Voltage Source Inverter Connected to the Grid with Nonlinear Filter Inductor

Georgi Kunov[1], Elissaveta Gadjeva[2], Dimitar Todorov[3]

Abstract – **In this paper, the grid connected voltage fed inverter with a hysteresis current control is investigated. The influence on the minimal and the maximal commutation frequency for the transistors when applying filter inductor with a nonlinear inductance is a subject of consideration. A computer *PSpice* macromodel of the nonlinear inductance is developed. A control system, realizing this mode of operation, is presented. The simulation results of the developed control system with a nonlinear inductance are given.**

Keywords – **Full bridge transistor DC-AC converter, Hysteresis limits control system, PSpice simulation**

I. Introduction

Many types of voltage fed inverters are used in the contemporary power electronic devices to convert dc to ac. There are two types of inverters: stand-alone and grid connected. These two inverter types have several similarities, but they are different in terms of control function. A stand-alone inverter is used in off grid applications with battery storage. Grid interactive inverters must follow the voltage and frequency characteristics of the utility generated power presented on the distribution line.

A typical application of the grid connected voltage inverter is in the photovoltaic (PV) systems [1]. The main two requirements from the power supply to the inverter are: the requirement for the inverted current to be in same phase with the voltage of the mains network, and the requirement for the inverted current to be with minimal high-order harmonic components. The second requirement means that the waveforms of the inverted current have to be near to sinusoidal signals. In order to obtain sinusoidal current, a number of algorithms for voltage inverter control are used. They are presented in a synthesized form in [2].

In the case of grid connected voltage inverters, the average current mode control [3] and the hysteresis current control [4] are mostly used.

In the present paper, the method of hysteresis current control is used. Besides the near to sinusoidal shape of the inverted current and the low values of the high-order harmonics, this method is characterized by a variable commutation frequency of the inverter transistors. A subject of investigation of the paper is the influence on the minimal and the maximal commutation frequency for the transistors when applying filter inductor with a nonlinear inductance.

II. Principle of Operation of Grid Connected Voltage Inverter

The circuit of the grid connected voltage inverter is shown in Fig. 1. The value of the DC source has to be greater than the magnitude of the line voltage in order to ensure normal operation of the circuit. In this manner, the principle of operation of the circuit is reduced to the principle of operation of BUCK DC-DC converter with a load the line voltage.

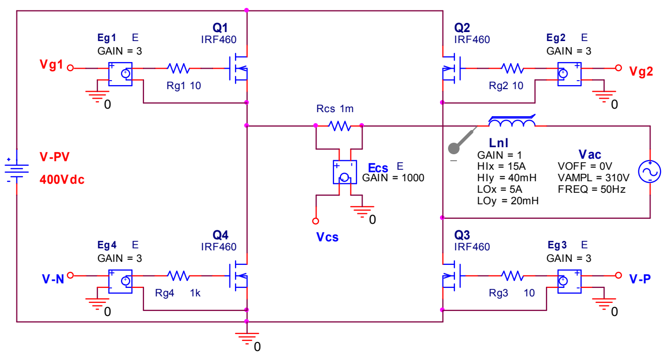

Fig. 1. Grid connected voltage inverter

During the positive waveform of the line voltage, the inverter works according to the equivalent circuit shown in Fig. 2. In this time-interval the transistors Q2 and Q4 are turn-off, Q3 is turn-on during the whole half-period, and Q1 is commutated by the frequency, defined by the control system. The incorporated reverse diode of the transistor Q4 acts as a free-wheeling diode of the BUCK DC-DC converter.

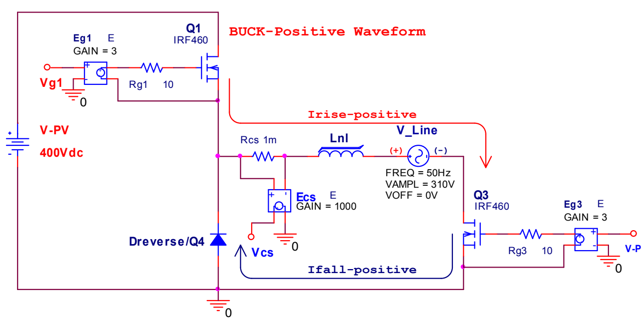

Fig. 2. Equivalent circuit for the positive waveform

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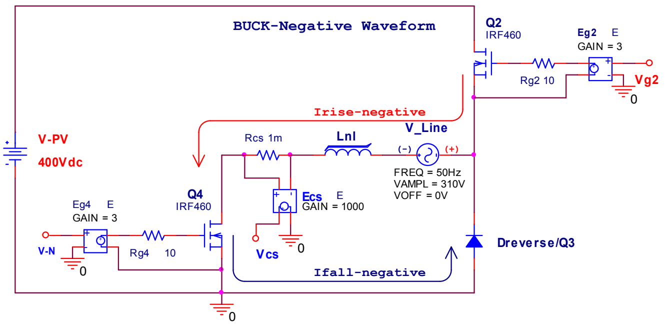

Fig. 3. Equivalent circuit for the negative waveform

During the negative waveform of the line voltage, the inverter works according to the equivalent circuit shown in Fig. 3. In this time-interval the transistors Q1 and Q3 are turn-off, Q4 is turn-on during the whole half-period, and Q2 is commutated by the frequency, defined by the control system. The incorporated reverse diode of the transistor Q3 acts as a free-wheeling diode of the BUCK DC-DC converter.

The algorithm of operation of the power circuit, described above, is illustrated by the waveforms shown in Fig. 4.

The concrete control system with a hysteresis current control [5], realizing the described algorithm, is presented in Fig. 5.

III. Modeling of Nonlinear Inductance

A. *Description of the parameterized PSpice model of nonlinear inductance*

The nonlinear dependence $L_{nl} = f(i)$ shown in Fig. 6 is modeled by the following expression:

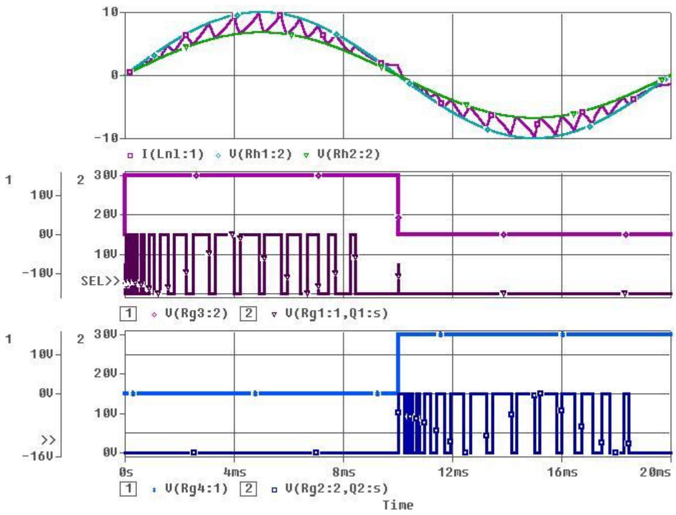

Fig. 4. Illustration of algorithm of operation

$$L(i) = -B_y - A_y \tanh\left(G\frac{\mathrm{abs}(i) - B_x}{A_x}\right) + LO_y + HI_y \quad (1)$$

where

$$A_y = \frac{HI_y - LO_y}{2} \quad ; \quad B_y = \frac{HI_y + LO_y}{2}$$

$$A_x = \frac{HI_x - LO_x}{2} \quad ; \quad B_x = \frac{HI_x + LO_x}{2}$$

$$LO_x = i_{\min} \qquad HI_x = i_{\max}$$

$$LO_y = L_{\min} \qquad HI_y = L_{\max}$$

The nonlinear inductance model is developed in the form of parameterized subcircuit in two variants: using schematic view and using subcircuit description in text form.

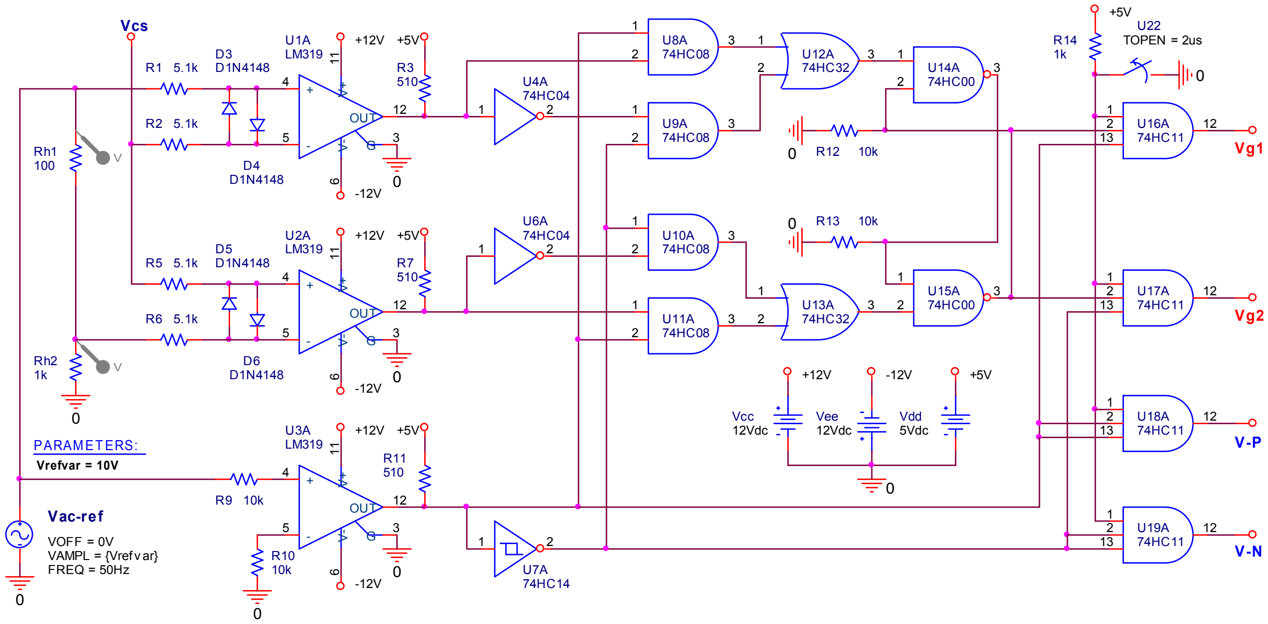

Fig. 5. Hysteresis current mode control system

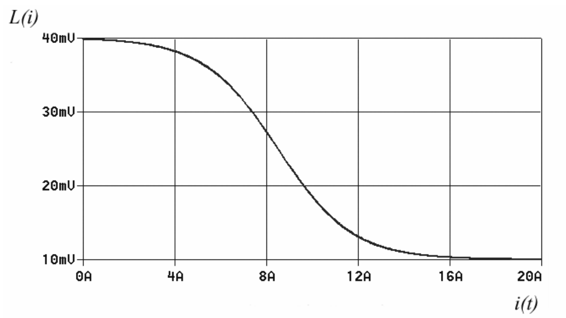

Fig. 6. The nonlinear dependence $L_{nl} = f(i)$

Fig. 7. Block definition of the inductance model

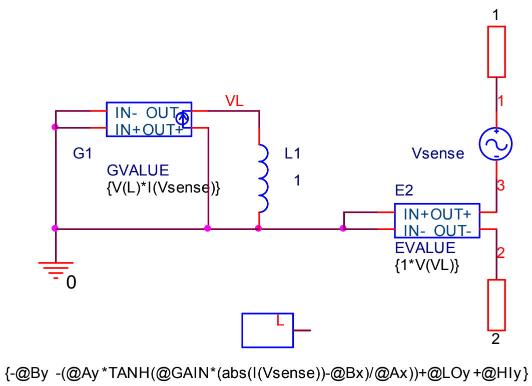

Fig. 8. Schematic description of the inductance model

B. *Parameterized PSpice model of nonlinear inductance using ABM elements*

A block definition is used to construct the model as shown in Fig. 7. The schematic description of the model is presented in Fig. 8.

The **ABM** block models the dependence $L(i)$ according to (1), represented by the value $V(L)$ .The dependence $L(i)$ according to (1) is realized by the PSpice expression:

```
{-@By -(@Ay*TANH(@GAIN*(abs(I(Vsense))-
@Bx)/@Ax))+@LOy+@HIy}
```

The dependent current source $G1$ models the flux $\psi = L(i).i$, represented by the value

V(VL)= {V(L)*I(Vsense)}

The voltage $u_L(t)$ has the form:

$$u_L(t) = \frac{d\psi_L(t)}{dt} = \frac{d}{dt}\left(L(i_L(t)).i_L(t)\right) . \qquad (2)$$

$u_L(t)$ is obtained across the inductance L1 in the model shown in Fig. 8. The VCVS E2 is of value {1*V(VL)}. As a result, the block realizes an inductor with nonlinear inductance, connected between nodes 1 and 2.

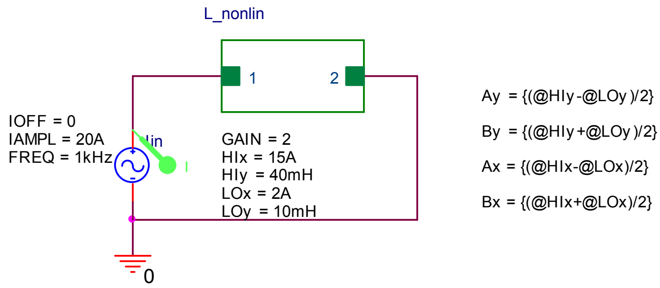

Fig. 9. Testing of the inductance model

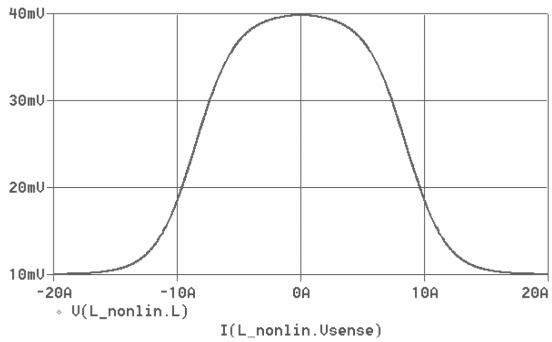

Fig. 10. The modeled dependence $L(i)$

In order to test the behavior of the inductance model, the circuit shown in Fig. 9 is used. The sinusoidal independent current source I_{in} with a amplitude 20A is used. The modeled dependence $L(i)$ is shown in Fig. 10.

C. *Parameterized PSpice model of nonlinear inductance using subcircuit description in text form*

In this case the block is connected to the *PSpice* subcircuit model in text form. The description of the library element has the form:

```
.subckt Lnl1 1 2 Params: Ax=1 Bx=1 Ay=1
+ By=1  GAIN=1 LOy=1 HIy=1
Vsense 1 3 0
E_VL 3 2 VALUE={1*V(VL)}
E_L L 0 VALUE {-By -(Ay*TANH(GAIN*
  (abs(I(Vsense))-Bx)/Ax))+LOy+HIy}
G_PSI 0 VL VALUE={V(L)*I(Vsense)}
L_VL VL 0 1
.ends
```

The block description is in the form:

```
X_Lnl1 %1 %2 Lnl1 PARAMS:  Ax={(@HIx-
@LOx)/2} Bx={(@HIx+@LOx)/2} \n+
Ay={(@HIy-@LOy)/2} By={(@HIy+@LOy)/2}
GAIN={@GAIN}  \n+ LOy={@LOy} HIy={@HIy}
```

In this way, the block parameters are transferred to the subcircuit. The circuit input file has the form:

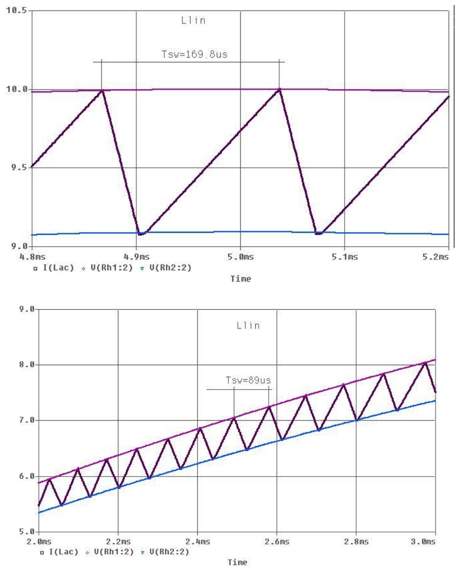

Fig. 11. Simulation results for the case of linear inductance – L_{lin}=12mH

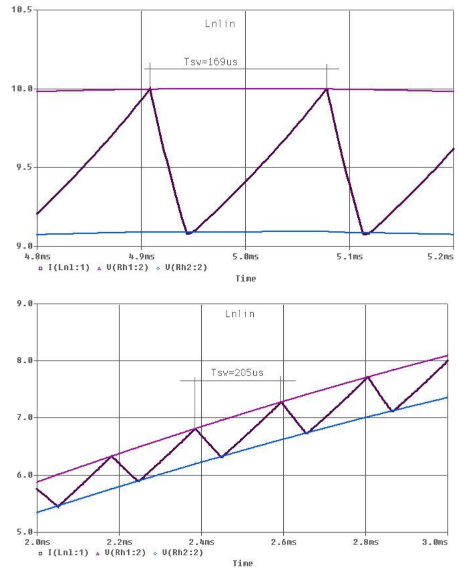

Fig. 12. Simulation results for the case of nonlinear inductance – L_{nonlin}=12mH/10A; L_{nonlin}=30mH/1A

```
.LIB ".\lnonl.lib"
.lib "nom.lib"
.TRAN  0 5ms 0 1u SKIPBP
.PROBE V(*) I(*) D(*)
R_R1  0 UL  1T
X_Lnl1 UL 0 Lnl1 PARAMS:  Ax={(15A-1A)/2}
+ Bx={(15A+1A)/2} Ay={(40mH-10mH)/2}
+ By={(40mH+10mH)/2} GAIN={2}
+ LOy={10mH} HIy={40mH}
I_Iin 0 UL DC 0Adc AC 0Aac
+SIN 0 20A 1kHz 0 0 0
.END
```

IV. Simulation Results

The simulation results of the grid connected voltage inverter with sine band hysteresis control are shown in Fig. 11 and Fig. 12. It is seen that for the value of linear inductance equal to the nonlinear inductance corresponding to the magnitude value of the sinusoidal current, the commutation frequency of the inverter transistors is the same. As a result of the fact, that the nonlinear inductance value increases when the value of the sinusoidal current $i(t)$ decreases, the commutation frequency of the inverter transistors decreases compared to the case with linear inductance. When using nonlinear filter inductance, the mode of operation is near to the case of the fixed band hysteresis control [4], conserving best shape of the inverter current as in case of sine band hysteresis control.

V. Conclusion

The grid connected voltage fed inverter with a hysteresis current control has been investigated. The dependence of the minimal and the maximal commutation frequency for the transistors when applying filter inductor with a nonlinear inductance is considered. A computer macromodel of the nonlinear inductance is developed in accordance with the input language of the *PSpice* simulator and the model description is given. The simulation results of the developed control system with a nonlinear inductance are presented.

Acknowledgement

The investigations are supported by the R&D project 091ni041-03/2009 with the Technical University of Sofia.

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