DESIGN METHODOLOGY FOR A SELF-OSCILLATING RESONANT CONVERTER BASED ON NORMALIZED ANALYSIS APPLIED TO A LOW POWER TOPOLOGY

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Abstract—This work presents a design methodology for resonant converters with self-oscillating switching with focus on low power and voltage applications. For this, the concepts of parameter normalization are used, in which it is possible to design the converter independent of the circuit variables, considering only the resonant characteristics such as quality factor, normalized angular frequency, among others. Applications involving low power systems, ranging from tens to hundreds of milliWatts, with energy conversion from alternative sources, also known as Energy Harvesting (EH) systems, have been the focus of several studies involving resonant converters. The use of such converters is favorably viewed due to the reduction of switching losses as well as higher power density because the used topology operates in a self-oscillating manner. The simulation and experimental results are presented to validate such theoretical analysis.

Index Terms—Self-Oscillating DC-DC Converter, Low Voltage and Power Circuit, Resonant Converters, Normalized Analysis, Soft Switching.

I. INTRODUCTION

The need for external power devices (batteries) is directly linked to the load. It’s possible, for example, an EH (Energy Harvesting) based system to use only a capacitor as power storage element. [1].

The quick evolution of microelectronic industry and CMOS (Complementary Metal Oxide Semiconductor) process technology has reduced the circuits power consume allowing the use of auto-powered power systems. [3].

The common battery-based power source has important maintenance, discard and lifetime limitations, being the latter quite reduced, making undesired for some application, like wireless sensors nodes.

There is a need to implement new power strategies for such autonomous sensors, increase technology awareness and absorption, eliminating battery replacement as an important operational and environmental issue. [15].

As evidenced, the battery has limited charge, in other words, there is a limited power quantity drain from the battery to the electronic circuit [4]. The autonomy of a circuit depend, therefore, of his power drain, as well battery power storage capability. Besides that, the battery occupies a significant area of the electronic device, as an example, a sensor node. Battery-powered sensors, if exposed to unfavorable conditions, such high temperature, chemical environment, and others, have their use unfeasible. [6].

The need to use a battery, on the other hand, is a common solution when the EH system cannot provide enough power for the continuum run of the application. In this case, the EH system can periodically recharge the battery, condition that increases the autonomy of the device but do not prevent...
the need of a battery replacement over time. This situation exacerbates the solid waste scenario, making its management a major global challenge and a bottleneck for the electronic device development industry of primary battery-powered. [9].

Many physical processes occur around nodes, whose energy can be captured and used to power wireless sensors [16]: sun brightness, moonlight, vibration, low potential heat, electromagnetic radiation at different frequencies, thermal energy using thermoelectric generators.

This paper proposes a project methodology for a self-oscillating resonant converter for low voltage and power. It is used a normalization of parameters technique allowing the system to be designed from abacus, independently of real system parameters. The system becomes dependent only of the normalized parameters, such as: normalized resonant frequency, and the inverse of the transfer power ratio. The document is organized as follows: Section II presents the converter and principles of operation, in III brings the modeling through circuit variables, in IV the normalized analysis is presented for the converter under study and, in V presents the project considering specifications for an EH application. The results are presented in section VI and finally in section VII the conclusions are presented.

II. SELF-OSCILLATING RESONANT CONVERTER BASED ON MEISSNER OSCILLATOR

The proposed converter operates with low voltage levels and power, being indicated for applications such as sensors nodes, or other applications involving such features. In order to exemplify the application was used a sensor node that requires a power drain of 3mW to 15mW.

Low power converters require especial attention and specific projects [14]. The main features to be analysed is the efficiency and starter voltage levels of the converter.

There are basically two possibilities for starting a low power converter: the first solution is with an external assistant for the start and the other possibility is the use of a circuit for starting at low voltage. Considering the first solution there are three assistant possibilities such as: an external battery, a pre-charged capacitor or a mechanical switch. [6].

The low voltage switched capacitor converters are widely used in applications involving voltages below 1V [10]. The architecture for this converter topology is optimized for operation at low voltage.

There are several techniques that are used to reduce the threshold voltage values of the semiconductor switches. The starting voltage can be 300mV or lower, however, small voltage values may present stability issues. [13].

The second category involving self-powered converters makes use of DC-DC resonant converters. In this category, the Meissner oscillator use is generally present [11]. The main advantage of using this topology is the low starting voltage value, as well as the capacity of obtaining high voltage values, by using a transformer.

The proposed resonant converter is in the voltage and power levels of the order of tens of miliWatts and miliVolts, where the converters are self-starting and correspond to a low input voltage (starting at 45mV).

A. Converter Operation

The analyzed converter for this application uses a starting circuit due to low voltage power supply, such circuit is shown in Figure 1 where the main converter and the starting auxiliary circuit are presented. It should be noted that the starting circuit offers small influence with the main converter, and its analysis scored in this paper.

For the first operation mode the switch \( J_1 \) (JFET) is connected in parallel to switch \( S_1 \) (NMOS) and allows the autonomous start, due to their ability to conduct with voltage thresholds close to zero. When applying a positive voltage through \( V_{CC} \), the current \( I_1 \) circulates through the primary winding induces voltage in the secondary winding of the transformer. From the positive polarization in \( S_1 \) and the capacitor \( C_1 \) is discharged, so there is current in the intrinsic diode of \( S_1 \) and the voltage at \( C_1 \) becomes negative. When it reaches a sufficiently high value, the current \( I_1 \) makes the trigger voltage of \( J_1 \) decreases and, because the conduction resistance is high, the \( J_1 \) switch stop the conduction.

In this context, the auxiliary starting circuit operates in to disconnect the load from the oscillator circuit, during initialization of the circuit via \( S_2 \) switch. This disconnection is intended to reduce the equivalent capacitance of the secondary and ensure that there is a longer time constant even during the switching of only the \( J_1 \) switch.

In the second mode of operation the switch \( J_1 \) is turned-off conduction, and the \( V_{CC2} \) voltage is sufficiently large to force conduction through the \( S_1 \) switch, marking the passage of the transitory state to the stationary state, with high efficiency, since the conduction losses in \( S_1 \) are much smaller than in \( J_1 \). By means of the increasing voltage in the secondary of the transformer, the Greinacher voltage multiplier, formed by the diodes and capacitors (\( D_1, D_2, C_3 \) and \( C_4 \)), operates as follows: during the stage where the voltage \( V_{CC2} \) is negative, current flows through the diode \( D_1 \) charging the capacitor \( C_3 \) with the \( C_5 \) capacitor voltage and, in the moment that \( V_{CC2} \) voltage changes polarity, the \( C_3 \) capacitor discharges part of its energy through the \( D_2 \) diode, charging the \( C_4 \) capacitor with the \( C_5 \) capacitor voltage, plus the secondary winding voltage \( V_{CC2} \), ensuring a voltage value sufficient to trigger the \( S_2 \) switch in order to impose the input in conduction, then the transfer of energy to the load occurs. The \( D_3 \) and \( D_4 \) diodes are part of the signal rectification circuit allowing the output signal to be DC.

The waveforms for \( G_{S1} \) switch signal, \( V_{out} \) output, voltage on \( V_{S1} \) switch and current \( I_{S1} \), on switch are shown in Figure 2.

III. CONVERTER MODELING THROUGH CIRCUITS VARIABLES

Considering a state-space model with the state arrays \( A_I \), \( A_{II} \) and input arrays \( B_I \), \( B_{II} \), where subscript "I" means the first mode of operation, when the switch is on and the
Main Converter

based on the Meissner oscillator. For the proposed system is represented per:

For the equation, it is considered $V_{in}$ as the input voltage, $V_{out}$ as the output voltage, $V_{Lm2}$ the voltage at the $L_{m2}$ inductor, $V_{C1}$ the voltage at the $C_1$ capacitor, $V_S$ the voltage at the $S_1$ switch, $i_{in}$ the input current, $i_{out}$ the output current, $i_{Lm2}$ the current at the $L_{m2}$ inductor, $i_{C1}$ the current in the $C_1$ capacitor, $i_{S1}$ the current in $S_1$ switch, $V_{CC2}$ the voltage in the secondary winding of the connected inductor, $N_1$ is the number of turns in the primary winding, $N_2$ the number of turns in the secondary winding and $I_{CC2}$ the current in the secondary winding of the connected inductor. For the proposed converter, consider the vector $x$ as being $x = \{i_{Lm2}, v_{C1}\}$. The system is represented per:

$$X = \frac{dX(t)}{dt} = A_1(X) + B_1V_{CC2}$$  \hspace{1cm} (1)

By means of the Kirchoff’s Laws of voltage and Current it is possible to establish the equations below.

$$A_1 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_1R_i} \end{bmatrix}; B_1 = \begin{bmatrix} \frac{1}{L_{m2}} \\ 0 \end{bmatrix}$$  \hspace{1cm} (2)

$$A_{II} = \begin{bmatrix} -\frac{R_i}{L_{m2}(R_i+R_L)} & \frac{R_i}{L_{m2}(R_i+R_L)} \\ \frac{R_i}{C_1(R_i+R_L)} & -\frac{1}{C_1(R_i+R_L)} \end{bmatrix}; B_{II} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$  \hspace{1cm} (3)

Defining the output variables of interest in a output vector, the representation is given by:

$$y(t) = \begin{bmatrix} i_{Lm2} \\ i_{C1} \\ i_{out} \\ i_{in} \\ v_{Lm2} \\ v_{S} \\ v_{C1} \\ v_{R1} \end{bmatrix} = \frac{1}{V_{CC2}} \begin{bmatrix} I_{CC2} \\ I_{CC2} \\ I_{CC2} \\ I_{CC2} \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$  \hspace{1cm} (4)

considering the output equations as:

$$Mode I: y(t) = C_1x(t) + D_1V_{CC2}$$  \hspace{1cm} (5)

$$Mode II: y(t) = C_{II}x(t) + D_{II}V_{CC2}$$  \hspace{1cm} (6)

$$C_1 = \begin{bmatrix} \frac{1}{I_{CC2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{R_i L_{m2}} & \frac{1}{I_{CC2}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{R_i L_{m2}} & \frac{1}{I_{CC2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_i L_{m2}} & \frac{1}{I_{CC2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{R_i L_{m2}} & \frac{1}{I_{CC2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_i L_{m2}} & \frac{1}{I_{CC2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_i L_{m2}} & \frac{1}{I_{CC2}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_i L_{m2}} \end{bmatrix}; D_1 = \begin{bmatrix} \frac{1 + \frac{R_i}{R_L}}{R_L} \frac{1}{I_{CC2}} \\ \frac{1}{R_L} \frac{1}{I_{CC2}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$  \hspace{1cm} (7)

$$C_{II} = \begin{bmatrix} \frac{1}{I_{CC2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{R_i}{R_L+R_i} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{R_i}{R_L+R_i} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{R_i}{R_L+R_i} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{R_i}{R_L+R_i} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_i}{R_L+R_i} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_i}{R_L+R_i} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_i}{R_L+R_i} \end{bmatrix}; D_{II} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$  \hspace{1cm} (8)
IV. NORMALIZED ANALYSIS FOR THE RESONANT CONVERTER

The independent variable $t$ is changed by $\omega t$ by means of the following mathematical operation:

$$
\frac{d[x(t)]}{dt} \rightarrow \frac{\omega}{\omega} \frac{d[x(\omega t)]}{d\omega t}
$$

(8)

With the change of variable in relation to time it is possible to obtain the normalized resonance frequency $A_1$ relating the operating frequency $\omega$ and the angular frequency $A_1$ through of $[10]$ and $[9]$.

$$
A_1 = \frac{\omega_1}{\omega}
$$

(9)

$$
\omega_1 = \frac{1}{\sqrt{L_0 C_1}}
$$

(10)

The combination of dissipate components with reactive components of a resonant circuit forms the quality factor $Q$. The number of quality factors present in a circuit is equal to the number of resistors simplified or also known as reduced resistances $[12]$. For the converter addressed in this study, it is defined a number of two quality factors, which is justified by the number of reduced resistances presented in $[11]$.

$$
Q_L = \frac{R_L}{L_0 \omega_1} = C_1 \omega_1 R_L
$$

$$
Q_1 = \frac{R_1}{L_0 \omega_1} = C_1 \omega_1 R_1
$$

(11)

By using the aforementioned relationships, it is possible to converter the state-space matrices into a normalized representation as a function of $A_1$, $Q_1$ and $Q_L$. The normalized state space is presented in: $[12]$.

$$
Mode I : \dot{\mathbf{X}} = \frac{d[x(\omega t)]}{d\omega t} = \mathbf{E}_I(x) + \mathbf{F}_I
$$

(12)

$$
Mode II : \dot{\mathbf{X}} = \frac{d[x(\omega t)]}{d\omega t} = \mathbf{E}_{II}(x) + \mathbf{F}_{II}
$$

in which,$$
\mathbf{E}_I = \begin{bmatrix} 0 & 0 \\ 0 & -Q_1 A_1 \end{bmatrix} ; \mathbf{F}_I = \begin{bmatrix} 1 \\ Q_1 A_1 \end{bmatrix}
$$

$$
\mathbf{E}_{II} = \begin{bmatrix} -Q_1 A_1 \\ \frac{A_1 + Q_L}{A_1 + Q_L} \\ \frac{Q_1}{Q_1 + Q_L} \end{bmatrix} ; \mathbf{F}_{II} = \begin{bmatrix} 0 \\ A_1 \\ 0 \end{bmatrix}
$$

(13)

(14)

where:

- $\mathbf{E}_I$ is the normalized state matrix related to $A_1$;
- $\mathbf{F}_I$ is the normalized input matrix related to $B_1$;
- $\mathbf{E}_{II}$ is the normalized state matrix related to $A_{II}$;
- $\mathbf{F}_{II}$ is the normalized input matrix related to $B_{II}$;

The inverse transfer power ratio $a$, is defined as,

$$
a = \frac{V_{CC2}}{I_{CC2}} R_L
$$

(15)

The voltage $V_{CC2}$ will be automatically normalized from the arrays $D_I$ and $D_{II}$. The output equations for the normalized system are:

$$
Mode I : \mathbf{y}(\omega t) = \mathbf{G}_I \mathbf{x}(\omega t) + \mathbf{H}_I
$$

$$
Mode II : \mathbf{y}(\omega t) = \mathbf{G}_{II} \mathbf{x}(\omega t) + \mathbf{H}_{II}
$$

(16)

Rearranging the terms according to the normalization elements, the results are presented in $[17]$ e $[18]$.

$$
\mathbf{G}_I = \begin{bmatrix} a A_1 Q_L & 0 \\ a A_1 Q_L & a Q_L \end{bmatrix} ; \mathbf{H}_I = \begin{bmatrix} 0 \\ a \left(1 + \frac{Q_1}{Q_L} \right) \end{bmatrix}
$$

$$
\mathbf{G}_{II} = \begin{bmatrix} -a A_1 \frac{Q_1}{Q_1 + Q_L} & 0 & -a Q_1 \\ 0 & a \frac{Q_1}{Q_1 + Q_L} & 0 \\ -a \frac{A_1}{Q_1 + Q_L} & 0 & 1 \end{bmatrix} ; \mathbf{H}_{II} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
$$

(17)

(18)

where:

- $\mathbf{G}_I$ is the normalized output matrix related to $C_I$;
- $\mathbf{H}_I$ is the normalized transmission matrix related to $D_I$;
- $\mathbf{G}_{II}$ is the normalized output matrix related to $C_{II}$;
- $\mathbf{H}_{II}$ is the normalized transmission matrix related to $D_{II}$;

By defining soft-switching conditions as, initial capacitor $C_1$ voltage $v_{C1}(0)$ equal to the inverse of the normalized angular frequency, the system operated in ZVS for any operating point. The generative hypothesis of ZVS is that the initial voltage of the capacitor $v_{C1}(0)$, is equal to the inverse of the normalized angular frequency, $\frac{1}{\omega}$.

The system solution returns the behavior of the output variables for any input.

V. NORMALIZED DESIGN OF THE SELF-Oscillating RESONANT CONVERTER

The converter design may involve the design option for one or more elements, however, it was decided to use a
commercially coupled inductor. The input voltage \( V_{CC} \), the power output \( P_{out} \), switching frequency \( f \) and the duty cycle \( D_c \) are defined by the designer. The parameters \( A_1 \), \( Q_1 \) and \( Q_L \) are defined according to the selected operating point.

1) Definition of the duty cycle \( D_c \), frequency \( f \), \( V_{CC} \) voltage input voltage and output power \( P_{out} \).
2) Select \( A_1 \), \( Q_1 \) and \( Q_L \) and the transfer power ratio for ZVS condition according to the duty cycle.
3) Calculate the operating frequency \( f \) and the voltage at the secondary winding \( V_{CC2} \):

\[
\omega = 2\pi f 
\]

\[
V_{CC2} = V_{CC} \left( \frac{N_2}{N_1} \right) 
\]

4) Calculate resistors \( R_L \) and \( R_1 \) and capacitor \( C_1 \) by the following equations:

\[
R_L = \omega Q_L A_1 L_m \]

\[
R_1 = \omega Q_1 A_1 L_m 
\]

\[
C_1 = \frac{Q_L}{\omega A_1 R_L} 
\]

It should be noted that the converter operates at a duty cycle of 50%, however, the project predicts that the variation can be realized also characterizing a converter with controllable duty cycle.

The design parameters obtained through simulation in mathematical software are presented in Table I.

### VI. RESULTS

The theoretical, simulation and experimental results are going to be presented. Theoretical results were obtained in the software Mathematica 10 and simulations by using the LTspice VII software. Table I shows the converter parameters:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_m )</td>
<td>75 mH</td>
</tr>
<tr>
<td>( f_s )</td>
<td>10 kHz</td>
</tr>
<tr>
<td>( V_{CC} )</td>
<td>50 mV</td>
</tr>
<tr>
<td>( P_{out} )</td>
<td>10 mV</td>
</tr>
<tr>
<td>( Q_1 )</td>
<td>1.6</td>
</tr>
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</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>1 nF</td>
</tr>
<tr>
<td>( A_1 )</td>
<td>1.82944</td>
</tr>
<tr>
<td>( D )</td>
<td>0.5</td>
</tr>
<tr>
<td>( R_L )</td>
<td>470 kΩ</td>
</tr>
</tbody>
</table>

Table II presents a comparison among some DC-DC type converters with shared similar characteristics of low voltage and power.

The converter of the present study stood out in two relevant factors, the starting voltage and also the output voltage, however, left something to be desired in terms of efficiency, however, the results for a discrete implementation were satisfactory.

![Fig. 3. Simulation result for switch S1 voltage.](image)

![Fig. 4. Experimental results for switch S1 voltage.](image)

![Fig. 5. Experimental results for input and output voltage, respectively.](image)

![Fig. 6. Experimental results for switch S1 voltage.](image)

### TABLE I

**DESIGN PARAMETERS**

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</tr>
<tr>
<td>( R_L )</td>
<td>470 kΩ</td>
</tr>
</tbody>
</table>

### TABLE II

**COMPARISON AMONG DC-DC CONVERTERS FOR LOW VOLTAGE AND POWER APPLICATIONS**

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototyping</td>
<td>Mixed Integrad Discrete Discrete</td>
<td>120 mV</td>
<td>210 mV</td>
<td>200 mV</td>
</tr>
<tr>
<td>Minimum input voltage</td>
<td>1.2 V</td>
<td>1.1 V</td>
<td>2.5 V</td>
<td>3.7 V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>50 mV</td>
<td>50 mV</td>
<td>50 mV</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>30%</td>
<td>71%</td>
<td>25%</td>
<td>12.50%</td>
</tr>
</tbody>
</table>
VII. CONCLUSION

An design methodology based on normalized analysis was developed for a self-oscillating resonant converter, whose application was used for low voltage and power. The auxiliary starting circuit had the analysis disregarded by noting that it is not part of the circuit of steady state operation. One of the main objectives of the design methodology was the independence of circuit parameters and specifications, such as, frequency, input and output voltage, power, among others. Another purpose was that the circuit had its operation in the ZVS region, minimizing switching losses, increasing the efficiency of the converter, which is interesting considering that the circuit is designed for low power levels. The auxiliary starting circuit based on a voltage multiplier of the Greinacher type, played its role successfully. In addition to being a low cost circuit, being formed only by capacitors and diodes, its principle of operation is simple, not interfering directly in the operation of the main converter. The proposed work presented theoretical and simulation results in the software LTspice VII and Mathematica 10, which are in agreement with the waveforms obtained by experimental means, which confirms the hypothesis of this research.