Thermal and Surge Current Protection Means for Semiconductor Non-Isolated Power Converters

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***Abstract*—The combined calculation of electromagnetic and thermal processes in semiconductor non-isolated power converters and the analysis of semiconductor switch junction overheating were carried out to develop thermal and surge current protection means, which are based on soft start system control depending on semiconductor switch junction temperature and normalization of the inductor parameters depending on converter temperature changing.**

Keywords—PWM converter; electro-thermal modelling; state differential equations; stability; standards

I. Introduction

A relevant issue for designing semiconductor power converters is development of thermal and surge current protection means for normal operation and transient modes. Nearly 60% of failures are temperature or surge current induced [1]. Heating of inductors, capacitors and transformers leads to transient changes, which cause surge current value increase in the circuits of the converters. These deviations are undesirable and dangerous for semiconductor devices during device restart, load drop or short circuit.

II. Goal Statement

The prototype converter considered in this study includes a half-bridge inverter with a soft start system, loaded with an output bridge inverter with control system (voltage feedback). Despite of using the soft start, there is a danger that surge currents will lead to device breakdown. Fig. 1 represents transistor current curves deviations, caused by the components heating, during device restart and load drop. Fig. 1 *a* shows surge current of half-bridge inverter transistors during restarting the heated device. Fig. 1 *b* shows surge current of bridge inverter transistors during load drop. Both modes are unsafe for semiconductor devices and require special solutions, which combine protection from surge current and thermal processes.

The aim of this work is to create surge and thermal protection means for semiconductor devices of DC-DC non-isolated converters, using thermal changes of magnetizing inductance for transient current chopping and through restart of adaptive soft start system after load drop or short circuit, and considering actual surge protective and inductive elements standards.

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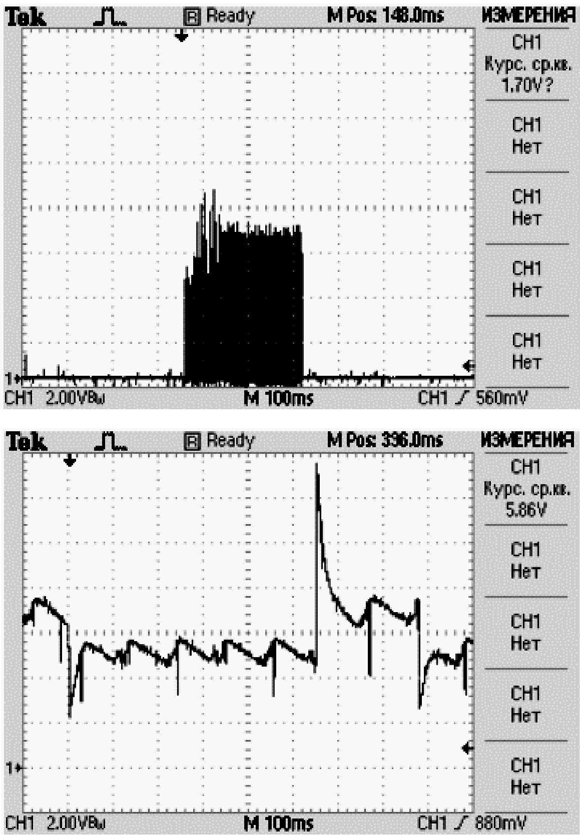

a)

b)

Fig. 1. Transistor current curves deviations, caused by the components heating: a) surge current of half-bridge inverter transistors during restarting the heated device; b) surge current of bridge inverter transistors during load drop

The use of suggested surge and thermal protection means should increase productivity and lifetime of semiconductor converters operating in pulse mode, reduce maintenance expenses and number of failures caused by the breakdown of power semiconductor elements and elements of filter.

III. Using the Standards

To calculate and test the temperature derating and the temperature coefficient of breakdown voltage, the standard C62.35-2010 [2] will be used. According to the standard, the analysis, the calculation and the testing of components will be carried out under normal conditions (normal operating range: –5°C to +55°C, extended operating range: –40°C to +85°C; the components were applied in the systems where the frequency is between zero (DC) and several GHz, depending on the component's capacitance and leakage current; the component surge ratings exceeds the expected amplitude, wave shape and occurrence rate of surges in the system application over the expected system ambient temperature range; the component electrical ratings and characteristics, after temperature derating for the expected ambient temperature range of the system, meet the system needs). In the operation points of the breaking normal conditions, new component builds, or additional protection solutions were built. Untypical conditions, which will be tested, are the following: temperature values that exceed the normal service conditions; abnormally high system surge currents whereby the rating of the device is exceeded; the maximum transient repetition rate of specified waveform that normally occurs in the system can't be safe for heated devices (during junction temperature rise, maximal safe current for junction goes down).

According to the standard C62.35-2010, the following failure mode tests will be applied: degradation failure mode test, where the components have a stand-by current greater than the specified value; short-circuit failure mode test; open circuit failure mode test.

The important for the given research values to test: rated peak impulse power; rated average power dissipation; the capacitance will be measured at a specified signal level, frequency, and bias voltage; rated forward surge current; temperature derating; temperature coefficient of breakdown voltage.

Rated forward surge current will be tested in the circuit of buck converter as follows (fig. 2):

1. Apply a half cycle of the rated forward surge current (I_{FSM}) through the unidirectional component in the forward direction.

2. Repeat the test described in step 1, above, for a total of 10 times with a maximum interval between surges of 2 minutes.

3. Measure the stand-by current. The stand-by current shall not be greater than the maximum specified value after the surges.

To provide the test of the buck converter, the inductance (impedance) unbalance, the electric strength test, the magnetizing inductance measurements, and the temperature rise tests, the standard IEEE 388-1992 [3] will be used for non-isolated buck (step-down) converter topology.

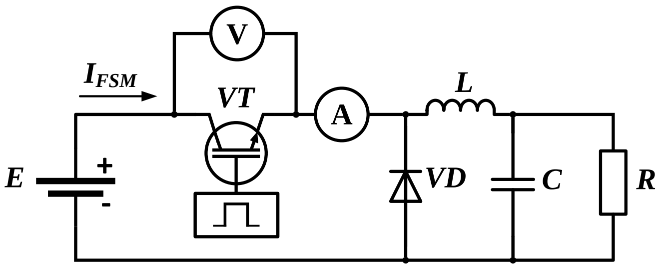

Fig. 2. Test circuit of buck converter for forward surge current: A – peak reading ammeter; V – peak reading digital voltmeter.

To create surge current and thermal protection system with transient waveform control using inductor magnetic core parameters changing, it is necessary to calculate and test the following parameters: the ratio of transformation, the inductance (impedance) unbalance, the electric strength, the magnetizing inductance, the transformer losses and capacitance (the control of induction by parallel magnetically dependent inductor circuit works in the same way as a normal transformer), temperature rise tests.

The measurements of the temperature rise and the inductance are the most important for providing the thermal and surge current protection system reliability.

The maximum temperature rise of a transformer can be measured by embedding a thermocouple at the hot spot of the coil. If this is not possible, the average temperature rise can be determined by measuring the resistance change of the inside winding of the coil. To determine the average coil temperature rise, it is necessary to use the following equation:

$$t_2 = \frac{R_2}{R_1}(K + t_1) - K \,, \quad (1)$$

where t_2 is the mean temperature that produces a change of resistance, R_2, in a coil from resistance, R_1, established at temperature, t_1. Temperatures are expressed in degrees Celsius. For copper wire whose volume conductivity is 100% and whose temperatures is between 0 °C and 125°C, K = 234.5.

The used pulse inductance measurement method for high-frequency power magnetics consists in determining inductance through the dynamic values of voltage and current under actual operating conditions of a switched circuit. To do this, three values are needed:

1. E = Peak value of the voltage pulse, in V, across the inductor (or winding of interest) during time, t.

2. t = The increment of time, in s, between the 50% rise and fall voltage points of the voltage pulse.

3. I = Increment of current, in A, over time, t. It is assumed that this current ramp is essentially linear over this time.

The inductance of the winding can then be calculated:

$$L(\&H_{ys}) = \frac{E \cdot t}{I} \,. \quad (2)$$

To calculate the junction temperature, the thermal response and the peak currents, and to analyze the failure modes of thyristor diodes and other semiconductor elements operating in pulse mode, that is required to test the developed protection means, the standard C62.37-1996 [4] will be used. To create a mathematical model of semiconductor components, the following parameters will be used: breakover current, breakover voltage, holding current, repetitive and non-repetitive peak on-state current and peak pulse current, off-state capacitance, off-state current, off-state voltage, on-state current, on-state voltage, breakdown current, critical rate of on-state current rise, forward current, forward voltage, impulse reset time, insulation resistance, lifetime rated pulse currents, peak pulse impulse current, switching current, switching resistance, maximum junction temperature, temperature coefficient of breakdown voltage, temperature derating, thermal resistance, transient thermal impedance, variation of holding current with temperature, virtual junction temperature.

The transient thermal impedance is the most important parameter for creating a thermal model of semiconductor devices. The purpose of transient thermal impedance test is to determine the power capability of a component for a specified power pulse duration, *t*. The thermal impedance, *Z*(*t*), permits the calculation of the power capability at different reference and junction temperatures. The value of *Z*(*t*) is calculated as follows:

transient thermal impedance junction to ambient for time interval *t*

$$Z_{JA(t)} = \frac{T_{JPK} - T_A}{P_{TOT}} \tag{3}$$

transient thermal impedance junction to case for time interval *t*

$$Z_{JC(t)} = \frac{T_{JPK} - T_C}{P_{TOT}} \tag{4}$$

transient thermal impedance junction to lead for time interval *t*

$$Z_{JL(t)} = \frac{T_{JPK} - T_L}{P_{TOT}} \tag{5}$$

where: T_A is the ambient temperature reference; T_C is the case temperature reference, maintained at a constant value by cooling; T_L is the lead temperature reference, maintained at a constant value by cooling; T_{JPK} is the peak junction temperature, $0.8T_{JM} < T_{JPK} < T_{JM}$; P_{TOT} is the power pulse amplitude; *t* is the pulse width of power pulse.

IV. Electro-Thermal Modelling

To analyze the electromagnetic and thermal processes during the converter operation, it is necessary to create a mathematical model, which will be describe them. The differential equations of the state were obtained to describe the electromagnetic processes. They are convenient for calculating the converter parameters depending on the temperature changes of the circuit components.

A general form of the equation can be written as:

$$\frac{dX}{dt} = AX + B \tag{6}$$

where $X = \begin{vmatrix} i \\ u \end{vmatrix}$ – vector of state variables, A – matrix of coefficients, B – vector of external influence.

The solution of this equation can be represented as a matrix exponent [5]:

$$X = \int_{mT}^{t} e^{A(t-\tau)} B d\tau \tag{7}$$

where *T* – switching period of the converter transistors, *m* – period number, *t* – analyzed time of operation, *τ* – coefficient of integration.

The main value characterizing the matrix exponent is the eigenvalue of the matrix *λ*. To calculate *λ*, the following form should be used:

$$\det(A - \lambda I) = \begin{vmatrix} a_{11} - \lambda & a_{12} \\ a_{21} & a_{22} - \lambda \end{vmatrix} = 0, \ I = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} \tag{8}$$

Analyzing the ratios of the switching frequency to the roots of the characteristic equation, the characteristics of the device such as bifurcation diagrams of the switching points, the dependence of the error signal on time in the steady state, and other parameters can be found [6]. The dependence of the transient's value of semiconductor power converters on the complex component of the characteristic equations roots is used, and the thermal motion of these roots is investigated.

For a buck converter connected to a constant load, the equation of the state for electromagnetic and thermal processes has the following view:

$$\begin{vmatrix} \frac{di_L}{dt} \\ \frac{du_C}{dt} \\ \frac{dT_{VT}}{dt} \\ \frac{dT_{VD}}{dt} \\ \frac{dT_L}{dt} \\ \frac{dT_C}{dt} \end{vmatrix} = \begin{vmatrix} -\frac{r(T_{VT},T_{VD},T_L)}{L(T_L)} & -\frac{1}{L(T_L)} & 0 & 0 & 0 & 0 \\ \frac{1}{C(T_C)} & -\frac{1}{RC(T_C)} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{R_{thjcVT}C_{thjcVT}} & \frac{Z_{thDT}}{Z_{thjcVT}} & \frac{Z_{thLT}}{Z_{thjcVT}} & \frac{Z_{thCT}}{Z_{thjcVT}} \\ 0 & 0 & \frac{Z_{thTD}}{Z_{thjcVD}} & -\frac{1}{R_{thjcVD}C_{thjcVD}} & \frac{Z_{thLD}}{Z_{thjcVD}} & \frac{Z_{thCD}}{Z_{thjcVD}} \\ 0 & 0 & \frac{Z_{thTL}}{Z_{thL}} & \frac{Z_{thDL}}{Z_{thL}} & -\frac{1}{R_{thL}C_{thL}} & \frac{Z_{thCL}}{Z_{thL}} \\ 0 & 0 & \frac{Z_{thTC}}{Z_{thC}} & \frac{Z_{thDC}}{Z_{thC}} & \frac{Z_{thLC}}{Z_{thC}} & -\frac{1}{R_{thC}C_{thC}} \end{vmatrix} \begin{vmatrix} i_L \\ u_C \\ T_{VT} \\ T_{VD} \\ T_L \\ T_C \end{vmatrix} + \begin{vmatrix} \frac{E \cdot s}{L} \\ 0 \\ \frac{Q_{VT}}{C_{thjcVT}} \\ \frac{Q_{VD}}{C_{thjcVD}} \\ \frac{Q_L}{C_{thL}} \\ \frac{Q_C}{C_{thC}} \end{vmatrix} \tag{9}$$

where $r = r_{VT} \cdot s + r_{VD} \cdot (1-s) + r_L$; s – switching function; i_L, u_C – state variables: the inductor current and the capacitor voltage; the values *r, L, C* depend on the temperature; T_{VT}, T_{VD}, T_L, T_C – temperature of the components; elements of the main diagonal show thermal response of the components, to establish the thermal dependence between the converter elements, the corresponding values of thermal resistance are used; values Z_{th} for capacitors and inductors can be taken as constant; the values Z_{th} for transistor and diode junctions and between components are calculated and tested as Z_{jc}, Z_{ja}(VT) with Z_{ja}(VD) (standard C62.37-1996).

To calculate electromagnetic and thermal processes together using combined mathematical model, it is necessary to consider the integration step and the rate of the processes. In Table 1, different types of models are represented depending on the process rate.

TABLE I. MODELS DEPENDING ON THE PROCESS RATE

Processes	Devices	Fast models	Slow models
Electromagnetic processes	***Semiconductor***	*S, R, RS, R(I)S*	–
	Passive	*LC, L(I)C(U)*	–
Thermal processes	***Semiconductor***	*R(Tj)*	*R(Tcs)*
	Passive	–	*L(T)C(T)*
Electro-thermal processes	***Semiconductor***	*R(Tj)S, R(Tj,I)S*	*R(Tcs)S*
		R(Tj,Tc)S, R(Tj,Tc,I)S	
	Passive	–	*L(T(P))C(T(P))*
		L(T(P),I)C(T(P),I)	

In this research the combined model with different rates of processes *R*(*Tj*,*Tc*)*SL*(*T*(*P*))*C*(*T*(*P*)) with possibility to expand to *R*(*Tj*,*Tc*,*I*)*SL*(*T*(*P*),*I*)*C*(*T*(*P*),*I*) is used.

Transformation of the state equation into a system of two equations, where the first equation refers to fast electromagnetic processes, and the second one to the slow thermal processes, which are associated with the heating of passive components, cases and radiators of semiconductor devices, gives the following form:

$$\begin{cases} \dfrac{dX_1}{dt} = A_1 X_1 + B_1 \\ \dfrac{dX_2}{dt} = A_2 X_2 + B_2 \end{cases} . \quad (10)$$

In this system of the equations, the coefficients matrix and vectors of external influence are not static coefficients, but depend on the temperature and electromagnetic state of the system. It is shown in the following form using diakoptics solutions [7]:

$$\begin{cases} \dfrac{dX_1}{dt} = A_1 \cdot X_1 + B_1 \\ \dfrac{dX_2}{dt} = A_2 \cdot X_2 + B_2 \end{cases} . \quad (11)$$
$$A_1, B_1 = A_1, B_1 + f(X_2)$$
$$X_2 = X_2 + g(P_1(X_1))$$

where the values of the coefficient matrix of the first equation depend on the temperature of the corresponding components calculated in the second equation, and the values of the dissipation power of the components of the second equation (P_1) are determined by the results of calculations according to the first equation.

Due to the slowness of the passive components thermal processes, the thermal change of the parameters of the coefficient matrices and the vector of external influence for electromagnetic processes can be calculated discretely:

$$\begin{cases} \dfrac{dX_1}{dt} = A_1 \cdot X_1 + B_1 \\ \dfrac{dX_2}{dt} = A_2 \cdot X_2 + B_2 \end{cases}$$
$$A_1, B_1[nT] = A_1, B_1[(n-1)T] + \Delta A_1[X_2], \quad (12)$$
$$P_2[nT] = P_1(X_1[nT])$$

where n = (1, 2,…) – communication step between equations; h – the coefficient of the step, which depends on the time, at which the slow process equation gets a significant influence on the fast process equation.

The actual problem of integrating the system of differential equations is the choice of integration step. Choosing a big step violates the stability of the calculation method, the choice of a small step causes an overestimated cost of the calculation.

To optimize the calculations, the matrix is divided into an independent temperature component matrix with static parameters and a temperature-dependent component matrix with dynamic parameters:

$$\frac{dX}{dt} = \left(A_e + A_t\left[nT\right]\right) X + B . \quad (13)$$

Therefore, it can be assumed that the equation of communication is linear and has the form $X_1 = kX_2$.

Considering this linearity and the reaction inertia of slow heat processes to fast electromagnetic ones, the step of communication between equations must correspond to the magnitude when rapid processes begin to significantly affect the slow processes.

$$A_1[nT] = A_1[(n-1)T] + \Delta A_1(X_2[mh_2])$$
$$P_2[nT] = P_1[mh_1] \quad , \quad (14)$$

where h_1 – transferring data step from the equation of thermal processes to the equation of electromagnetic processes; h_2 – transferring data step from the equation of electromagnetic processes to the equation of thermal processes.

Fig. 3 graphically represents the current and the temperature, and their interconnections using the constituent equations of communication.

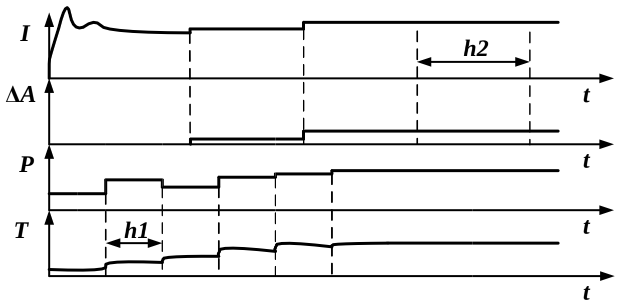

Fig. 3. Current and temperature in communication

The eigenvalues determine the oscillation and time scale of transient processes. For rigid systems, the ratio of roots is significant. Fig. 4 shows the zone of suitable values for the implicit Euler method, where μ and ν are eigenvalues of electromagnetic and thermal matrices.

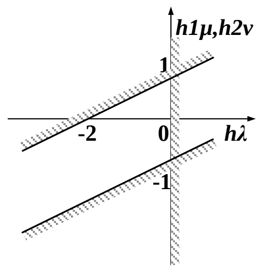

Fig. 4. Zone of implicit Euler method stability

In a case of selecting an integration step according to the equations $-h\lambda_{\min}+2h\mu_{\max}<2$, $h\lambda_{\max}-2h\nu_{\min}<2$, $h\lambda<0$, the most suitable value can be calculated as:

$$\frac{h_1}{h_2}\approx\frac{\nu}{\mu}=\frac{\lambda_2}{\lambda_1}. \tag{15}$$

The stability zone of the computational process is not constant. The boundaries of the zone dynamically change with the thermal change of component parameters. Correspondingly, the integration steps and the step of equations of communication will be also changed. Consequently, at each recalculation of the temperature-dependent component matrix, it is necessary to determine the integration steps. Acceleration of the adjustment process is achieved in two stages:

1. The choice of the communication equations step, considering the sensitivity to the thermal motion of the eigenvalues $\frac{S_{\lambda_i}}{\Delta T}\to 0$.

2. Finding the stability zone of the integration method.

In some cases, to develop the thermal protection systems, it is sufficient to analyze the thermal motion of the characteristic equation roots.

Using the bisection matrix formulas based on binary vectors [7], getting:

$$\begin{gathered}\det(A-\lambda I)=\det(A_e-\lambda I)+\\ +\sum(-1)^{\sigma}\Delta_e(d_i)\Delta_t(\overline{d_i})-\lambda^2+\det(A_t-\lambda I)\end{gathered}, \tag{16}$$

where:

$$\begin{gathered}\sum(-1)^{\sigma}\Delta_e(d_i)\Delta_t(\overline{d_i})=a_{11}\cdot a_{22}(\theta)-\\ -a_{12}\cdot a_{21}(\theta)-a_{21}\cdot a_{12}(\theta)+a_{22}\cdot a_{11}(\theta)\end{gathered}. \tag{17}$$

As example, in case of the buck converter in the open state of the transistor, $mT\le T\le mT+DT$:

$$\begin{gathered}\begin{vmatrix}I\\U\end{vmatrix}=\int_{mT}^{t}e^{A_1(t-\tau)}\begin{vmatrix}\frac{E}{L}\\0\end{vmatrix}d\tau=\\ =e^{A_1(t-mT)}\begin{vmatrix}I(mT)\\U(mT)\end{vmatrix}+A_1^{-1}\left(e^{A_1(t-mT)}-I\right)\begin{vmatrix}\frac{E}{L}\\0\end{vmatrix}\end{gathered}. \tag{18}$$

On the interval of the closed state of the transistor, $mT+DT\le T\le(m+1)T$:

$$\begin{vmatrix}I\\U\end{vmatrix}=\int_{mT+DT}^{t}e^{A_2(t-\tau)}d\tau=e^{A_2(t-mT-DT)}\begin{vmatrix}I(mT+DT)\\U(mT+DT)\end{vmatrix}. \tag{19}$$

Eigenvalues:

$$\lambda_{1,2}=-\frac{1}{2}\left(\frac{r}{L}+\frac{1}{RC}\pm\sqrt{\left(\frac{r}{L}+\frac{1}{RC}\right)^2-\frac{4}{LC}\left(\frac{r}{R}+1\right)}\right), \tag{20}$$

where $\lambda_{\min}$ – minimal real component of eigenvalue, which determines the length of the transients, being a value inversely proportional to the time of regulation.

The type and duration of the transients depend on the distance of the eigenvalues to the imaginary axis, which calculates as:

$$tg\varphi=\frac{\mathrm{Im}(\lambda)}{\mathrm{Re}(\lambda)}. \tag{21}$$

Characteristic equation:

$$\lambda^2+b\cdot\lambda+c=0, \tag{22}$$

where:

$$b=-a_{11}-a_{22}-a_{11}(\theta)-a_{22}(\theta), \tag{23}$$

$$\begin{gathered}c=a_{11}a_{22}-a_{12}a_{21}+a_{11}(\theta)\cdot a_{22}(\theta)+a_{11}a_{22}(\theta)+\\ +a_{22}a_{11}(\theta)-a_{12}(\theta)a_{21}(\theta)-a_{12}a_{21}(\theta)-a_{21}a_{12}(\theta)\end{gathered}, \tag{24}$$

$$\theta = t^\circ - 25^\circ C\ . \tag{25}$$

Characteristic equation can be written as:

$$\lambda^2 + \frac{b}{\Omega} \cdot \Omega \cdot \lambda + \Omega^2 = \lambda^2 + B \cdot \Omega \cdot \lambda + \Omega^2 = 0\ , \tag{26}$$

$$\Omega = \sqrt{\lambda_1 \lambda_2}\ , \tag{27}$$

B – describes the transition form, Ω – the time scale of the process: $\tau = \Omega \cdot t$.

V. Adaptive Thermal and Surge Current Protection Systems

One of the most dangerous operation mode in power converters is restart of the heated device. Since the junction temperature of semiconductor components increases, their boundary parameters are reduced. Due to this understatement of the parameters during restart, the current value and the thermal spikes ($tg(\varphi)$) of the transient process are important parameters, since they can determine the accident rate of this process. To reduce the temperature spikes, a thermal and surge current system based on decreasing the oscillating component of the transient process is proposed (Fig. 5) [8].

The system implements the temperature feedback of the converter (C) through the microcontroller (MC) containing the thermal models. The variation of the smoothing filter inductance is provided by the current regulation through magnetically connected inductor coil, which is determined by the MC and amplified by the operational amplifier (OA). To calculate the stabilization current value, it is required to consider the temperature of filter inductor coil. To do this, it is necessary to approximate test data taken using IEEE 388-1992 standard into mathematical model. For these purpose, a regression analysis was applied, and the temperature dependences of the coil were given as $\mu(\theta_L) = a_n\theta^n + a_{n-1}\theta^{n-1} + ... + a_1\theta + a_0 = \Delta\mu(\theta_L) + \mu$, where μ – magnetic conductivity at 25° C; $\theta = t° – 25$.

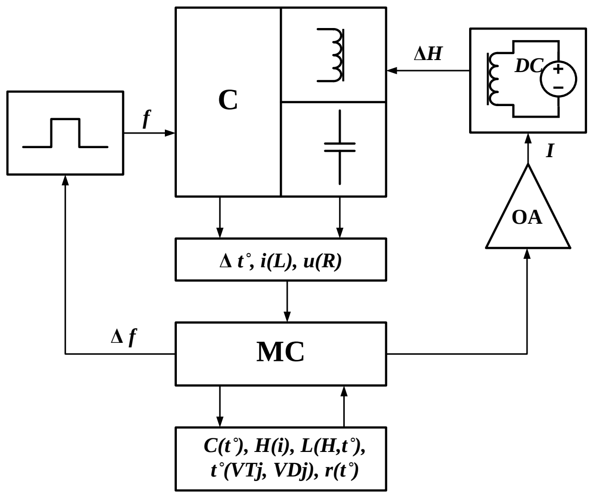

Fig. 5. Thermal and surge current protection with transients' waveform stabilization

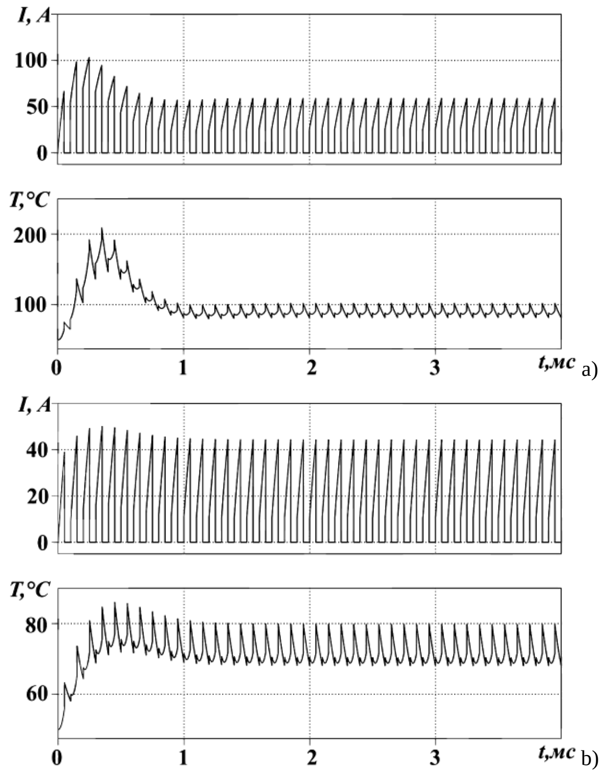

Fig. 6. Buck converter junction current and temperature: a) normal transient; b) transient obtained using the protection system, which decreased the thermal spike to extended normal operating range (C62.35-2010)

The parameters of electromagnetic processes were also corrected by changing the switching frequency of the converter input transistor. This double correction ensures that the parameters of the semiconductor junctions are within the limits of the maximum permissible values when the temperature changes. Using the means of MATLAB/Simulink [9, 10] and Plecs [11], the simulation of the circuit was carried out, and its effectiveness was confirmed (Fig. 6).

To solve the problem of junction thermal spikes during a short circuit and a current drop, a system for restarting a temperature dependable smooth start after a short circuit is proposed (Fig. 7).

During short circuit, the load voltage decreases sharply. Upon short circuit exclusion, the output voltage is registered, which is a signal for the restart of the smooth start system. To control the duration of smooth start, a microcontroller (MC) containing the electro-thermal models is used. Based on the data of the temperature sensors, on the inductor current and the load voltage, the semiconductor junction temperature is calculated. The signal from the MC goes through the system of smooth start (SS) to the control system (CS) by specifying the duration of a smooth start with the coefficient of pulse filling, depending on the junction temperature. The simulation results confirmed the possibility of reducing the temperature spike of the buck converter transistor junction from 180°C to 85°C (fig. 8).

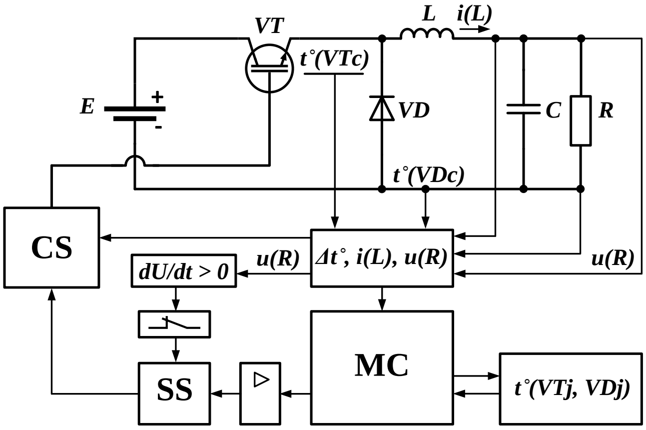

Fig. 7. System of surge current and thermal protection with restart of temperature dependable smooth start after short circuit

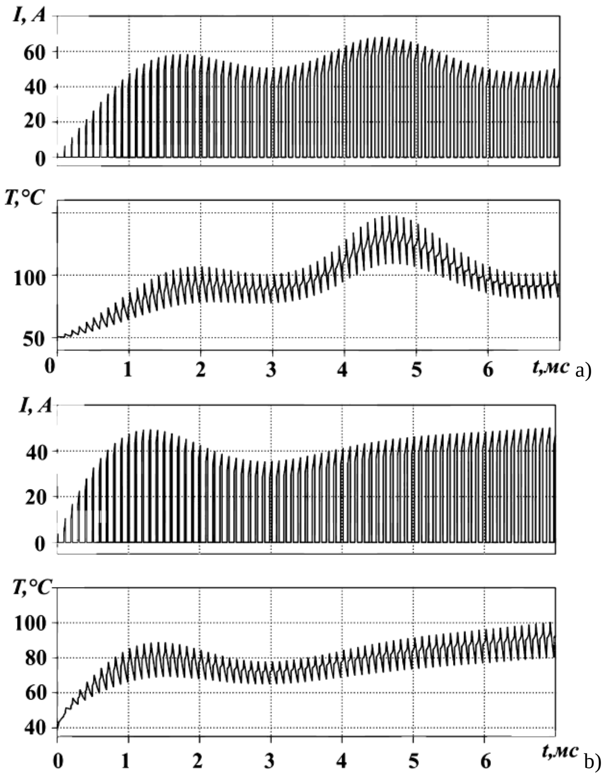

Fig. 8. Transistor junction current and temperature during restart of the smooth start system: a) without thermal feedback; b) using adaptation of the smooth start duration to the transistor junction temperature and current, which decreased the thermal spike to extended normal operating range (C62.35-2010)

VI. Practical Implementation of the Systems

The peculiarity of modern surgery lies in wide implementation of electrocoagulation equipment. The application of such devices makes it possible to substantially reduce the duration of surgery intervention, the blood loss and the time of postoperative recovery. The development of new types of electrocoagulators enables the use of new methods of surgery. One of the most relevant problems of the development and use of such equipment is its reliability.

The research is devoted to the development of surge current and thermal protection equipment to prevent malfunction of power converter, which is a part of electrocoagulator.

The specific feature of operation of such type of medical devices is the use of repeated intermittent modes characterized by both idle mode and short circuit.

The electrical modes of operations of the elements of prototype electrocoagulator were studied. The calculations of extreme modes of operation of semiconductor elements were carried out. The parameters of LC-filter were determined, and the types of magnetic throttle materials were suggested as well as the capacity providing the permissible spikes of semiconductor junction current. The smooth start system with adaptive time constant limiting the spikes of junction current of the electrocoagulator converter was used. Fig. 9 shows the difference between prototype electrocoagulator smooth start system and adaptive smooth start system, described earlier.

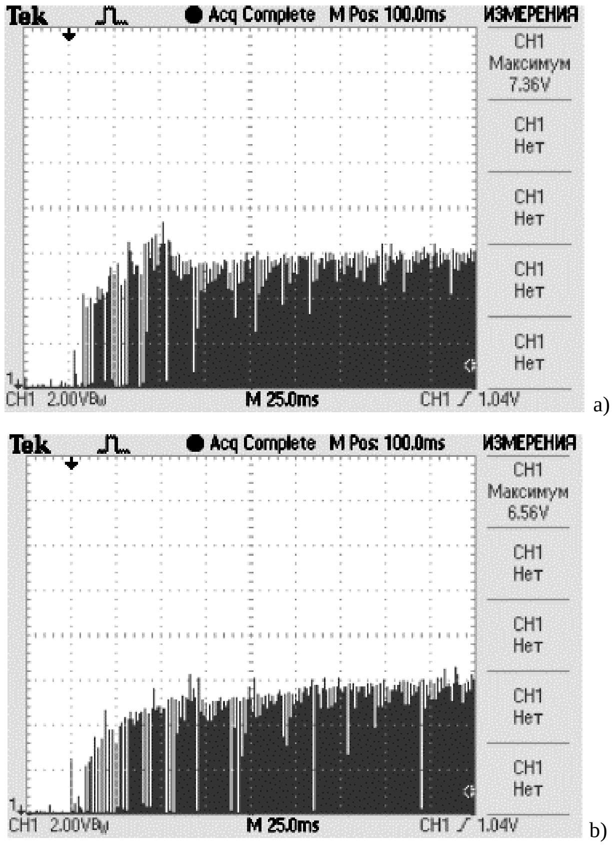

Fig. 9. Scope data of electrocoagulator operation: a) using smooth start system; b) using smooth start system with junction temperature feedback

The use of developed surge current and thermal protection systems made it possible to substantially increase the reliability of the welding electrocoagulator. The number of failure of power semiconductor elements is 14 times reduced to 1.2% comparing to the prototype electrocoagulator.

VII. Conclusion

The task of designing the surge and thermal protection means with thermal feedback, providing the permissible limits of heat and electric parameters, for semiconductor power non-isolated converter was solved due to carrying out a combined analysis of its electromagnetic and thermal processes.

Using the standards C62.35-2010, IEEE 388-1992, C62.37-1996, the calculation and check of temperature derating and temperature coefficients of breakdown voltage, the test of inductance unbalance and magnetic core parameters, the analysis of temperature rise, the calculation of junction temperature, thermal response, peak currents, and the analysis of failure modes of pulse semiconductor elements, were done.

Based on suggested mathematical model of the semiconductor converter, which considers the thermal dependence of the parameters of active and passive components, the effect of temperature changes of the components' parameters on the electromagnetic processes and the limiting operation modes of the power switches was estimated.

The developed thermal protection systems were simulated in the combined Plecs/MATLAB/Simulink environment. The simulation of the protection system with the adaptation of the smooth start time constant to current and temperature values showed the possibility of reducing the thermal spike on the transistor junction from 180°C to 80°C. The simulation of the system based on the normalization of the parameters of the passive components depending on the temperature changes showed the possibility of reducing the thermal spike on the transistor junction from 210°C to 85°C. The simulation results confirmed the advisability of using the developed protection systems in semiconductor converters. The system of protection with thermally depending smooth start adaptation is used in electrocoagulation devices.

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