Modeling and Investigation of an Inductive Cumulation Inverter

Hristo Z. Karailiev[1], Hristo P. Hinov[2], Valentina V. Rankovska[3]

Abstract – **A class of inverters for little and medium power, characterized with dynamic change of the load parameters, have been studied. A real time control is needed to maintain an optimal operation mode of inverters with inductive cumulation. An approach for inverter modeling and investigation by means of MATLAB, SIMULINK and PLECS is suggested in this paper. As a result of modeling the relation of the cumulation time and the load change having in mind the maximum admissible transistor current and the maximum admissible voltage between collector and the emitter is studied.**

Keywords – **inverter, induction heating, inductive cumulation, modeling, cumulation time.**

I. Introduction

In many practical cases using the inverters for little and medium power for hardening and metal melting etc. is needed. Varying the heating temperature in a definite range, the load parameters Z_T (R_T,L_T) change accordingly. The active and reactive load components change leads to a change of the free oscillations of the oscillating circuit.

The time for forced energy accumulation in the oscillating circuit inductivity has been added as a parameter at inductive cumulation inverters. There is a risk of oscillations failing if the cumulation time is defined too short, and if it is defined too long there is a risk to exceed the puncture voltage of the transistor and his current value.

The major aim of this report is modeling and investigation of an inductive cumulation inverter. The goal is to accumulate data needed as a base in designing a microprocessor control device.

Major problems solved in the report:

- To study a single-switch inverter operation modes at parameters varying at admissible limits;
- To study the admissible cumulation time limits at changing the real load consumption without exceeding the transistor puncture voltage $(U_{CE})_{доп}$ and the maximum admissible current value $(I_{TP})_{доп}$.

II. Formulation of the Task for Modeling and Investigation of an Inductive Cummulation Inverter

The base inverter circuit used for modeling and investigation is shown in Fig. 1.

The components of the circuit are the following:

[1] Hristo Z. Karailiev is with the Technical University, 4 H. Dimitar str. 5300 Gabrovo, Bulgaria, E-mail: hkarailiev@gmail.com

[2] Hristo P. Hinov is with the Technical University, 4 H. Dimitar str. 5300 Gabrovo, Bulgaria, E-mail: hino@abv.bg

[3] Valentina V. Rankovska is with the Technical University, 4 H. Dimitar str. 5300 Gabrovo, Bulgaria, E-mail: rankovska@tugab.bg

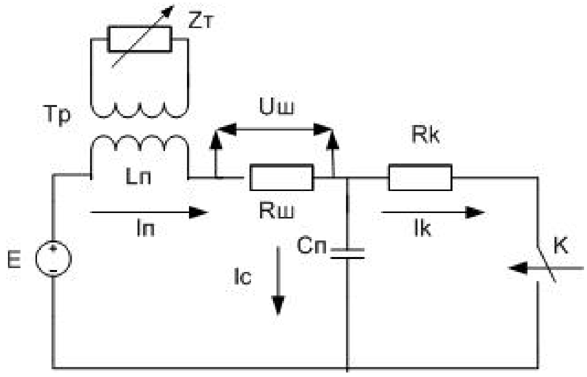

Fig. 1. Inductive cumulation inverter circuit

E	Direct voltage source
T_P	Linear transformer for galvanic isolation of the load Z_T from the source
Z_T	(R_T,L_T) – inductor parameters varying with temperature change
$L_П$	Transformer primary side inductivity
$C_П$	Capacitance in the serial oscillating circuit
$R_Ш$	Shunt resistor for monitoring the current value in the oscillating circuit
R_K	Switch K resistance when it is closed
K	Switch, when it is open it allows cumulating energy in $L_П$

The major analytical dependencies of the oscillation circuit free oscillations, when there is no load connected in the secondary side and no cumulation are given below:

$$\rho = \sqrt{\frac{L_П}{S_П}} \text{ - characteristic impedance} \quad (1)$$

$$Q = \frac{\rho}{P_П} \text{ - Q-factor of the circuit} \quad (2)$$

$$\delta = \frac{R}{2L} \text{ - oscillating circuit damping} \quad (3)$$

$$\varepsilon = \frac{\delta}{\omega} = \frac{1}{2Q} \text{ - phase oscillating circuit damping} \quad (4)$$

$$\omega = \sqrt{\frac{1}{L_П C_П} - \delta^2} = \sqrt{\frac{1}{L_П C_П} - (\frac{R_П}{2L_П})^2} \quad (5)$$

- own resonant frequency of the circuit

$$T = \frac{1}{f} = \frac{2\pi}{\omega} \text{ - own oscillations period} \quad (6)$$

When there is a cumulation, i.e. when the switch K is opened for time τ, the operation mode of the inverter and its major characteristics change. This fact can be used further to control the operation mode of the inverter. Then the period and the oscillation frequency will be as follows:

$$T_K = T + \tau \text{, or } f_K = \frac{1}{T + \tau} \quad (7)$$

On the other hand when increasing the temperature in the heated metal qualitative changes have been done in it. The active impedance value R_T increases and at the magnet distortion point μ_r becomes 1. These qualitative changes lead to increasing the equivalent impedance R_{PE} and L_{PE} at the primary side of the oscillating circuit.

$$R_{\Pi E}=R_{\Pi} + R_{BH} \quad (8)$$
$$L_{\Pi E}= L_{\Pi} - L_H$$

As a result the equivalent characteristic impedance ρ_e decreases and $R_{\Pi E}$ increases. This leads to decreasing the equivalent Q-factor Q_e, i.e.:

$$t^{\circ}C \to L_{\Pi E} \downarrow \to \rho_e \downarrow \to R_{\Pi E} \uparrow \to Q \downarrow \quad (9)$$

The following conclusions can be made as a result of the upper reasoning:

1. At the technological process the qualities of the heated metal and the equivalent parameters of the oscillating circuit have been changing and the generated oscillations in the inverter may fail at high temperatures.
2. It is necessary to gather information about the inverter operation mode continuously and to generate control signal with regulated duration for the switch *K* for optimal energy cumulation in the inductivity.
3. It is necessary to accumulate data about the time parameters of the oscillating circuit and together with cumulation time regulation it is necessary not to exceed the admissible values of the voltage $(U_{CE})_{\partial on}$ and the transistor current $(I_{TP})_{\partial on}$.

III. MODELING AND INVESTIGATION OF THE OPERATION MODES OF AN INDUCTIVE CUMULATION INVERTER

A base for the modeling is the results got about single-switch cumulation inverter at variable temperature from t_{min} to t_{max} [1]. From the results it can be seen, that R_T increases 3,5 times at t_{max} in relation to its value at $t_{min}= 20^{\circ}C$. The inductivity decreases 2,5 times at the magnet distortion point in relation to L_T at temperature $t_{min}= 20^{\circ}C$.

The modeling of the single-switch inductive cumulation inverter has been made based on upper conclusions. The program SIMULINK and the instrumentation toolbox PLECS have been used for that purpose [2], [3].

The model of the control circuit using the SIMULINK library is shown in Fig. 2. The electrical circuit of the inverter has been modeled using the PLECS library and it is shown in Fig. 3.

The block circuit for the modeling of the inverter control part has been built up using the blocks – multiplexer, multiplying block and scopes for monitoring the measured values. Considerable place has given to the Setting Cumulation Time Block (SCTB). It has been built up using the approach DDS (Data Direct Synthesis). The change step of the cumulation time duration has been set by setting the parameters of the *Delays* block. In our case a step 1.10^{-7} [s] has been selected, but if it is necessary it can be decreased.

The cumulation time duration has been set by the operator by the block *Constant 3* (Fig. 2) and it can vary from $\tau_{\min}$, at which damping oscillations occur, to $\tau_{\max}$.

The maximum value of $\tau_{\max}$ has been limited by two factors – the transistor (capacitor) puncture voltage and the maximum admissible transistor current value.

The voltage maximum value $(U_{CE})_{bb}$ is:

$$(U_{CE})_{bb}=U_{CEmax}(t_1)- U_{CEmin}(t_2) \quad (10)$$

where t_1 and t_2 are the moments at which U_{CE} has got maximum and minimum value accordingly. In order not to occur a puncture in the capacitor and the transistor the following condition should be fulfilled:

$$(U_{CE})_{bb} \le k(U_{CE})_{\partial on} \quad (11)$$

where $0{,}9 \le k \le 0{,}95$ is a sure coefficient.

The second factor liming $\tau_{\max}$ is the maximum admissible current value of the transistor, i.e. it is necessary to fulfill the condition:

$$I_{TP} \le k(I_{TP})_{\partial on} \quad (12)$$

The moment, at which the control signal for switching on the transistor is generated, is important. In order not to dissipate needless thermal power on the transistor it is advisable it's switching on to be made during the interval when $U_{CE} \le 0$. That's why it is necessary the transition moment to be fixed, when U_{CE} changes it's sign from (+) to (-). At modeling it have been done by the means of zero voltage comparator which input signal has been taken from the voltage U_{CE} by resistor divider *R5* and *R6* (Fig. 3).

At the moments t_1 and t_2 when the transistor voltage has maximum value U_{CEmax} and minimum value U_{CEmin} accordingly the oscillator circuit current value is zero. That's why it is advisable to use a zero current comparator receiving an input signal from the resistor R_{III}.

Having in mind Figs. 2 and 3, the change range of L_{Π} and R_{Π} when varying the temperature from $\tau_{\min}$ to $\tau_{\max}$ at previously defined primary values of the oscillator circuit parameters, information about the operation modes has been gathered (voltages, currents, power, time intervals). Simultaneously the cummulation time changes in advisable limits by SCTB. Three values have been taken for the source voltage: E, E+10%, E-10%. The simulation data results are shown in Table I. Some typical timing diagrams about voltages, currents and time intervals are shown in Figs. 4 and 5.

The relation between the inductor current (position 1) and the transistor voltage (position 2), the time interval τ_1 (position 3), and the cumulation time (position 4) are shown in Fig. 4. The voltage has maximum and minimum values accordingly at zero current values. That is why the maximum allowed values can be selected and controlled by means of a zero current comparator.

The relation between the primary inductor winding currents (position 1) and the transistor current (position 2) is shown in Fig. 5.

TABLE I

INVERTER SIMULATION DATA AT CHANGING L_T, R_T AND τ

E [V]	$R_T[\Omega]$	L_T [μH]	$\tau[\mu S]$	$\tau_1[\mu S]$	I_{TP}[A]	P_1[kW]	$U_{ce(+)}$[v]	$U_{ce(-)}$[v]	U_{ce}[v]	P_2[kW]	U_t[v]	I_T[A]
279	2	30	6,4	11.5	29.2	1.2	740	-103	843	0,8	207	42,5
310	2	30	6,4	11	32	1.3	833	-123	956	0,9	234	48,4
341	2	30	6,4	3.4	20	1.5	915	-135	1050	1	258	53,2
279	6,6	30	30	5.5	33	3.4	810	-40	850	2,7	395	52,1
279	6,6	30	80	8.7	38	6.5	910	-93	1003	5,8	455	61
310	6,6	30	25	3.5	34	3.8	860	-15	875	2,9	412	53,5
310	6,6	30	80	8.5	43.1	7.2	1010	-105	1115	6,5	507	68
341	6,6	30	30	5.7	40	6	1000	-47	1047	4,8	482	63,8
341	6,6	30	40	7.0	43.8	7	1050	-80	1130	6	525	69,7
279	6,6	12	35	3.5	31.1	3.8	800	-18	818	3,4	385	55,3
279	6,6	12	80	5.8	38.9	7.2	850	-47	897	5,8	418	60,5
310	6,6	12	35	3.2	39.9	4.5	890	-20	910	4	425	62,3
310	6,6	12	100	8.9	43.4	8	950	-55	1005	7,2	485	67,5
341	6,6	12	35	4.1	43.4	6.1	980	-25	1005	5,5	470	67,6
341	6,6	12	100	6.0	47.6	11.2	1045	-60	1105	9,7	535	74,3

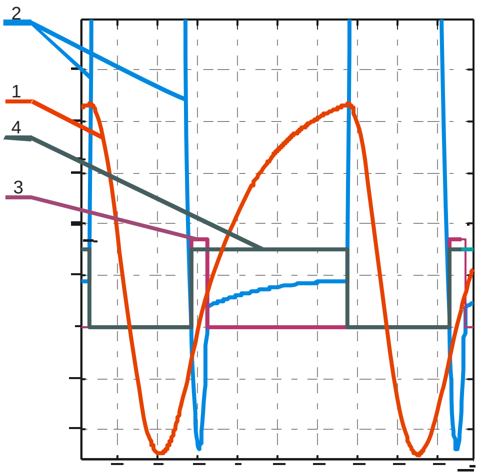

Fig. 4. Inductivity and transistor currents and voltages

Position 1 inductivity current

Position 2 transistor voltage

Position 3 time interval duration τ_1

Position 4 cumulation time duration τ

VIII. CONCLUSIONS

The following conclusions can be made from the modeling of the single-switch inverter circuit at varying load parameters and from the results:

- The time interval τ_1, when the transistor voltage is negative, varies in the range of $\tau_{1\min}$ to $\tau_{1\max}$ and the negative amplitude Uc(-) must be measured and transformed into digital form.
- The cumulation time τ at zero initial values of R_T and L_T for the defined circuit has minimum value $\tau_{\min}$ and it must be changed with step $\leq 0{,}1\mu S$.

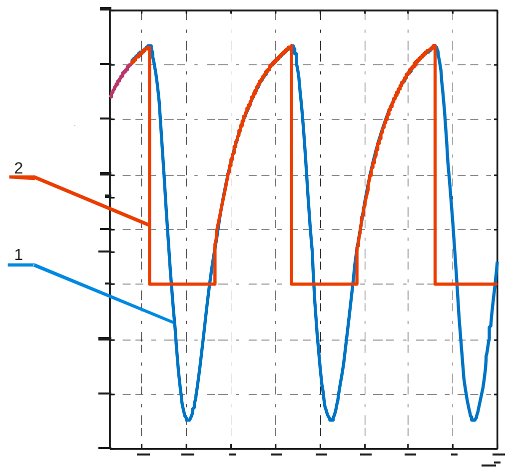

Fig 5. Inductivity and transistor currents

Position 1 inductivity current

Position 2 transistor current

- The maximum value of the cumulation time is limited by the maximum allowed value U_{CE} of the transistor and the maximum allowed transistor current $(I_{TP})_{\partial on}$. Therefore the voltages $U_{C(+)}$ and $U_{C(-)}$ and the current I_{TP} must be measured.
- The structure of the block SCTB in Simulink is suggested. It is based on the DDS approach. The block SCTB allows generating programmable delays with duration and step, defined by an operator.

REFERENCES

[1] Dr Ch. Hinow, Dr Georg Hinow, “Betrieb eines Wechselrichters mit inductiver Kummulation”, Elektrische Bahnen., Heft 11/2004, 28.08.2004, pp.490-493

[2] “Simulink. Model-Based and System-Based Design. Using Simulink”, The MathWorks, Inc., 2004, www.mathworks.com.

[3] “PLECS User Manual”. Plexim GmbH, 2002-2004, www.plexim.com

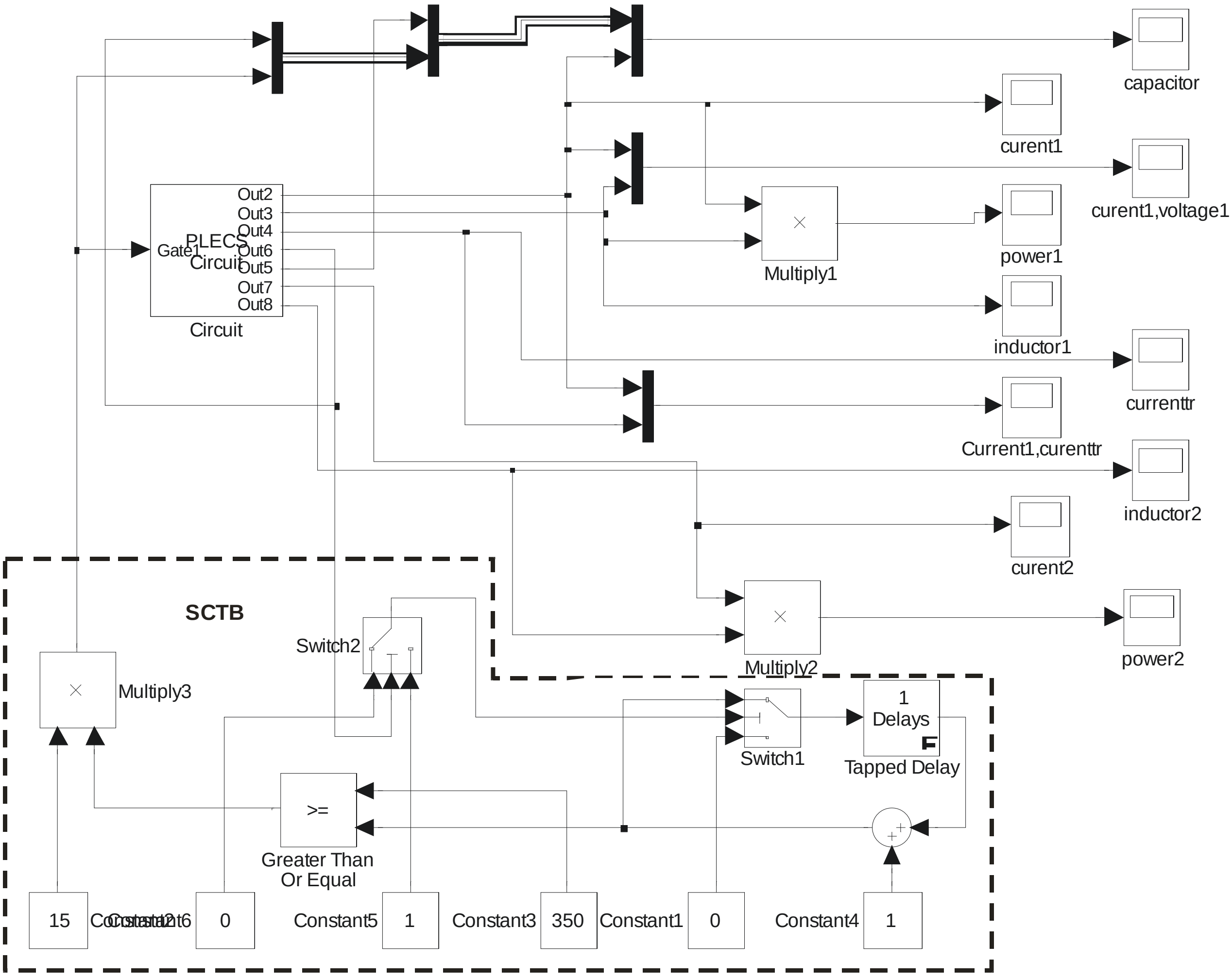

Fig. 2. Control part model of the inductive cumulation inverter

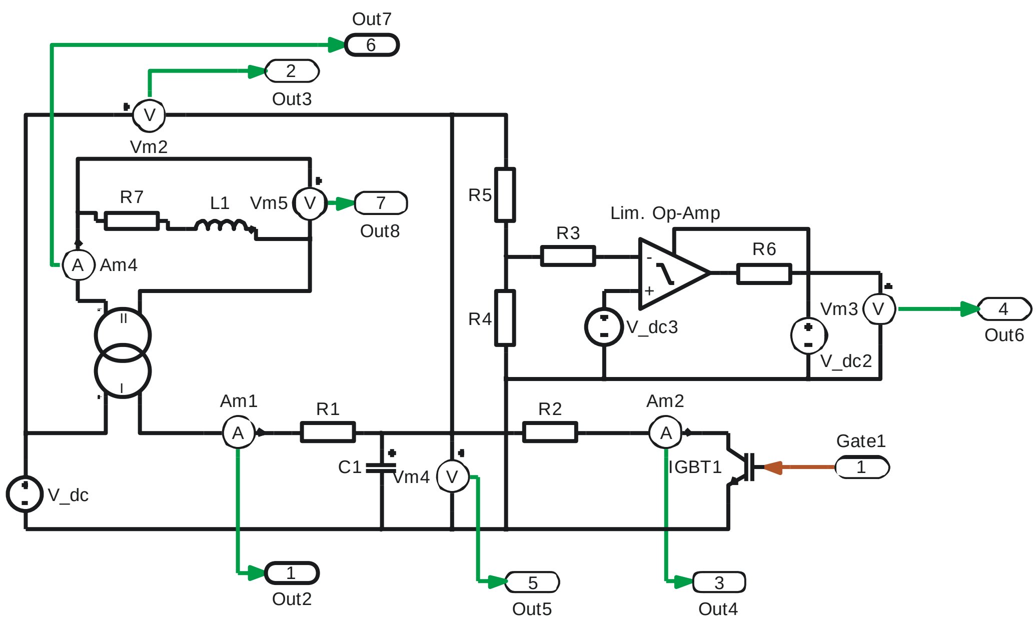

Fig. 3. Inductive cumulation inverter circuit