

## SPICE COMPATIBLE MODEL OF SELF-OSCILLATING CONVERTER

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### ABSTRACT

A SPICE compatible model for simulating self-oscillating DC-DC converters that are based on magnetic saturation is developed and tested. The simulation method applies a non-linear inductor model that is based on dependent sources that reflect a linear inductor in a non-linear manner. The model was tested on a flyback type self-oscillating converter by simulation and was verified experimentally.

### 1. INTRODUCTION

Self-oscillating converters have some advantages over forced driven converters: they are simpler to implement, have a lower components count and they do not need an auxiliary power supply. The operation of the self-oscillating converters is normally based on some non-linear circuitry such as magnetic saturation of transformers or inductors and they are especially advantageous for low input voltage (below 1 Volt) [1], [2]. The theoretical analysis of such magnetic relaxation circuits leads to non-linear differential equations, which are difficult to solve, while the analysis and design of the linear section of the circuit is also complex [3]. The objective of this study was to develop a modeling methodology that will be applicable to SPICE simulation of self-oscillating converters based on magnetic saturation.

### 2. THE SELF OSCILLATING CONVERTER

The generic circuit of Fig. 1 describes the basic operation of a self-oscillation converter. The switch is normally conducting and it toggles to the non-conducting state whenever the inductor enters the saturation region. The switch turns on again after some time delay. It is thus evident that a prerequisite for carrying out a simulation of such a system is the ability to model a non-linear inductor.

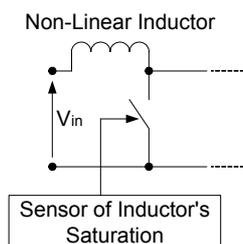


Fig. 1. Generic self-oscillating converter.

The self-oscillating converter that was examined in this study is based on the flyback topology (Fig. 2). The first and second windings of the core function as an oscillator, while the third winding is used to output the energy, stored in the core during the 'on' time, to the load. The JFET used as a switch is a N type of the depletion mode. That is, the switch is conducting when the gate-source voltage is zero as is cutoff when the gate voltage is negative. The feedback winding provides positive feedback that sustains conduction when the switch is on. When the core collapses, as it enters saturation, the feedback voltage is becoming smaller and the positive nature of the feedback initiates a commutation process that ends when the switch is turned off and the output winding is clamped to the load voltage. The  $R_1C_1$  network is charged by the current flowing when the gate diode is briefly conducting at the beginning of the turn off duration. The voltage across the  $R_1C_1$  network is negative,

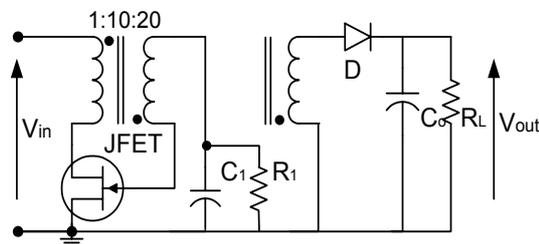


Fig. 2. Flyback implementation of self-oscillating converter.

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which helps to keep the switch in the cutoff state during the 'off' period. The 'off' period ends either when the current of the output winding drops to zero or when the discharge of the  $R_1C_1$  brings the gate voltage to the conduction region – whichever occurs first. It is clear that prerequisite for simulating the flyback self-oscillation converter in the PSPICE environment is a means to model the nonlinearity of the inductor.

### 3. THE NON-LINEAR INDUCTOR MODEL

The non-linear inductor  $L'$  model [4] based on the reflection of a linear inductor  $L$  via non-linear transformation system is shown in Fig. 3.

If:

$$E1 = V_{pr}/K = V_{sec} \quad (1)$$

and

$$G1 = I_{sec} = I_{pr} \quad (2)$$

then:

$$L' = K \cdot L \quad (3)$$

where  $K$  is a conversion constant.

If  $K$  is made current dependent ( $K(I)$ ) then the reflected inductor will be  $L' = K(I) \cdot L$ . The dependence of  $K$  on  $I$  can be obtained from manufacturers data or plots. For a linear inductor and choosing  $L = 1$  H, the expression for  $K$  will be:

$$K = \frac{n^2 A_e \mu_r \mu_o}{l_e} \quad (4)$$

where:  $n$  - number of turns;  $A_e$  - the core area;  $l_e$  - effective magnetic length;  $\mu_o$  - permeability constant; and  $\mu_r$  - relative permeability.

Non-linearity can be emulated by making the relative permeability current dependent. For example, by the experimental fitting equation:

$$\mu_r(I) = \frac{\mu_i}{1 + \left(\frac{I}{I_{sat}}\right)^n} \quad (5)$$

where  $I_{sat}$  is the saturation current,  $\mu_i$  is the initial relative permeability in the linear region and  $n$  is chosen to obtain the required sharpness of the permeability function as the core enters saturation.

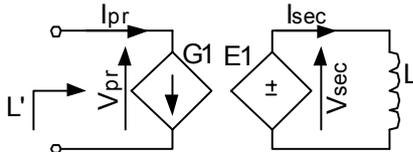


Fig. 3. The non-linear inductor model.

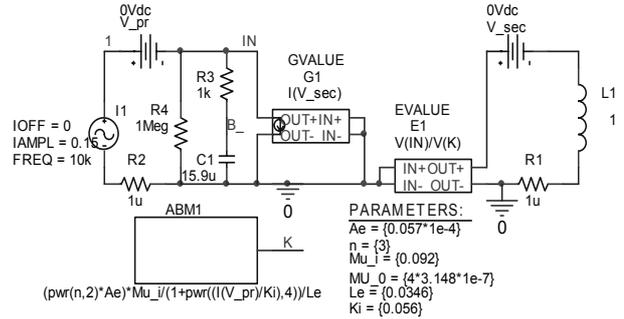


Fig. 4. SPICE implementation of a non-linear inductor model of Fig. 3.

The implementation of non-linear inductor in the SPICE environment is accomplished by applying behavioral dependent sources (EVALUE and GVALUE and ABM) [1] (Fig 4).

### 4. SIMULATION OF THE SELF-OSCILLATING CONVERTER

Simulation of the flyback type self-oscillating converter (Fig. 2) involves three pairs of dependent voltage and current sources (Fig 5). Two pairs ( $G_2, E_2$ ;  $G_3, E_3$ ) are used for modeling the two coupled-windings, and one pair ( $G_1, E_1$ ) for modeling the non-linear (saturation) effect. The definitions of the dependent sources are as follows:

$$G_1 = I_1 \quad (6)$$

$$G_2 = I_2 \quad (7)$$

$$G_3 = I_3 \quad (8)$$

$$E_1 = V_{pr}/K(I_1) \quad (9)$$

$$E_2 = N_1 \cdot V_{pr} \quad (10)$$

$$E_3 = N_2 \cdot V_{pr} \quad (11)$$

$N_1$  is turn ratio primary and feedback winding;  $N_2$  is turn ratio primary and output winding.  $K(I_1)$  is the experimental function describing the saturation of the core (relative permeability as a function of current) that can be obtained from the manufacturers data or experimentally.

The PSPICE compatible (CADENCEe/ORCAD, USA, evaluation version 9.2) simulation circuit with additional elements to overcome convergence problems, is given in Fig. 6. The fitting equation for this case (ABM1) was:

$$K(I) = \frac{\mu_i}{1 + \left(\frac{I}{K_{sat}}\right)^4} \cdot \frac{n^2 \cdot A_e}{l_e} \quad (12)$$

where  $A_e$  is the core effective area;  $\mu_i$  initial permeability;  $l_e$  effective magnetic path length;  $n$  number of turns;  $K_{sat}$  the current that initiates saturation.

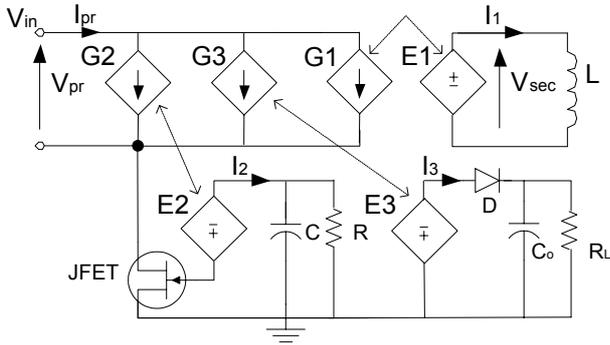


Fig. 5. Behavioral model of a flyback self-oscillator circuit.  
 Definition of dependent sources:  $G_1=I_1$ ,  $G_2=I_2$ ,  $G_3=I_3$ ,  
 $E_1=V_{pr}/K(I_1)$ ,  $E_2=N_1 \cdot V_{pr}$ ,  $E_3=N_2 \cdot V_{pr}$ .

## 5. EXPERIMENTAL

The simulation methodology was tested by comparing it to an experimental circuit that was based on the topology of Fig. 2. In the experimental circuit:  $C_1=0.1 \mu\text{F}$ ,  $R_1=1\text{M}\Omega$ ,  $C_o=47 \mu\text{F}$ ,  $R_L=10 \text{ k}\Omega$ , JFET= J105, diode= MBR160. The core was a toroid type made of amorphous material, MP1305P4AF (Metglass, Inc.). The dimension of the core area: inner diameter 7.8 mm; outer diameter 14.4 mm; height 6.7 mm; initial relative permeability  $0.47 \cdot 10^6$ ; saturation at  $H= 6 \text{ A/m}$  and  $B= 0.57 \text{ Tesla}$ . The non linearity of the core was approximated by equation (12).

The main winding of the core had 5 turns, the feedback winding 50 turns and the output winding 100 turns.

Fig. 7 shows the experimental and simulated waveforms.

## 6. DISCUSSION AND CONCLUSIONS

The simulated current and voltage shapes (Fig. 7) clearly match well with the experimental ones, including the fine details of the reflected gate current at the beginning of the 'on' state, and the drop in the gate voltage at the end of the 'on' period. There are, however, some differences between the measured and simulated waveforms. One difference is in the curvature of the main winding. This could be a result of the approximate nature of the fitting used to describe the saturation effect (equation (12)). A second discrepancy was found in the frequency of oscillation. This could also be a result of the approximate nature of the fitting as well as due to the fact that the operating point of the simulated circuit and the experimental one were not exactly the same. A better fitting to the physical behavior of the relative permeability may improve the accuracy of the simulation.

Notwithstanding the discrepancies, the simulation model replicated very well the general behavior of the experimental circuit. The proposed model can thus be a useful tool to explore, in the PSPICE environment, the behavior of self oscillating converters of the flyback type

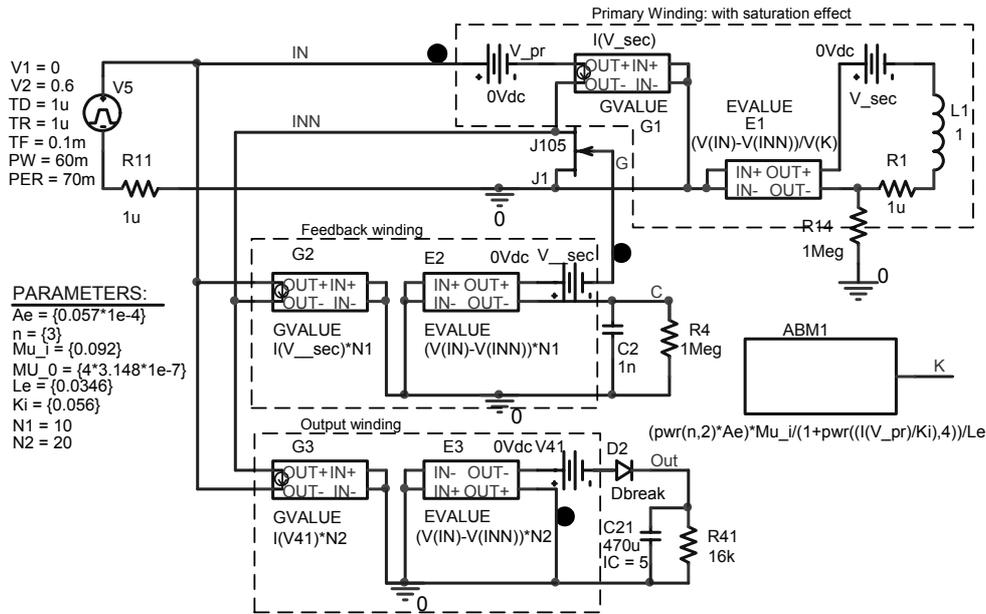
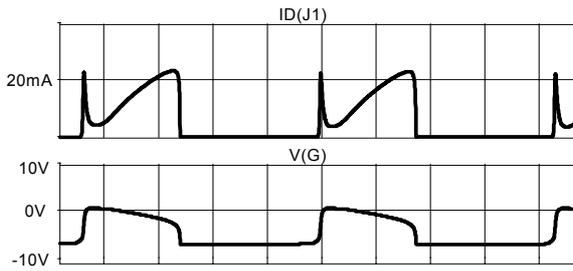
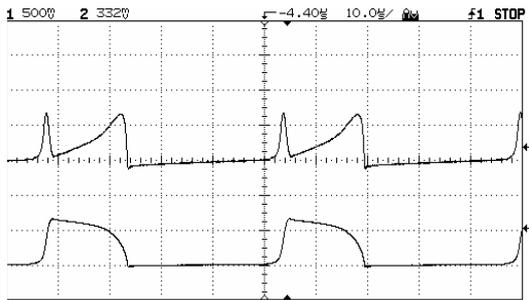


Fig. 6. PSPICE model of the flyback self-oscillating converter.



(a)



(b)

Fig. 7. Simulated (a) and experimental (b) waveforms of main winding current (upper traces) and JFETs gate voltage (bottom traces). Time base: for (a):  $5\mu\text{s}/\text{div}$ ; for (b):  $10\mu\text{s}/\text{div}$ .

as well as other topologies, and to help optimize the circuits in terms of starting condition, efficiency and other practical parameters.

#### ACKNOWLEDGMENT

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#### 7. REFERENCES

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