseconds or less) voltage source through it and comparing the measured voltage. An example setup involves connecting the shunt in series with a resistive load and a specially designed GaN-based half-bridge. The switch node voltage can be easily measured, from which the current flowing through the shunt resistor and the load resistor can be derived. However, this setup requires a relatively expensive and complex arrangement.

In this paper, we propose a cheaper and simpler alternative for shunt bandwidth measurement generator, utilizing off-the-shelf logic elements and generally accessible hardware.

Key words: *Gallium Nitride (GaN), power converters, wide bandgap semiconductors, shunt characterization, pulse generator.*

Introduction and Problem Statement. Wide bandgap semiconductors, specifically high electron mobility transistors (HEMTs) in gallium nitride (GaN), outpace silicon-based power semiconductors in switching speeds. This rapid switching introduces challenges in accurately measuring voltage and current. While devices capable of measuring fast transient voltages exist, current measurement techniques lag behind, particularly for high-frequency applications. Current measuring devices often need physical integration into the circuit or magnetic coupling, which can disrupt the circuit's operation.

For power converters below 1MHz, current measurement technology is well-established. However, these devices have limited bandwidth, suffer from response time delays, and struggle with high-frequency accuracy, increasing their susceptibility to interference. As switch times decrease, these non-ideal characteristics intensify, eventually obscuring critical measurements. In miniaturized circuits, methods like current probes require looping the circuit wire to accommodate measurement devices, such as hall-effect sensors or Rogowski coils. This looping introduces harmful inductance, altering the circuit's behavior at quick response times.

A typical method involves characterizing the coaxial shunt resistor or another resistive measurement technique by running a well-defined, sharp rise time current pulse through it and comparing the resulting voltage measurement. For example, one might connect the shunt in series with a resistive-load half-bridge [1] (Figure 1).

Measuring the switch node voltage allows us to determine the current through both the coaxial

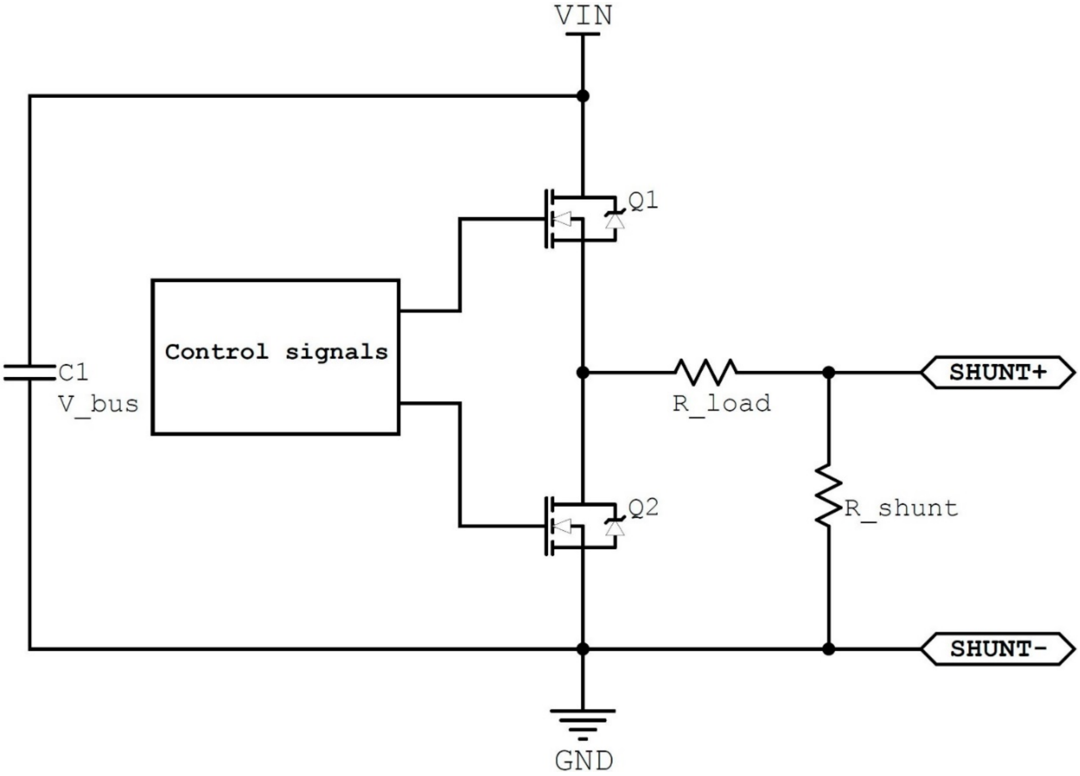

Fig. 1. Resistive-load half-bridge

shunt resistor and the load resistor. However, this configuration struggles with bandwidth measurements extending into several GHz. The frequency content of the rising edge can be calculated as [2]:

$$f_c = \frac{0.35}{t_r} \tag{1}$$

Despite the superior speed of wide bandgap devices over silicon devices, producing such fast-rising pulses poses a substantial challenge. This paper suggests a more cost-effective and straightforward alternative for measuring shunt bandwidth, using readily available logic elements and accessible hardware.

Analysis of recent research and publications. he development of measurement shunts with high bandwidth and the integration of short-rise time generators for shunt bandwidth measurement have become an important topic in modern power electronics. Current shunts are characterized by their wide frequency response and short rise times, making them highly accurate for resistance measurements in high-frequency environments. According to a study published on NCBI (2021), these current shunts exhibit excellent performance, demonstrating their crucial role in applications requiring precise current measurement at high speeds (P Piekielny, A Waindok) [3].

The construction and installation of shunts are critical factors influencing measurement accuracy. An investigation into miniaturized measurement shunts reveals the potential for significant errors due to improper design, leading to either too short or too long rise times. This underscores the need for meticulous engineering in the development of shunt resistors to ensure reliable performance in high-frequency applications and provided foundational insights into the challenges and solutions related to high-frequency shunt measurements. (J L Joannou et. al.) [4].

Research focusing on shunt resistor-based current measurements for fast-switching GaN devices has shown that shunt resistors with very low inductance or current viewing resistors (CVRs) can measure high currents at high frequencies with minimal offset. This capability is crucial for accurately capturing the behavior of fast-switching devices in power electronics (T Wickramasinghe et al.) [5].

The design and implementation of pulse generators capable of producing signals with extremely short rise times are essential for testing the bandwidth and response of measurement equipment. Discussions on platforms like EEVblog provide practical insights into constructing pulse generators with known rise times to evaluate the performance of shunt resistors (EEVblog) [6].

Recent advancements in probing techniques have enabled voltage and current measurements with high bandwidths without compromising PCB layout, particularly for signals with very short rise times. A key development in this field is the introduction of a monolithic microwave integrated circuit (MMIC) comb generator, which can produce repetitive narrow pulses with a duration of 7.1 ps and sharp edges with a 4.2 ps fall time. This circuit, designed using 250 nm indium phosphide (InP) heterojunction bipolar transistor (HBT) technology and differential pairs, was characterized using a 110 GHz sampling oscilloscope. The band-limited frequency spectrum of the pulse was de-embedded at the circuit reference plane, showing a pulse duration of 7.1 ps and a peak amplitude of -0.333 V. In the frequency domain, the comb generator provided -48.7 dBm of output power at 110 GHz with a 1 GHz input signal, as reported by M. E. Urteaga et al. from Bristol University (2022) [7]. This innovation is crucial for capturing rapid transients in modern power electronics.

A notable study by W Zhang et al. on high-bandwidth, low-inductance current shunts for wide-bandgap devices further confirms these advancements, emphasizing the dynamic characterization required for precise measurements [8]. Their research, published in 2021, marks a significant step forward in the field.

Additionally, research on a novel calibration method of broadband shunts by Z Yang et al. has introduced innovative approaches to enhance the accuracy and reliability of broadband shunt measurements. This method, discussed in their 2022 study, addresses the challenges of calibration in high-frequency environments, ensuring better performance and reliability [9].

These advancements in shunt bandwidth measurement and short-rise time generators have significantly enhanced the accuracy and reliability of high-frequency measurements in modern electronics. Despite the all advancements in the field, there is a room for improvement for low-cost, short-rise time pulse generator.

Task statement

In this paper, we propose a cost-effective and simplified method for shunt bandwidth measurement using off-the-shelf logic elements and accessible hardware. Traditional methods for bandwidth measurement often involve complex and expensive setups that add detrimental inductance, affecting measurement accuracy. Our approach minimizes these issues by leveraging readily available components to achieve fast-switching transients, ensuring reliable characterization of shunt resistors under nanosecond-level switching conditions. This innovation provides a practical alternative to conventional methods, offering both efficiency and accuracy in high-frequency measurement applications.

Outline of the main material of the study

The ultra-short rise time pulse generator circuit described here is tailored for shunt bandwidth measurement applications, which are critical in analyzing the fast-switching transients of modern wide bandgap devices such as gallium nitride (GaN) and silicon carbide (SiC). These devices achieve switching transients within a few nanoseconds or even faster, necessitating high bandwidth sensors that introduce minimal additional parasitic inductance to the switching power loop [10]. As switching times decrease, non-ideal effects become more pronounced, potentially obscuring useful signal measurements. Traditional current measurement methods, such as current probes and magnetic field-based devices, are unsuitable for high-frequency, wide-bandwidth current measurements due to the additional inductance they introduce. Instead, shunt resistors are preferred for their minimal inductive impact.

To accurately characterize a shunt resistor's bandwidth, a well-defined, sharp rise time voltage source is required. This source must apply a voltage through the shunt resistor, allowing for the measurement of the resulting voltage drop. The pulse generator circuit described here provides a cost-effective and simple alternative to more expensive and complex setups traditionally used for this purpose.

The proposed circuit (Figure 2) is divided into three main sections: the power supply LDO, IC's decoupling, and the pulse generator and driver.

The power supply section ensures a stable voltage supply for the circuit. It starts with an input protection diode (VD1) that protects against reverse voltage. Capacitors C1 and C3 provide bulk capacitance for input voltage smoothing, while the LDL1117S50R LDO regulator ensures a regulated output voltage. Output capacitors C2 and C4 further smooth the output voltage, and an indicator LED (VD2) signals the presence of the output voltage. This stable supply is crucial for the reliable operation of the subsequent stages.

The decoupling section focuses on stabilizing the power supply for the integrated circuits (ICs). Decoupling capacitors C5 and C6 provide local filtering to minimize noise and ensure stable operation of the ICs. The Schmitt trigger inverter (D3G, SN74AHC14DRG3) used in this section is critical for generating the fast edge transitions needed for the pulse.

The core of the circuit lies in the pulse generator and driver section. The Schmitt trigger inverter (D3A, SN74AHC14DRG3) is configured with a feedback

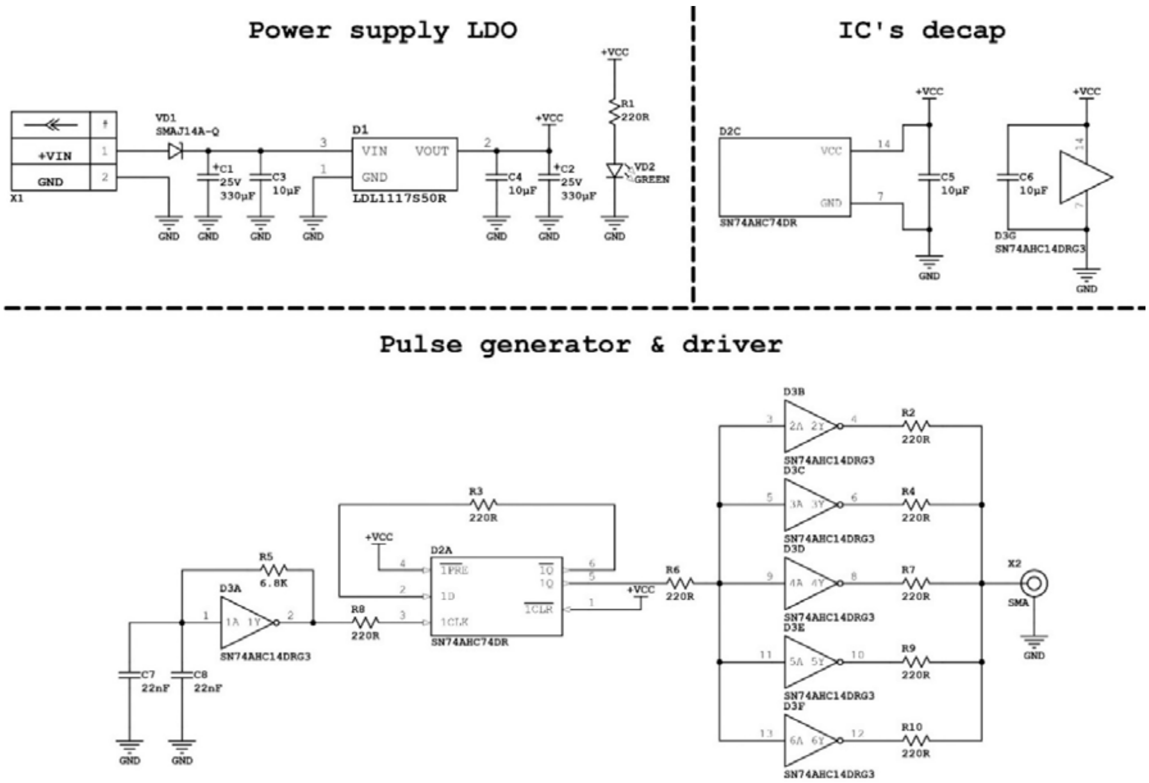

Fig. 2. Proposed generator schematic

resistor (R5) and capacitors (C7, C8) to create an oscillator. This configuration generates a square wave with very fast rising and falling edges. The frequency of oscillation is set to approximately 12 kHz by the RC network comprising R5, C7, and C8. This relatively low frequency allows the circuit to be used for characterizing shunt resistors with minimal impact from the oscillation frequency. The oscillation frequency can be estimated using following formula [11]:

$$f = \frac{1}{RC\,ln\left(\frac{V_{cc} - V_{T-}}{V_{cc} - V_{T+}} \cdot \frac{V_{T+}}{V_{T-}}\right)} \qquad (2)$$

where V_{cc} is supply voltage (5V), V_{T+} – positive-going threshold, V_{T-} – negative-going threshold, R and C – values of configuration resistor and capacitor.

The D-type flip-flop (D2A, SN74AHC74DR) is configured into a divider circuit, ensuring a 50% duty cycle of produced pulses, regardless of input signal characteristics.

The generated square wave is then fed into the remaining inverters (D3B-D3F) connected in parallel. This parallel configuration boosts the drive capability and maintains the integrity of the fast edges, which are essential for accurate shunt bandwidth measurements. Each inverter output is coupled with a series resistor (R2, R4, R7, R9, R10) to ensure appropriate output impedance matching. These resistors approximate a 50-ohm output impedance, crucial for minimizing signal reflections and ensuring efficient power transfer to the measurement setup. Additionally, the resistors provide protection against potential short circuits by limiting the current.

The pulse generator's output is connected to an SMA connector (X2), facilitating easy connection to a measurement setup that includes the shunt resistor and an oscilloscope. When a pulse is transmitted through the shunt resistor, the voltage drop across the resistor can be measured. This measurement allows for the determination of the current flowing through the shunt, thereby characterizing the resistor's bandwidth. The fast rise time of the pulse ensures that the measurement captures high-frequency characteristics accurately.

This pulse generator circuit offers an economical and efficient solution for generating the fast rise time pulses required in shunt bandwidth measurement applications. Its design leverages a Schmitt trigger inverter and carefully selected passive components to achieve rapid edge transitions, making it suitable for high-resolution analysis of fast-switching transients in modern wide bandgap devices. By providing a simpler and cheaper alternative to traditional setups, this circuit enables precise bandwidth characterization of shunt resistors, facilitating better design and

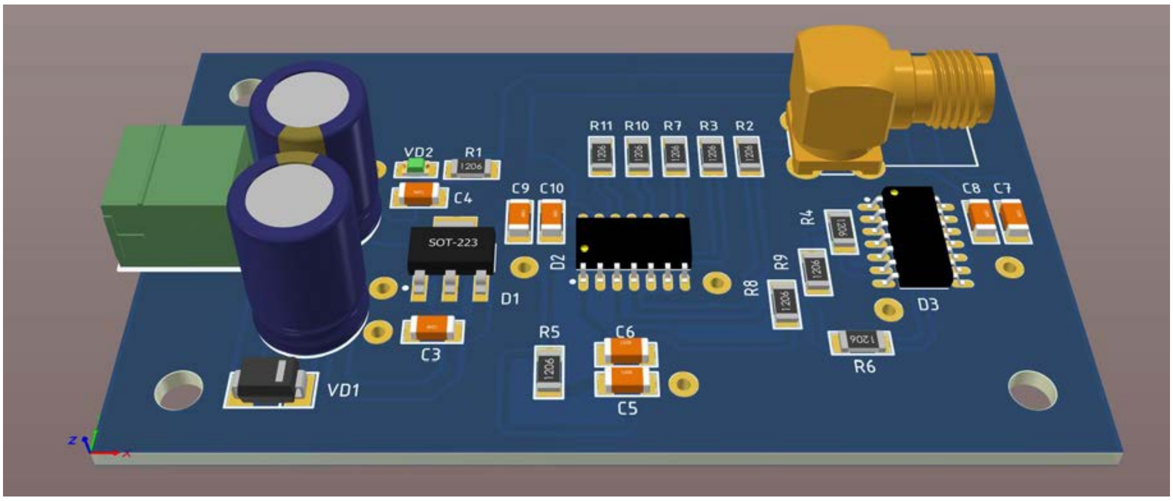

Fig. 3. 3D model of PCB of the generator

analysis of high-speed electronic systems. 3D model of designed PCB is displayed on Figure 3.

The pulse generator circuit described was tested, and the output waveforms were captured using an oscilloscope. The first waveform shows a square wave with a frequency of approximately 6.536 kHz, a peak-to-peak voltage of 5.52V and rise and fall times around 10 nanoseconds (oscilloscope limit). This confirms the circuit's capability to produce sharp edges essential for bandwidth characterization applications (Figure 4).

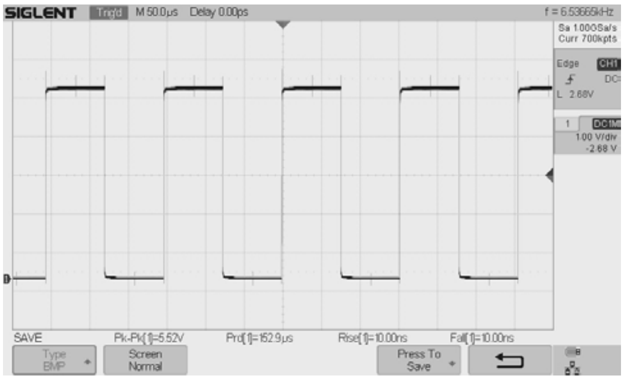

Fig. 4. Square Wave Output from Pulse Generator Circuit

The second waveform (Figure 5) provides a closer look at the rising edge of the pulse, displaying a rise time of approximately 1.94 nanoseconds. This rise time is limited by the oscilloscope's measurement capabilities, indicating that the actual rise time could be even faster. Despite some ringing observed in the waveform, the fast rise time is adequate for accurately measuring the bandwidth of shunt resistors in high-speed electronic circuits, ensuring minimal introduction of parasitic inductance. This performance demonstrates the circuit's suitability for precise characterization of high-frequency current measurement devices.

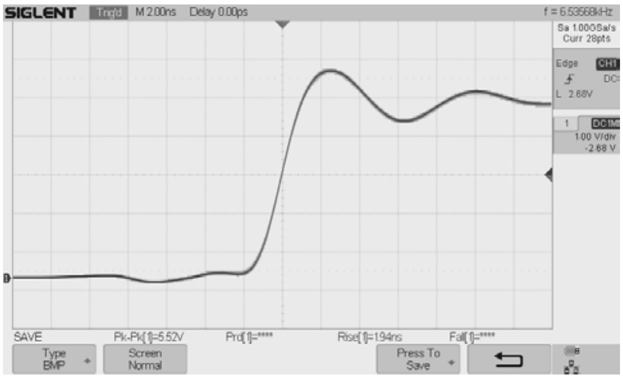

Fig. 5. Detailed Rising Edge of Pulse from Pulse Generator Circuit

Conclusions. The proposed pulse generator circuit provides a cost-effective and efficient solution for generating ultra-short rise time pulses necessary for shunt bandwidth measurement in high-speed electronic circuits. Utilizing readily available off-the-shelf components, this design offers an alternative to more complex and expensive setups traditionally used for this purpose. The circuit leverages a Schmitt trigger inverter to achieve rapid edge transitions, essential for accurately characterizing the bandwidth of shunt resistors used in modern wide bandgap devices double-pulse testing such as gallium nitride (GaN) and silicon carbide (SiC).

Oscilloscope measurements confirm the circuit's performance, displaying a square wave with a frequency of 6.536 kHz, a peak-to-peak voltage of 5.52V, and rise and fall times around 10 nanoseconds, limited by the oscilloscope's capabilities. Detailed analysis of the rising edge reveals a rise time of approximately 1.94 nanoseconds, indicating the circuit's capability to produce even faster transitions.

This fast rise time is crucial for accurately measuring the bandwidth of shunt resistors, as it ensures higher bandwidth of the measurement setup. The simplicity and low cost of the circuit make it an accessible tool for engineers and researchers working with high-frequency, wide-bandwidth current measurements in power electronics.

Overall, this pulse generator circuit demonstrates its suitability for precise characterization of high-frequency current measurement devices, facilitating better design and analysis of fast-switching transients in modern wide bandgap semiconductor applications.

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Бурковський Я.Ю., Зіньковський Ю.Ф. ГЕНЕРАТОР ІМПУЛЬСІВ З КОРОТКИМ ЧАСОМ НАРАСТАННЯ ДЛЯ ВИМІРЮВАННЯ ХАРАКТЕРИСТИК ШУНТІВ ПЕРЕТВОРЮВАЧІВ НА ОСНОВІ НАПІВПРОВІДНИКІВ З ШИРОКОЮ ЗАБОРОНЕНОЮ ЗОНОЮ

Сучасні силові перетворювачі на основі нітриду галію (GaN) і карбіду кремнію (SiC) (напівпровідників з широкою забороненою зоною) можуть досягати перехідних процесів перемикання до кількох наносекунд або навіть швидше. Для ретельного вимірювання та аналізу цих перехідних процесів потрібні датчики зі значною смугою пропускання. Ці датчики повинні вводити мінімальну додаткову паразитну індуктивність до комутаційного контуру живлення. У міру того, як час перемикання зменшується, паразитні ефекти стають все більш значущими, потенційно вносячи недопустимі завади у корисний виміряний сигнал. У компактних перетворювачах індуктивні датчики струму та деякі інші методи вимагають пропускання силового дроту від комутаційного контуру через датчик. Створена петля додає значну паразитну індуктивність до схеми, змінюючи її робочі характеристики та час нарастання. Тому датчики струму та методи вимірювання струму на основі впливу магнітного *поля (наприклад, пристрої на ефекті Холла та котушки Роговського) менш придатні для вимірювання струму в високочастотних перетворювачах, де критичною є широка смуга пропускання.*

Шунтуючі резистори є основним методом вимірювання струмів високої частоти. Загальноприйнятий спосіб охарактеризувати шунтуючий резистор або інший пристрій/метод резистивного вимірювання струму полягає в прикладанні до нього джерела струму з чітко визначеним швидким часом наростання та порівняння виміряної напруги. Приклад такої установки передбачає послідовне з'єднання шунта з резистивним навантаженням і напівмостом на основі нітрид-галієвих силових елементів. Однак ця установка відносно дорога та конструкційно складна.

У цій статті ми пропонуємо дешевшу та простішу альтернативу для вимірювання смуги пропускання шунта, використовуючи готові логічні елементи та загальнодоступне обладнання.

Ключові слова: *Нітрид галію (GaN), перетворювачі потужності, широкозонні напівпровідники, вимірювання характеристик шунта, генератор імпульсів.*