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A Control Actuation Concept for Self-Oscillating Resonant Converters

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Abstract: This paper presents a new concept of controller actuator for Self-Oscillating Resonant Converters. Simplicity, robustness, and cost-effectiveness are amongst the main features that characterize this type of converter. Described as a self-oscillating system with intrinsic positive-type feedback, also known as the self-oscillating command circuit, it performs its gate-drive with fixed frequency and duty cycle. As a result, designers often disregard this converter as an explicit solution for closed-loop applications that require extra layers of control, due to its inherent inability to operate under controlled pulse frequency modulation without modifications. Thus, in this paper, the authors propose a robust, efficient and simple way of controlling the self-oscillating resonant converter through frequency modulation. The idea consists of varying the equivalent magnetizing inductance of the self-oscillating command circuit through the addition of an extra support winding, whose inductance is subject to a current-controlled Variable Inductor. Thus, through the injection of a small controllable DC current, it is possible to modify the self-oscillating frequency of this type of converter over a wide range of input voltage and load variation, maintaining the desired output level by PFM.

Keywords**: Self-Oscillating Command Circuit, Frequency Variation, Control Actuator Concept.**

1. INTRODUCTION

The advantages of resonant over hard-switched type converters are common subjects of discussion in the literature. Given certain operating conditions, resonant converters offer Zero Voltage Switching (ZVS), substantially reducing commutation losses on the switching devices when compared to hard-switched ones. As these losses diminish, the maximum switching frequency of the system potentially increases, thus reducing the size of the resonant converter's reactive components, further allowing its use for low-cost and high-density applications.

Due to the development of semiconductor switches capable of operating under ever-increasing high-stress conditions, the maximum switching frequency restrictions of a cost-effective resonant converter turns the gate-driver into a crucial subject of analysis. Although there are state-of-the-art commercially available Integrated Circuit (IC) gate-drivers with the capability of operating up to 50 MHz, as seen in Texas Instruments (2018), these devices often either have maximum bus voltage restrictions, require additional circuitry, or are deemed costly for given applications.

A simple, reliable and robust alternative for resonant converter's gate-drivers is the Self-Oscillating Command Circuit (SOCC). Composed by a three-winding current transformer and four back-to-back Zener diodes, this circuit has a magnetizing inductance that acts as a feedback between the converter's output filter and the commutation device, by utilizing the filter's current as the charge for the gate-driver. The SOCC does not require any additional circuitry, such as external timers or voltage sources, has no bus voltage restrictions and is highly cost-effective due to the reduced number of components.

Resonant converters with bridge topologies operating with the SOCC as gate-drivers are known as Self-Oscillating Resonant Converters (SORC). Usually, the personal benefits of SORC can outweigh those of hard-switched converters or improve less attractive aspects of soft-switched converters on specific applications, such as power converters for lighting systems. However, despite all its advantages, the SORC is generally overlooked when a closed-loop system is required. Mainly, this occurs because a suitable control actuation concept has not yet been proposed in the literature for this type of converter, due to the presence of an inherent positive-type feedback structure.

The nature of said self-driven oscillations in the form of positive feedback did only encourage a handful of efforts in the literature to regulate the SORC's output. Most approaches aimed to limit the amplitude of the magnetizing current by adding parallel branches, like Tao et al. (2001).. Alternatively, some contributions that referred to the operation of the SORC under closed-loop attempted different approaches, as the authors in Menke et al. (2015), which proposed a replacement of the filter's series inductor by a Variable Inductor (VI). Even though this alternative's benefits surpass those of the previous method, it doesn't act as a Pulse-Frequency Modulator (PFM), while also modifying the output filter characteristics, such as the quality factor, and requiring high values of DC current to perform properly.

To bypass the natural limitations presented by this type of converter regarding the closed-loop operation, in this paper, the authors present a new concept of control actuator for the SORC, where the equivalent magnetizing inductance of the SOCC is varied. Through the coupling of an extra fourth winding connected to a Variable Inductor (VI), the equivalent magnetizing inductance of the SOCC can be changed through the injection of a small DC level current. This method offers a minimal effect on both the system's efficiency and the gate-driver signal deterioration, having the convenience of not modifying the output filter characteristics while acting as a traditional PFM.

The first part of this paper expands the basic functionality of the SORC, giving the reader a solid understanding of the topology's characteristics needed for later sections. The second part concentrates into a more sophisticated analysis of the SOCC, where the goal is to elucidate the closed-loop limitations that motivates this analysis. The third part focuses on the essential characteristics of the VI, and how it provides an innovative solution for the closed-loop limitations of the SOCC.

2. THE SELF-OSCILLATING RESONANT CONVERTER

In the current section, we will focus our attention on the well-known open loop SORC topology from Fig. 1, with no regards given to the control or actuation. Its basic open-loop topology is composed of a set of well-defined parts. The start-up circuit (R_1, C_1, and *diac*) applies the first pulse on the system. The two MOSFETs (S_1, S_2) operate complementary, applying a square-wave voltage to the filter. The resonant band-pass filter (L_R, C_R) is responsible for filtering the higher-order harmonics of the square-wave voltage applied, establishing the required sinusoidal output filter current. The SOCC (L_M, $L_{M'}$, $L_{M''}$, and Zener diodes) uses the output filter current as the charge for the gate-driver. If the SORC is used to feed a string of Light-emitting Diodes (LEDs), as done and shown in the experimental section of this paper, a rectifier and filtering stage are required (d_{R1} through d_{R4}, and C_O) after the resonant filter. The LEDs can be represented as an ideal diode, a voltage source V_{TH} and a dynamic resistance r_D as their equivalent model.

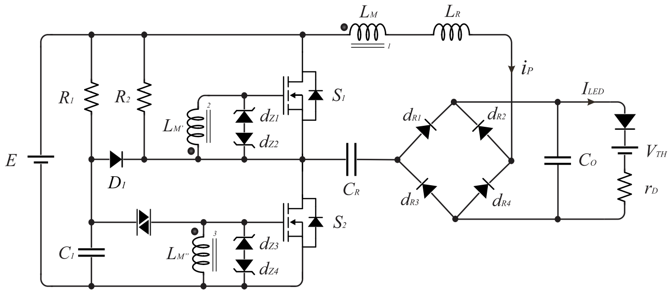

Fig. 1 Self-Oscillating Resonant Converter with LED load.

The frequency at which the MOSFET arm operates defines an appealing characteristic of this topology, the soft switching. When switched above the output band-pass filter's resonant frequency, the MOSFETs operate in the ZVS region. During a cycle of operation, their states are changed complementarily, and precisely when they turn ON while in the ZVS region, their current is oriented from source to drain, discharging the output MOSFET capacitances C_{DS} shortly before conducting. This effect considerably reduces commutation losses on these devices, and is one of the main points of interest in the SORC.

Usually, on non-self-oscillating resonant converter topologies, the frequency at which the semiconductors operate is defined by an external IC gate-driver. This fact makes it reasonably easy to achieve ZVS by fine-tuning the operation of the switches above the filter's resonant frequency. However, for the SORC, the switching frequency is defined by a more complex set of parameters, including and most importantly, the magnetizing inductance L_M of the three-winding transformer. For a clearer understanding of how this inductance and the SOCC contribute to the system's frequency of self-oscillation, a brief review of the operational principles is presented for the converter.

2.1 First Step of Operation: Conduction of S_2

An equivalent circuit that illustrates this step is shown in Fig. 2. The following components become active during this state of operation: ① the band-pass filter's series capacitor C_R and series inductor L_R; ② the three-winding current transformer's magnetizing inductance L_M; ③ the load, represented by the output rectifier d_{R2} and d_{R3}, the output filter C_O, and the LEDs.

The first step of operation begins with the conduction of the low-side MOSFET, S_2, after the start-up circuit connects the bus voltage E to the system. A positive gate-to-source voltage v_{GS} is then applied to S_2. The low-side MOSFET thus starts conducting, making a current path for the filter current i_P through the resonant filter. At this point, the SOCC begins its operation, as the appearance of i_P forces a redundancy on the positive v_{GS} of S_2, due to the coupling of the three-winding transformer, while, due to the opposing polarity, the v_{GS} of S_1 has negative value, maintaining the high-side MOSFET OFF.

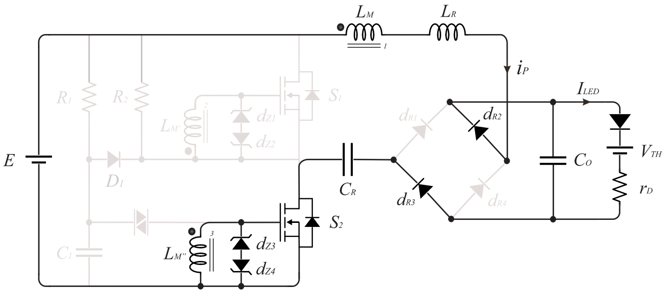

Fig. 2 First Step of Operation: Conduction of S_2.

This equilibrium state, where E encloses the resonant circuit, lasts until the sinusoidal current i_P evolves on its positive semi-cycle and then becomes zero. When this happens, as i_P becomes negative, the polarity of the SOCC's three-winding transformer now applies a negative v_{GS} voltage at S_2, which leads to the second step of operation.

2.2 Second Step of Operation: Conduction of S_1

An equivalent circuit that illustrates this step is shown in Fig. 3. The number of active components is the same as the previous step of operation, except for the absence of the bus voltage, that is no longer applied; however, the filter current i_P now flows in the opposite direction, activating the diodes d_{R1} and d_{R4}.

The second step of operation defines the conduction of the high-side MOSFET, S_1, while the bus voltage E disconnects from the system. The SOCC now applies a negative v_{GS} at S_2 and a positive v_{GS} at S_1. The low-side MOSFET stops conducting, while the current i_P now relocates to its high-side counterpart. The reactive components of the filter now resonate with the load, lasting until i_P becomes zero once again.

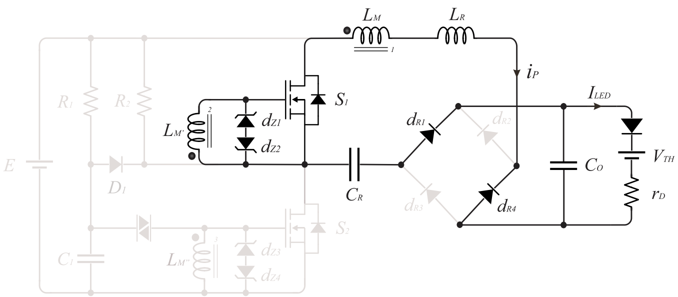

Fig. 3 Second Step of Operation: Conduction of S_1.

Given a proper design of the SORC, the first and second steps of operation will occur in a complementary fashion indefinitely, until the bus voltage is detached from the system or due to component failure. It is imperative to note that the duration of both steps of operation, thus the frequency, depend on the various parameters of the system, such as the filter components, the load, and most importantly, the magnetizing inductance L_M of the three-winding transformer in conjunction with the Zener voltage applied to it. This non-intuitive dependence of the frequency on the individual parameters of the converter is an intrinsic characteristic of self-oscillating type converters, and does not occur on traditional IC controlled converter.

2.3 Waveforms of the SORC

Fig. 4 shows a set of simulated waveforms that further illustrate the operation of the SORC, where the dashed lines represent the transition time between the two steps of operation. ① Both MOSFET drain current I_D and drain-to-source voltage V_{DS} highlight the aforementioned ZVS characteristics of this type of converter. The main currents of the SOCC, ② i_Z and i_G directly correlated to the gate-to-source voltages ③ v_{GS1} and v_{GS2}. These currents and voltages are correlated in the sense that, when v_{GS} is clamped at the Zener's breakdown voltage, there is a current i_Z flowing through the Zener diode. On the other hand, the voltage transition times, shown by the dashed lines, cause a current to flow through the gate of the MOSFETs, called i_G, whose function is to charge the input capacitances that allow for the device's state to change from ON to OFF, or vice-versa.

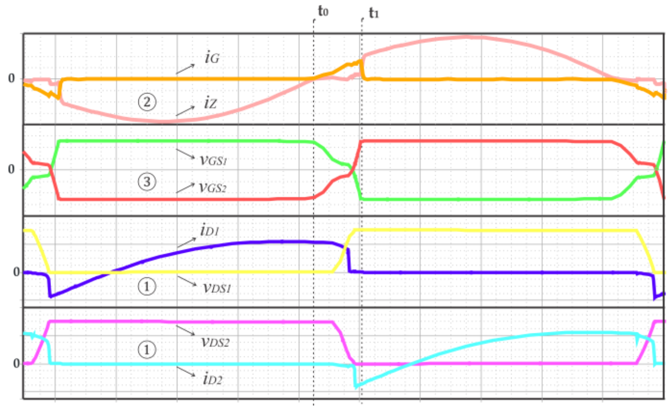

Fig. 4 Self-Oscillating Resonant Converter Main Waveforms

2.5 SORC Closed-Loop Limitations

Through the previous review of the SORC's basic operation, it is possible to infer some interesting points. First and foremost, there is no external gate-driver responsible for switching or controlling S_1 and S_2; and this function is performed by the conjunction of the three-winding transformer, and the four back-to-back Zener diodes, e.g. the SOCC.

The passive characteristic of such elements that, in essence, produce the switching of this type of converter, greatly restricts the feasibility of closed-loop operation for the converter. As shown before, the inductance of three-winding transformer that dictates the self-oscillation cannot be modified through trivial methods, nor can the Zener voltage be easily varied. The next section expands the functionality of the SOCC that clarifies this fact through the introduction of an equivalent model, reviews previously proposed methods of frequency variation for the SORC and proposes insights of more adequate methods.

3. THE SELF-OSCILLATING COMMAND CIRCUIT

In order to understand the methods previously proposed in the literature that focused on modifying the frequency of self-oscillation of SORCs, as well as to discuss new methods, a commonly used model for the SOCC will be helpful in the analysis.

3.1 SOCC Equivalent Model

A well-known equivalent circuit of the SOCC reflected to its secondary side, as seen in Ganzt (1962), is shown in Fig. 5. This model emulates the switching process of the SORC.

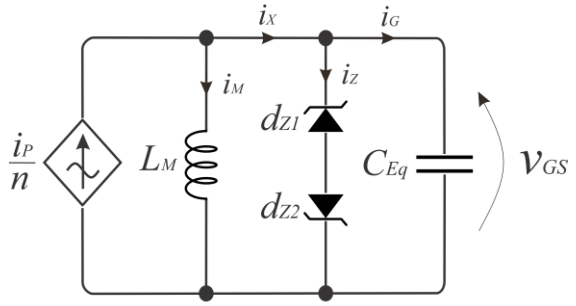

Fig. 5 Self-Oscillating Command Circuit Equivalent Model

The current dependant current source i_P/n represents the equivalent filter current that flows through the secondary windings of the three-winding transformer; the magnetizing inductance L_M of the three-winding transformer dictates how much of the feed-backed filter current flows through C_{EQ} in the form of gate-charge or through the Zener arm, d_{Z1}-d_{Z2}, to maintain the v_{GS} voltage clamped.

Due to the presence of an equivalent capacitance, which takes into account the parasitic behaviour of the MOSFET switching; this model represents, with acceptable precision, the real operation of the SOCC. The SOCC waveforms presented below elucidate the intrinsic positive-type feedback characteristics that dictate the operation of the converter. As the focus of this paper is the proposal of a control actuation concept that enables closed-loop operation of the SORC, the value of C_{EQ} will be treated as a practically neglected; in other words, high enough to allow the switching of the device, and low enough to prevent high transition times in v_{GS} that may cause errors in the design. This capacitance has been already discussed in the literature.

3.1 *SOCC Waveforms*

In order to facilitate the comprehension of the SOCC waveforms, the transition times of v_{GS} that cause i_G to flow through the MOSFET's capacitances will be neglected, as they were in the various compared methodologies, given that the MOSFETs are considered as ideal devices. As shown in Fig. 6, when the reflected filter current i_P/n starts growing positively, most of the current is would be conducted through the MOSFET's input capacitance C_{EQ}, which characterizes the switching dynamics of the device, turning it ON or OFF. Along with its charge, the voltage across the gate starts increasing, until it reaches the breakdown voltage of the Zener diode, at which point the current stops flowing through C_{EQ} and instead flows through the Zener branch, clamping the voltage across the gate. Given that the MOSFET's input capacitances are neglected, hence C_{EQ} equals zero, it can be seen that there is no transition time in v_{GS}.

In this case, the filter current i_P fed to the SOCC splits between the L_M, the Zeners and the MOSFET's C_{EQ} as i_M and i_Z, respectively, as given by (1). The correlation between these currents and the path they flow through is a key point both for the analysis of the standard and the closed-loop SORC.

$$\frac{i_P}{n} = i_M + i_Z \tag{1}$$

Where,

$$i_M(t) = \frac{1}{L_M} \cdot \int_0^T v_{GS}(t) \cdot dt + i_M(0) \cdot \tag{2}$$

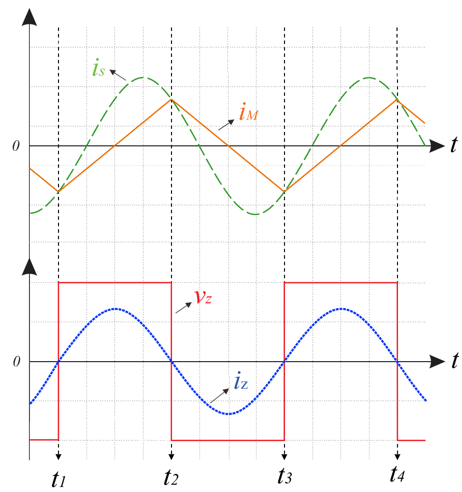

Fig. 6 Self-Oscillating Command Circuit Main Waveforms

From the waveforms, it is crucial to note the significance of the magnetizing current of the SOCC's three-winding transformer, i_M, on the self-oscillating frequency of the converter. The amplitude of this current defines the point at which the v_{GS} voltage gets clamped at the Zener voltage, and also affects the amount of gate-charge delivered to the switching semiconductor device. Both of these characteristics, in essence, allow us to understand at which frequency the converter with self-oscillate, and are vital for the proper design of the closed-loop SOCC presented in the next sections.

3.2 Proposed Methods for the SOCC Frequency Variation

Despite all its limitations, the frequency variation of SORC has been subject of analysis in a handful of works in the literature. This section focuses on displaying such works, discussing its methods, arguments and conclusions.

Method 1: i_M variation through parallel branches

The self-oscillating frequency of the SOCC is directly dependent on the value of i_M given by (2). Thus, according to Tao et al. (2001), a basic principle to act upon this frequency is to change the amplitude of i_M through the addition parallel branches, causing a deviation of the current that otherwise would flow through L_M, altering the moments of charge and discharge of the MOSFET input capacitances, changing the frequency as a result. The Fig. 7 depicts this concept through the addition of a resistor R_b.

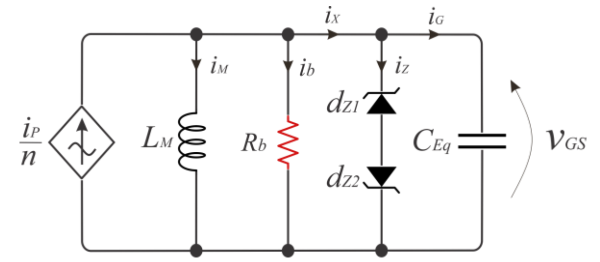

Fig. 7 Paralleled Branched Self-Oscillating Command Circuit

Even though this concept works, additional impedances inserted on a current source circuit like the SOCC can weigh heavily on the converter's efficiency, while also presenting gate signal deterioration. Furthermore, even though this is a feasible alternative in terms of frequency variation, it still lacks the desired closed-loop.

Method 2: Frequency variation through Variable Inductor

In order to analyze the feasibility of the VI as a dimming actuator, the authors in Menke et al. (2015) replaced the series inductor of the output filter of a SORC with a VI, as illustrates Fig. 8. This circuit is practically the same as the one from Fig. 1, however, shows a more simplified version that suppresses the switching of the SOCC, and concentrates only on the square wave voltage applied to the filter. This simplified circuit has been extensively employed in most SORC design methodologies, and is essential to design the filter elements, prior to the SOCC design.

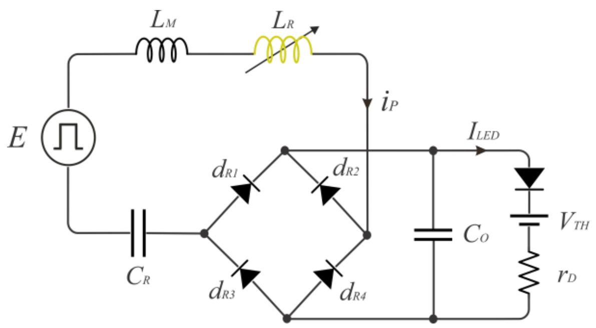

Fig. 8 Simplified Self-Oscillating Resonant Converter with filter Variable Inductor

This concept has three constraints; first, due to its intrinsic feedback characteristic, varying the SORC's filter inductor results not only in a variation of the self-oscillating frequency but simultaneously changes the filter's output power, as well as both the quality factor and resonant frequency of the filter.

Second, due to the absence of a more sophisticated model for the SORC, which leads to the prevailing need to employ non-linear control tools to analyse its self-oscillations, Seidel et al. (2007), dealing with several varying parameters is greatly discouraged, as its complexity tends to hinder the design unfeasible.

Third, in terms of efficiency, while a VI in the filter may be more desirable than associating impedances with L_M, as done in the previous method, the core volume and losses can escalate noticeably if this device is connected in series with the converter's main path of current; and this is especially true for high load currents.

3.2 A new method for Frequency variation

Both methods currently applicable to vary the frequency of the self-oscillation of SORCs were reviewed and discussed in this section. The first method, that provides an additional path of current for the secondary, through the addition of parallel impedance branches, while it works as a traditional PFM, has proven to be considerably inefficient. The second method acts upon the filter's inductor, and while it changes the frequency, it modifies also the general characteristics of the SORC output, like the quality factor and output power, which by definition, lacks the traditional PFM characteristic.

Hence, in order to operate the SORC as a traditional PFM converter, while also providing the ability to operate in closed-loop mode and maintaining its aforementioned desirable characteristics, a new method is proposed.

The methods consists of varying the value of i_M through (2), which can be accomplished through subtle changes in the magnetizing inductance L_M. For this endeavour, a VI is employed, where a DC level current can be injected into the external legs of a core, biasing its operating point in the BH curve and increasing the overall reluctance, allowing for a reduction in the inductance.

4. THE VARIABLE INDUCTOR AND THE SOCC

An interesting configuration achievable with a VI and the SOCC is called the Variable Current Transformer (VCT). In this configuration, shown in the right side of Fig. 9, the three-windings of the SOCC embrace two toroidal cores. Through the injection of a DC current I_{DC} in the remaining auxiliary windings, the equivalent magnetizing inductance L_M of the SOCC varies accordingly, changing the amplitude of the magnetizing current, i_M. In the left part of Fig. 9, we can see the inability that the standard three-winding transformer presents to vary L_M. According to Perdigao et al. (2016), the modelling of this device can be accomplished by two different techniques: through finite element analysis (FEA), or through SPICE simulation employing the Brauer's model.

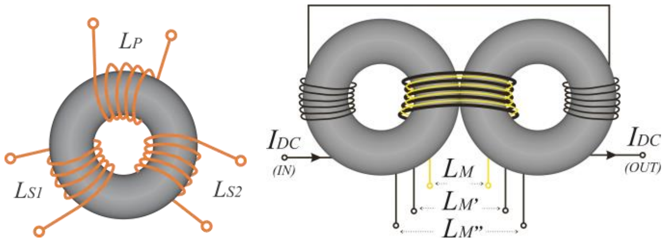

Fig. 9 The Standard and the Variable Three-Winding Current Transformers

A new equivalent model for the SOCC is shown in Fig. 10, which contemplates the insertion of a brand new equivalent variable inductance. From this model, we can see that the charge provided by the filter current i_P, that effectively switches the MOSFETs through C_{Eq}, can be altered by I_{DC}.

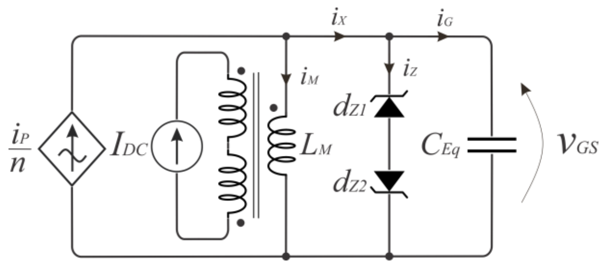

Fig. 10 Equivalent model of the new Variable SOCC

4. EXPERIMENTAL RESULTS

Table I shows the design parameters for the SORC tested.

Table I - SORC Design Parameters

Design Parameters		
Bus Voltage Range	E = 90 – 200 V	
Output Power of the LED String	P_O = 10 W	
LED String Current	I_{LED} = 300 mA	
LED String Voltage	V_{LED} = 33.8 V	
LED Dynamic Resistance	r_D = 24.47 Ω	
CT Turns Ratio	a_i = 1:7:7:7	
LED Filtering Capacitor	C_O = 1 uF	
Zener Voltage	V_Z = 15 V	
MOSFETs	IRF840	
Control Current Range	I_{CTRL} = 0 – 100 mA	
Frequency Range	f_S = 100 – 150 kHz	
LCC Resonant Filter		
LED equivalent resistance	Series Capacitor	Series Inductor
r_{ac} = 92 Ω	C_R = 100 nF	L_R = 175 μH

Figure 11 shows experimental results for the bus voltage E and the LED string power P_{LED} as functions of the DC bias current I_{DC}. The blue dashed line shows how P_{LED} decreases as we increase I_{DC}. This happens because, as I_{DC} increases, the magnetizing inductance L_M decreases, causing the switching frequency of the resonant filter f_s to also increase, while both the filter current i_P and the LED current I_{LED} fall due to the increased magnetic reactance. The green solid line shows the required amount of DC bias current I_{DC} to maintain a fixed power value of 10 W for P_{LED}. At E=90 V, P_{LED} = 10 W; and as we increase the bus voltage E applied to SORC, P_{LED} increases, thus we must increase I_{DC} to maintain the desired 10 W.

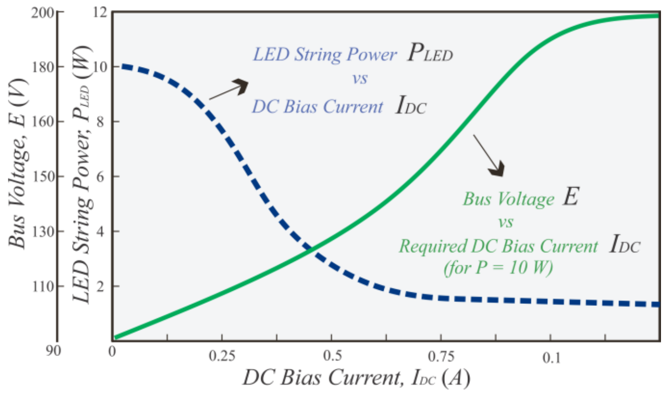

Fig. 11 Bus voltage and LED string power as a function of the DC bias current.

Figure 12 and Fig. 13 show experimental results for SORC the filter current i_P for minimum and maximum values of I_{DC}, respectively. For the lowest value of I_{DC}, the magnetizing inductance L_M it at its highest value, decreasing the switching frequency of the SORC, allowing it to operate shortly above the resonant frequency, hence the sinusoidal characteristic of Fig 12. For the highest value of I_{DC}, L_M has its lowest possible value, which leads the switching frequency f_s to increase highly above the resonant frequency, making i_P drop.

The generation of the biasing current I_{DC} was realized through external current sources, that were applied directly to the auxiliary windings of the V.I..

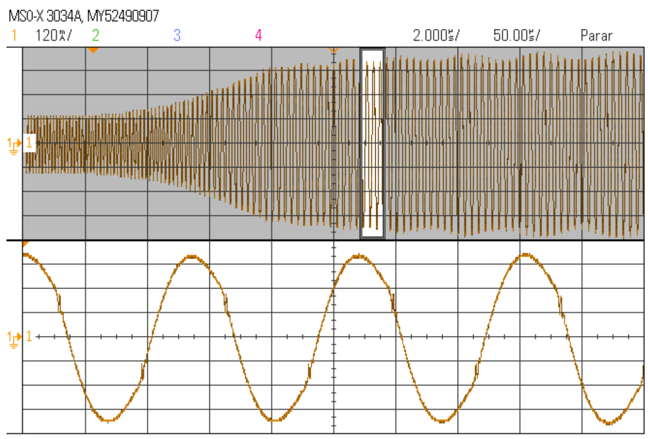

Fig. 12 Three-winding Current Transformer with extra variable winding

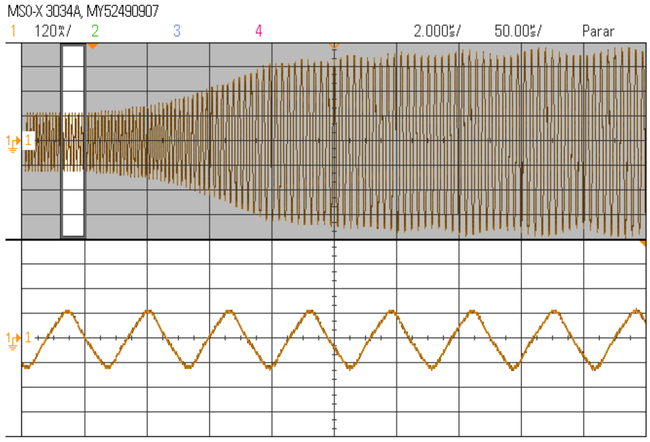

Fig. 13 Three-winding Current Transformer with extra variable winding

5. CONCLUSION

This paper presented a thorough analysis of the SORC, focusing on the current inability to operate under closed-loop. A new actuation concept for SORC that contrasts with the currently applicable ones available in the literature. The concept consists of controlling the amplitude of the SOCC magnetizing current through the Variable Current Transformer concept, capable of modulating the SORC frequency through PFM. This method does not interfere with the filter characteristics, but instead works similarly to a traditional frequency modulation actuator, as it changes the output filter gain only through the variation of the self-oscillating frequency. This concept can be used on any converters employing the SOCC, potentially achieving multiple layers of control on a system that is usually overlooked on closed-loop applications, due to its traditional intrinsic positive-type feedback characteristic.

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