

A 125 kHz Self-Oscillating Inverter for Inductive Power Transfer Applications With Power MOSFET In-Circuit Self-Test

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Abstract—Low-frequency, self-oscillating inverters are widely used in Inductive Power Transfer (IPT) applications such as induction heating, household appliances, and electric vehicles. Due to cost constraints, transistors are often operated close to their absolute maximum ratings, which has a significant impact on the system reliability. The gate charge required to turn on a MOS transistor is closely related to oxide damage and can therefore be used as an indicator of device stress and aging. This paper proposes a novel approach to measure the turn-on gate charge that does not require the drain/source terminals to be disconnected from the high-current path, making it possible to monitor a power MOSFET under real conditions. For the first time, the idea is applied to an IPT system based on a self-oscillating inverter. The inverter schematic is modified to allow automated In-Circuit Self-Test (ICST), and experimental results are obtained. The turn-on gate charge and plateau gate voltage measured in-circuit are consistent with those obtained for the isolated MOSFETs (i.e., with an off-circuit test fixture). Although preliminary, these results demonstrate that ICST is a promising method for reliability assessment and predictive maintenance of WPT and IPT systems.

Index Terms—Self-oscillating inverter, IPT, WPT, In-Circuit Self-Test, In-Situ Self-Test, power MOSFET, reliability, aging

I. INTRODUCTION

The transfer of power through inductive coupling represents an approach to wireless energy transmission, which is pivotal in numerous modern technological applications. Inductive Power Transfer (IPT) systems are widely implemented in devices ranging from electric vehicle (EV) charging stations [1], to implantable medical devices [2], offering a contactless and efficient solution for wireless power delivery (see for example the Qi standard). The core principle of IPT relies on the resonant coupling of electromagnetic fields between two circuits: a transmitter and a receiver usually composed of inductors and capacitors. Power oscillators play a critical role in this process by generating and maintaining the alternating current (AC) signals that drive the transmitter coil.

The design and optimization of self-oscillating inverters (i.e. the power oscillator) in inductive power systems significantly

impact overall efficiency, stability, and adaptability to varying load conditions. By creating consistent and precisely tuned frequencies, oscillators enable the system to achieve maximum power transfer. Despite the apparent simplicity of this concept, practical implementations must address several challenges, including energy losses due to non-ideal components, electromagnetic interference (EMI), and variations in the spatial alignment of the coils [3]-[5].

Due to cost constraints, inverter transistors are often operated close to their absolute maximum ratings, which has a significant impact on overall system reliability. Predictive maintenance is a methodology to proactively address reliability issues, and is therefore an emerging requirement for mission critical and operational safety systems. In-Circuit Self-Test (ICST) approaches have therefore been proposed in recent years to continuously monitor the aging of power transistors in the real circuit (and under the real conditions) in which they operate [6]-[8].

The gate charge required to turn on a MOS transistor is closely related to oxide damage and can therefore be used as an indicator of device stress and aging [9]. The turn-on gate charge can be measured with a simple transient experiment [10], as proposed by several authors [11], [12]. The main advantage of such an approach is that the gate charge (and its dependence on the gate-to-source voltage and gate-to-drain capacitances) can be determined without disconnecting the drain/source terminals of the power MOSFET from the high-current path, allowing true in-circuit (or in-situ) measurements.

In this paper, for the first time, a self-oscillating inverter for IPT applications is modified to enable the in-circuit self-test of the power MOSFETs. The turn-on gate charge is measured with the method proposed in [13]. To this purpose the oscillation loop is opened with the adoption of analog switches, the transistor gates are isolated and the gate-to-source voltage is measured during the turn-on transient. The oscillator has two operating modes, namely the inverter mode (or oscillator mode, which is the normal

one) and the self-test mode. Both modes are automatically controlled by an Arduino Uno R3 board which is also used to take the measurements and to upload the data to a PC. In the next sections, we will describe how to modify an oscillating inverter to allow in-circuit self-testing, and we will experimentally demonstrate the proposed idea.

II. MATERIAL AND METHODS

One of the most important transistor parameters is r_{ds}^{on} , the drain-to-source resistance in the on state. In fact, such a resistance has a significant impact on the switching losses and the maximum static current for a given thermal budget (thermal power dissipated by the package to reach the maximum junction temperature). A very important relationship states that r_{ds}^{on} is inversely proportional to the turn-on gate charge Q_g as:

$$r_{ds}^{on} = \frac{L^2}{\mu_n Q_g} \quad (1)$$

where L is the channel length and μ_n is the carrier mobility (electrons for a n-channel device). As a consequence r_{ds}^{on} can be indirectly monitored determining the turn-on gate charge, and this is the basic idea of the present study.

A. Self-oscillating inverter

To demonstrate the feasibility of in-circuit measurement of the turn-on gate charge and, more specifically, the gate-to-source voltage as a function of gate charge during the turn-on transient, the power oscillator shown in Fig. 1 is considered. The operation of such a circuit is explained in [5] and will not be repeated here.

The self-oscillating inverter consists of two equal n-channel MOSFETs, namely M1 and M2 with cross-coupled gate-drain. Cross-coupling is provided by diodes D1 and D2, which prevent M1 or M2 from entering the pinch-off region during the cycle. The drains of M1, M2 are connected to the coil L_t , which resonates with the capacitor C_t at the frequency f_0 . The WPT transformer is constituted by L_t (primary winding) and by another coil of the same size (secondary winding) placed at some distance (in the order of centimeters) from the first one. The secondary resonates with another capacitor. The RF power is then converted to DC by a full-bridge diode rectifier and used to supply a load. The gates of M1, M2 are biased by two voltage dividers (not shown), while two Zener diodes limit the maximum gate-to-source voltage and protect the transistors. The DC voltage (V_{dd} in the figure) is applied to the oscillator via a choke inductor.

The gate charge ICST is implemented by the red components in the schematic of Fig. 1. For simplicity the self-test is applied to M1 only, but with simple modifications both M1 and M2 can be monitored. The two switches S1 and S2 are required to isolate the gate terminals of M1 and M2 and to open the oscillator loop. When this is done, the oscillations are stopped and the circuit enters the measurement mode. The S3 switch is used to protect the Arduino analog input (A0 in the figure) from voltages above 5 V that appear at the gate during oscillation. It is open in inverter mode and closed in

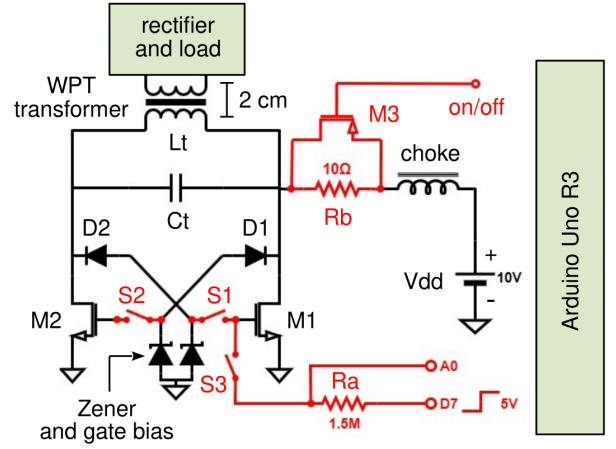


Fig. 1. Schematic of the self-oscillating inverter with gate charge ICST capability (components in red).

measurement mode. The ICST is completed by the resistor R_a , which is used to inject the charge into the gate.

The self-test procedure is as follows: first, the switches S1 and S2 are opened to stop oscillations. Then S3 is closed, the charge pin (D7 in the figure) goes high and R_a is set at 5 V. The gate-to-source voltage V_{gs} is measured and the gate charge Q_g is evaluated. Finally, the charge pin goes low and the charge is removed from the gate: this corresponds to a reset of the ICST, which is now ready for another measurement cycle. Opening S3 and closing S1, S2 restores the inverter oscillation. As can be seen, the method described does not require the drain/source terminals of M1, M2 to be routed to a specific test circuit and does not alter the high current path of the inverter.

The p-channel MOSFET M3 and the resistor R_b provide additional measurement capabilities. Normally M3 is on and the resistor R_b is shunted. This is always the case when the circuit is operated in inverter (oscillator) mode and used for WPT. In measurement mode, we can instead choose to leave M3 on or turn it off. When this is done, R_b is added in series with the inductor and the drain current is further limited.

The two modes are completely controlled by an Arduino Uno R3 board. The microcontroller is also used to set the charge pin, measure V_{gs} and calculate the injected charge. These measurements are taken periodically and the data is transferred to a PC via USB connection.

B. Measuring the gate charge

As described above, it is possible to measure the gate charge of transistor M1 with a few circuit elements. The proposed technique is similar to that previously reported in [13]. In particular the gate is fed with a step waveform through the resistor R_a . The gate-to-source voltage V_{gs} is then recorded over time and, knowing the feeding resistance, it is possible to estimate the transient gate current and thus the gate charge. The gate charge Q_g at the discrete time n is calculated with

the following iteration (equivalent to a discrete integration):

$$Q_g[n] = \frac{V_a - V_{gs}[n]}{R_a} \Delta t + Q_g[n-1] \quad (2)$$

where $V_{gs}[n]$ is the n th sample of the gate-to-source voltage. The iteration starts at $Q_g[0] = 0$ (initial conditions). In the above relationship, V_a is the voltage applied to the charge terminal of Fig. 1 (5 V in our case), and R_a is the corresponding series resistance (1.5 M Ω in our case), and Δt is the sampling time interval (104 μ s in our case). The discrete time n ranges from zero to the maximum number N_s of samples taken; the continuous time is given by: $t = n \Delta t$.

III. RESULTS

The self-oscillating inverter is based on two RFP50N06 silicon n-channel MOS transistors (60 V, 50 A, 22 m Ω) from ON-Semi. The analog switches required for ICST operation are implemented with the CD4016 from Texas Instruments. A Vishay IRF9640 silicon p-channel MOSFET is adopted to shunt the 10 Ω supply resistor during inverter operation. Two equal 70-mm ferrite coils from Würth-Elektronik are used for the WPT transformer. These coils, wound with 3mm Litz wire, have an inductance of 5.8 μ H and a typical quality factor of 220 at 125 kHz. The main supply voltage is $V_{dd} = 10$ V, and is supplied to the inverter via 70 μ H choke inductor. Two 10-V Zener diodes are used limit the maximum gate-to-source voltage and protect the transistors.

The circuit is designed according to [3], with the help of both transient and Harmonic-Balance (HB) simulations. The oscillation frequency is tuned to approximately 125 kHz. The inverter schematic is then modified as shown in Fig. 1 to allow the self-test of M1. The turn-on transient simulations are shown in the top panel of Fig. 2 with the pMOS M3 in off-state (blue curve). This transient is very close to the one obtained by simulating the schematic in the bottom panel of Fig. 2 (red dots).

After validating the ICST procedure with simulations, the self-oscillating inverter breadboard of Fig. 3 is implemented. In the first experiment, switches S1, S2 are open and the circuit stops oscillating (top panel). The gate charge transient is measured in this condition by closing S3. In the second experiment, S3 is opened (to protect the Arduino's analog input), S1, S2 are closed, and normal operation is restored. The circuit begins to oscillate and power is transferred to the rectifier and load via the WPT transformer (bottom panel). In the experimental conditions (2-cm distance between the transformer coils) the inverter delivers a power of about 12 W to an incandescent lamp. The waveforms measured at the gate (yellow) and drain (cyan) of M1 are shown in Fig. 4. The peak drain voltage is 27 V, while the gate voltage is limited to 10 V by the Zener diodes. The oscillation frequency is 80 kHz.

Several gate charge transients were automatically acquired using the breadboard described above. Fig. 5 reports a comparison between in-circuit (blue) and off-circuit measurements (red). These results are in good agreement with the circuit simulations of Fig. 2. Fig. 6 instead shows the

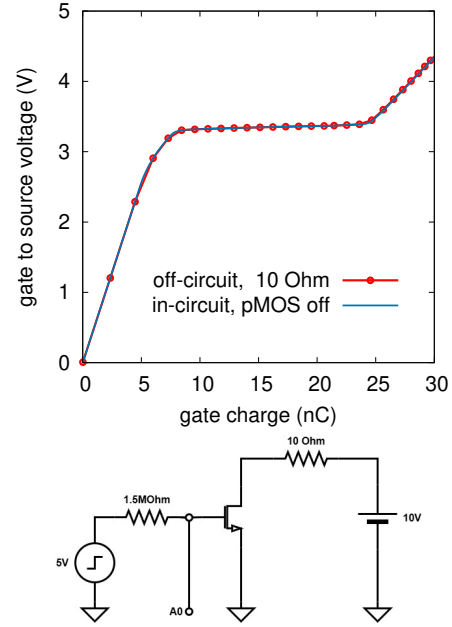


Fig. 2. Simulation of turn-on gate charge for both off-circuit (i.e., isolated) and in-circuit (i.e., integrated into the self-oscillating inverter) power MOSFET (top). Circuit used to simulate the off-circuit MOSFET (bottom). In both cases a drain resistance $R_b = 10 \Omega$ is considered. For in-circuit simulations this is achieved with the pMOS M3 in off state. The simulated gate charge is about 25 nC for $V_{dd} = 10$ V.

transient obtained with the in-circuit approach with the pMOS M3 in the off and on states. When M3 is off, the inverter is powered by the 10 Ω supply resistor, and this emulates the off-circuit setup. When M3 is on, the resistor is shorted and the inverter is powered only by the 70 μ H choke. In this state, an overshoot is recorded at the beginning of the charge transient. A similar overshoot is also reported in [12] and is associated with inductive loads. However, it is worth noting that both the turn-on gate charge (between 24 and 25 nC) and the plateau voltage (about 3.3 V) are quite similar in these cases.

In the above experimental conditions we measured the following performance of the self-oscillating inverter: 60% DC-to-DC efficiency; 88% RF-to-DC efficiency, 95% RF-to-RF efficiency; 68% inverter efficiency; 90% resonant full-bridge efficiency. The following data were measured with coils at 2-cm distance; their coupling factor was about 0.74. The power transferred to the load was 30 W.

IV. CONCLUSION

This paper reports, for the first time, a self-oscillating inverter for IPT applications with in-circuit self-test capability of the power MOSFET devices. The turn-on gate charge is an indicator of device reliability and lifetime aging, and has been determined without disconnecting the source/drain terminals from the high-current path of the inverter. Experiments have shown that the gate charge of the isolated transistor (off-circuit) and that measured in-circuit are compatible, thus validating the proposed methodology. Although preliminary, these results demonstrate that in-circuit

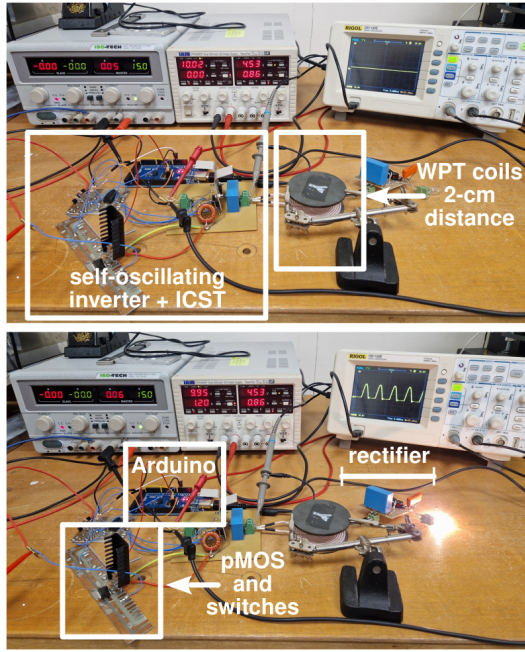


Fig. 3. Self-oscillating inverter breadboard with gate charge ICST capability (top) and IPT demonstration (bottom). At a distance of 2 cm the inverter delivers a power of about 12 W to an incandescent lamp.



Fig. 4. Self-oscillating inverter waveforms obtained for a main supply voltage of $V_{dd} = 10$ V. Both the gate (yellow) and drain (cyan) voltages of MOSFET M1 are measured. The peak drain voltage is 27 V, while the gate voltage is limited to 10 V by the Zener diodes. The measurements are made with the rectifier and the incandescent lamp connected to the secondary of the WPT transformer. Under these conditions, the oscillation frequency f_0 is 80 kHz.

self-tes is a promising methodology for reliability assessment and predictive maintenance of IPT systems.

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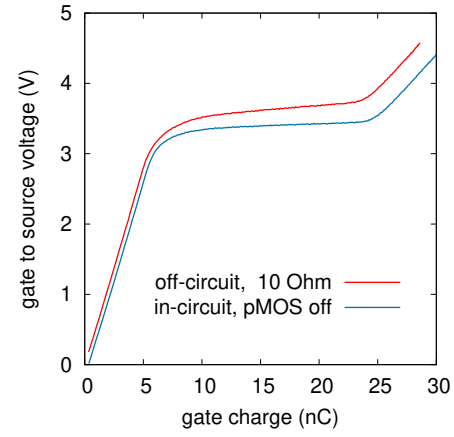


Fig. 5. Comparison between measured turn-on gate charge for an off-circuit and an in-circuit power MOSFET. In both cases $V_{dd} = 10$ V and $R_b = 10 \Omega$. The resistor is connected directly to the drain of the transistor for the off-circuit experiment and in series with the supply terminal for the in-circuit experiment. In the second case, the pMOS M3 is turned off. The measured turn-on gate charge is between 23 (off-circuit) and 25 nC (in-circuit).

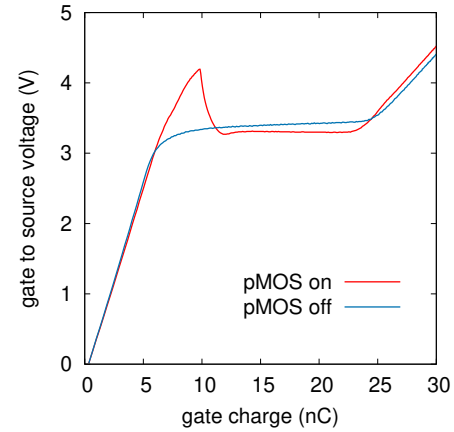


Fig. 6. Measured turn-on gate charge for the self-oscillating inverter with the pMOS M3 in off and on states for $V_{dd} = 10$ V. When M3 is off the inverter is powered via the 10Ω supply resistor, and this emulates the off-circuit setup. When M3 is on the resistor is short-circuited and the inverter is supplied only through the $70 \mu\text{H}$ choke. In this condition an overshoot is recorded at the beginning of the charge transient. It is worth noting that both the turn-on gate charge and the plateau voltage are quite similar in these cases.

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