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Minimization and Redistribution of Switching Losses Using Predictive PWM Strategy in a Voltage Source Inverter

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***Abstract*—This paper considers a PWM strategy with minimization of switching losses and their redistribution between the modules of the power converter. The strategy combines method of switching losses minimization by choosing the most efficient discontinuous PWM pattern and an active thermal control of the hottest IGBT module in the system. The algorithm predicts the total losses in the system for different PWM patterns and losses in the hottest IGBT module. The cost function takes into account both values. The provided simulation results display the decrease of maximum temperature in the system, while the total losses slightly increase.**

Keywords—active thermal control, PWM, switching losses, voltage source inverters, predictive control.

I. INTRODUCTION

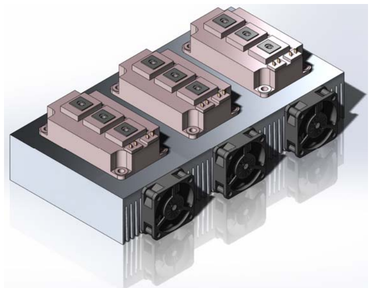
Most industrial drives are based on a voltage source inverter, in which IGBT power modules share a common heatsink. The design with separate modules for each inverter phase is normally utilized for frequency converters having rated power of 30 kW and higher. As there are three modules, the thermal conditions of the modules are not equal. For instance, the module located in the middle can be the hottest one for the design as illustrated in Fig. 1a. If the direction of the forced air-cooling changes according to Fig. 1b, then the hottest module can be the one farthest from the fans.

Unequal temperatures of the power modules result in a lower utilization of the power converter in general. While the farthest IGBT module from Fig. 1b can be overheated, the one nearest to the fans can still provide more power to the load.

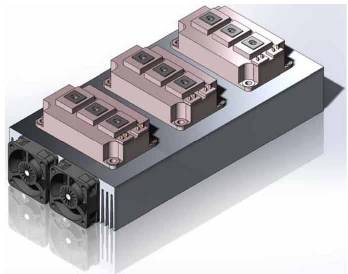
There are various PWM strategies that enable a decrease of switching losses in the system [1-3]. A referenced voltage vector can be applied with clamping to the negative or positive bus bar of the DC link. The technique with minimization of switching losses analyzes the current flowing in the phases of the inverter and selects the most efficient clamping with minimal switching losses. However, the minimization of switching losses only affects the average temperature, while the difference between temperatures of the modules still exists.

There are methods for active thermal control [4-7], which are mainly used for the improvement of thermal conditions of the semiconducting devices, but they mostly focus on thermal stabilization rather than on the decrease in temperature of a particular component of the inverter [6]. In [8], the problem of heat redistribution was resolved for the predictive control of the drive with open-end windings.

The aim of this paper is to modify the PWM strategy with switching losses minimization by including the difference of the modules temperature into consideration. It is suggested to use a predictive control approach with cost function definition for a more convenient determination of the optimization rule. Optimization can be performed by defining a cost function, which considers more than one variable. This will help to decrease the maximum temperature of the IGBT module by redistribute the losses in the power converter to the coldest power modules.



a)



b)

Fig. 1. Various heatsink configurations.

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II. PWM Strategy for Switching Losses Minimization

A. Duty Cycle Calculation

The voltage reference is represented as the magnitude and angle or voltages in stationary frames α,β. The reference phase voltages are provided by (1):

$$\left.\begin{aligned} v_a &= V_m \cos\theta; \\ v_b &= V_m \cos\left(\theta - \frac{2\pi}{3}\right); \\ v_c &= V_m \cos\left(\theta + \frac{2\pi}{3}\right), \end{aligned}\right\} \quad \text{or} \quad \left.\begin{aligned} v_a &= v_\alpha; \\ v_b &= -\frac{1}{2}v_\alpha - \frac{\sqrt{3}}{2}v_\beta; \\ v_c &= -\frac{1}{2}v_\alpha + \frac{\sqrt{3}}{2}v_\beta, \end{aligned}\right\} \qquad (1)$$

where v_a, v_b, and v_c are the phase voltage command for phases *a*, *b*, and *c* respectively; V_m represents the magnitude of the voltage reference; θ comprises the angle of the voltage reference; and v_α and v_β are the voltage references in the stationary frames α,β.

These voltage references can be implemented by inverter using clamping to negative or positive bus bars of the DC link. The duty cycles for each leg of the inverter can be evaluated as follows:

$$\left.\begin{aligned} &\text{clamp to negative bus bar DPWM:} \\ &\gamma_a^N = \frac{v_a - v_{min}}{V_{DC}}; \gamma_b^N = \frac{v_b - v_{min}}{V_{DC}}; \gamma_c^N = \frac{v_c - v_{min}}{V_{DC}}, \\ &\text{clamp to positive bus bar DPWM:} \\ &\gamma_a^P = 1 + \frac{v_a - v_{max}}{V_{DC}}; \gamma_b^P = 1 + \frac{v_b - v_{max}}{V_{DC}}; \gamma_c^P = 1 + \frac{v_c - v_{max}}{V_{DC}}, \end{aligned}\right\} \qquad (2)$$

where $v_{\min} = \min(v_a, v_b, v_c)$; $v_{\max} = \max(v_a, v_b, v_c)$; and V_{DC} represents the DC link voltage. The switching patterns are illustrated in Fig. 2. These patterns are the negative clamped discontinuous pulse width modulation (NCDPWM) and the positive clamped discontinuous pulse width modulation (PCDPWM).

B. Switching Losses Minimization

Switching losses depend on the value of the current and voltage to be switched. For DPWM strategies with clamping to positive (PCDPWM) or negative (NCDPWM) bus bar, the number of commutations is reduced from 6 to 4 for every PWM cycle as compared to the continuous pulse width modulation (CPWM), and this saves 33% switching losses.

For the referenced voltage vector from Fig. 2, the DPWM pattern can be implemented with clamping to either the positive bus bar of the DC link or to the negative. For NCDPWM, the top switch of phase *c* is always off during PWM cycle, and for PCDPWM, the top switch of phase *a* is always on. In order to minimize switching losses, it is preferable to select the pattern with respect to the currents flow in the phases. For example, if the instant absolute value of the current in phase *a* for the implemented voltage vector is bigger than that in phase *c*, then it is preferable to choose the PCDPWM pattern [1, 9].

III. Predictive PWM Strategy for Switching Losses Minimization and Redistribution

A. Why Predictive Method Should be Used for PWM Strategy?

The method of predictive control is efficient for the systems in which it is not possible or is difficult to establish analytical connection between the desired behavior and control references. Additionally, it may be useful if various optimization criteria are applied. For instance, the goal of the PWM strategy in question is to minimize switching losses with a simultaneous reduction in the temperature of the most heated part of the heatsink. As it will be presented later, the use of the cost function with a single criterion will not improve the thermal mode in general.

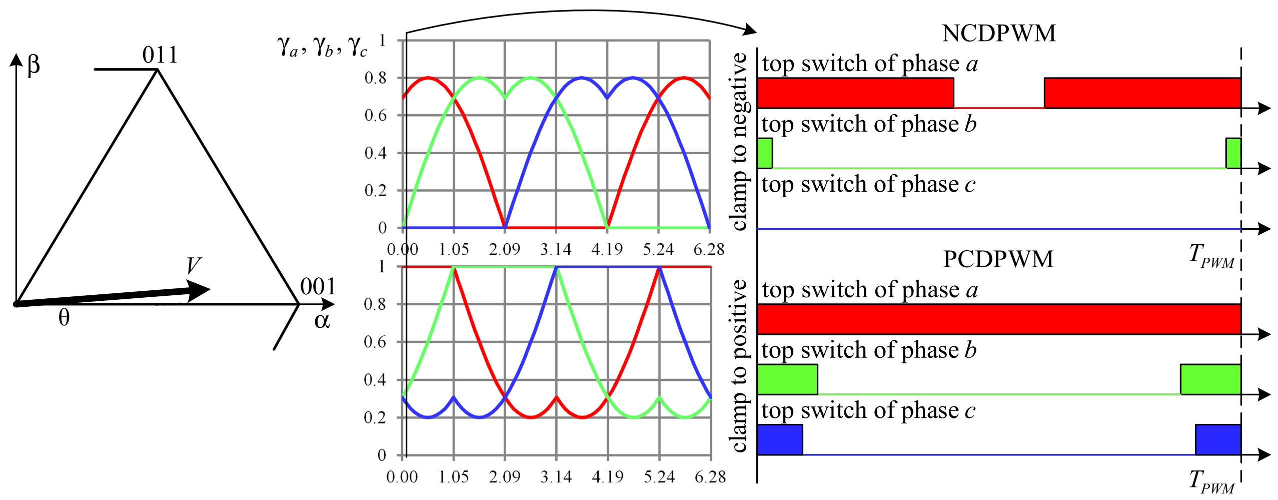

Fig. 2. Voltage commands using different PWM strategies.

B. *Inverter Losses Model*

For the sake of simplicity, it can be assumed that the current and the voltage rise and fall with a constant slope as it is reflected in Fig. 3. In this case, the switching losses during a single commutation can be expressed as follows [10]:

$$\Delta P_{sw} = \frac{1}{6} i_{load} V_{DC} \frac{t_{sw}}{T_{PWM}}, \tag{3}$$

where i_{load} represents the current in the load, t_{sw} is the sum of the switching on and the switching off times, and T_{PWM} represents duration of PWM cycle.

Assuming that the voltage drop in the switch and the freewheeling diode is approximately the same, the conductive losses are not considered in the proposed method. Thus, the switching losses are to be estimated through the following equations:

$$\begin{aligned} \Delta P_{sw}^{N} &= \frac{V_{DC} t_{sw}}{6T_{PWM}} \cdot \\ &\cdot \left(\begin{cases} 0, \gamma_a^N = 0 \\ |i_a|, \gamma_a^N > 0 \end{cases} + \begin{cases} 0, \gamma_b^N = 0 \\ |i_b|, \gamma_b^N > 0 \end{cases} + \begin{cases} 0, \gamma_c^N = 0 \\ |i_c|, \gamma_c^N > 0 \end{cases} \right), \\ \Delta P_{sw}^{P} &= \frac{V_{DC} t_{sw}}{6T_{PWM}} \cdot \\ &\cdot \left(\begin{cases} 0, \gamma_a^P = 1 \\ |i_a|, \gamma_a^P < 1 \end{cases} + \begin{cases} 0, \gamma_b^P = 1 \\ |i_b|, \gamma_b^P < 1 \end{cases} + \begin{cases} 0, \gamma_c^P = 1 \\ |i_c|, \gamma_c^P < 1 \end{cases} \right), \end{aligned} \tag{4}$$

where ΔE_{sw}^{P} and ΔE_{sw}^{N} are the predicted switching losses for the positive and the negative clamping respectively.

C. *Cost Functions*

1) Cost function for minimization of switching losses:

The cost function that optimizes switching losses will be considered a reference for all other competing control strategies. It provides the lowest temperature of the heatsink on average as follows:

$$\left. \begin{aligned} g_N &= \Delta P_{sw}^{N}; \\ g_P &= \Delta P_{sw}^{P}. \end{aligned} \right\} \tag{5}$$

The evaluated cost functions for the positive and negative clampings are compared, and the option with minimal cost is to be selected.

2) Cost function for the minimization of switching losses in the hottest leg of the inverter:

As the third leg of the inverter that corresponds to phase c is the hottest due to the maximum cooling air temperature, the cost function is defined to minimize the switching losses in this particular part of the inverter. It contains only the switching losses of phase c as follows:

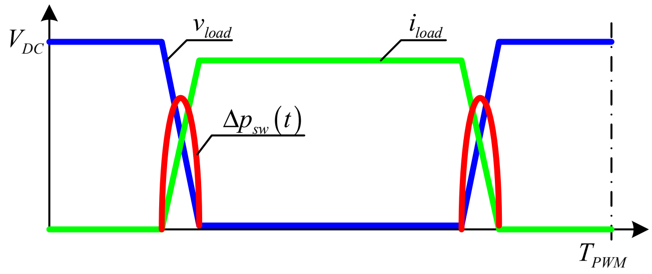

Fig. 3. Explanation of the voltage and current profiles during switching for losses evaluation.

$$\left. \begin{aligned} g_N &= \Delta P_{c\,sw}^{N} = \frac{V_{DC} t_{sw}}{6T_{PWM}} \begin{cases} 0, \gamma_c^N = 0 \\ |i_c|, \gamma_c^N > 0 \end{cases}; \\ g_P &= \Delta P_{c\,sw}^{P} = \frac{V_{DC} t_{sw}}{6T_{PWM}} \begin{cases} 0, \gamma_c^P = 1 \\ |i_c|, \gamma_c^P < 1 \end{cases}. \end{aligned} \right\} \tag{6}$$

This cost function will decrease switching losses in this particular phase of the inverter, but it does not affect the total decrease in losses; thus, the decrease of the temperature in a single phase may result in an overall increase of losses in the inverter and also increase of the average temperature.

3) Cost function for simultaneous minimization of losses and temperature in the hottest leg of the inverter:

The cost function can consider various factors. For instance, it can evaluate the total losses in the inverter, but if the difference in total losses is not high, the losses in the most heated module can be taken into account. The impact of each component in the cost function is defined by coefficients, which are to be defined while tuning the system. An example of the cost function that consider the total losses and losses in the phase c is provided below:

$$\left. \begin{aligned} g_N &= A \cdot \Delta P_{sw}^{N} + B \cdot \frac{V_{DC} t_{sw}}{6T_{PWM}} (\tau_3 - \tau_1) \cdot \begin{cases} 0, \gamma_c^N = 0 \\ |i_c|, \gamma_c^N > 0 \end{cases}; \\ g_P &= A \cdot \Delta P_{sw}^{P} + B \cdot \frac{V_{DC} t_{sw}}{6T_{PWM}} (\tau_3 - \tau_1) \cdot \begin{cases} 0, \gamma_c^P = 1 \\ |i_c|, \gamma_c^P < 1 \end{cases}. \end{aligned} \right\} \tag{7}$$

This cost function has an extra variable $(\tau_3 - \tau_1)$, which increase the impact of the second factor in case of high difference in the temperatures.

IV. Thermal Model of the Power Converter

The thermal model is used to estimate the temperature of the power modules in operation. The thermal model of any device can be represented with different levels of accuracy. The fastest simulation can be done for a single-mass model, while the finite element model is more accurate but time consuming. In this case study, it is possible to use the threemass model of the heatsink (see Fig. 4) according to the number of heat sources in the system. This model is accurate enough to test the PWM strategies and easy for the implementation by means of a simulation software.

The heatsink has been split into three parts. Each part has its individual thermal capacity C_a, C_b, and C_c with their temperatures τ_a, τ_b, and τ_c, and they are thermally connected to the nearest ones, with some amount of thermal resistances — R_{a-b} and R_{b-c}. The thermal resistances from the segments of heatsink to the cooling air are R_{a-air}, R_{b-air}, and R_{c-air}. The cooling air temperatures for the parts of the common heatsink can be varying due to the heating up of the cooling air flowing along the ribs of the heatsink for configuration, as noted from Fig. 1b. The increase of the cooling air temperature depends on the power that is transferred from the particular part of the heatsink to the flowing air, and for the sake of simplicity, it is presented as a coefficient k_τ, which depends on the airflow speed. The temperature of the cooling air for the second and third power modules can be evaluated as follows:

$$\left.\begin{aligned} \tau_{air\,b} &= \tau_{air\,a} + R_{a-air}\left(\tau_a - \tau_{a\,air}\right)k_\tau; \\ \tau_{air\,c} &= \tau_{air\,b} + R_{b-air}\left(\tau_b - \tau_{b\,air}\right)k_\tau, \end{aligned}\right\} \quad (8)$$

where $\tau_{air\,a}$, $\tau_{air\,b}$, and $\tau_{air\,c}$ represent the cooling air temperatures of the first, second, and third parts of the heatsink for IGBT modules of phases *a*, *b*, and *c* respectively.

V. MODELING RESULTS

The parameters used for the model are presented in Table I. The inverter was connected to the induction motor, which operated at 300 V and 45 Hz under a rated load, with 27.2 A (RMS) in each phase. The ambient temperature was 30°C. The simulation time was fixed at 12000 seconds. This duration was adequate for reaching the steady temperature during four consecutive experiments. Each experiment lasted 3000 seconds and implemented various PWM strategies, which are as follows:

- A positive clamped DPWM;
- A DPWM with the minimization of total switching losses;
- A DPWM with the minimization of switching losses in the hottest leg of the inverter (phase *c*); and
- A DPWM with the simultaneous minimization of losses and decrease in temperature of the hottest leg of the inverter.

The first experiment was conducted applying a standard DPWM with the clamping to the positive bus bar of the DC link. The maximum temperature of the IGBT module of phase *c* reached the temperature of 99.65°C at 3000 seconds (see. Fig. 5). The duty cycle references are displayed in Fig. 6. There was no clamping change in that PWM strategy.

The operation according to the cost function (5) results in a lower average temperature of all the modules (see Fig. 5). The highest temperature of phase *c* reached 95.22°C at 6000 seconds. The PWM strategy changed the clamping to positive or negative bus bars according to the value of the flowing current in each phase (see Fig. 7).

In case of the operation applying the cost function (6), the switching losses in phase *c* were reduced, but the average losses remained the same as they were in the first experiment. Therefore, the maximum temperature (see Fig. 5 at 9000 seconds) is approximately 96.69°C, which is higher than that for the previous PWM strategy. The clamping was changed for minimizing the switching losses in phase *c*, as it is reflected in Fig. 8. This cost function is inefficient, because by decreasing the switching losses in a single phase, the other phases suffer extra unnecessary losses.

The lowest temperature was achieved by the last (7) cost function. The hottest module reached a temperature of 94.22°C (see end of simulation in Fig. 5). This is a better result by 1.0°C compared to the simple switching losses minimization technique. The PWM duty cycles are presented in Fig. 9. The duration of the clamped state for each phase is different, which is based on the permitted amount of switching losses in that particular phase. The complete set of data is provided in Table I.

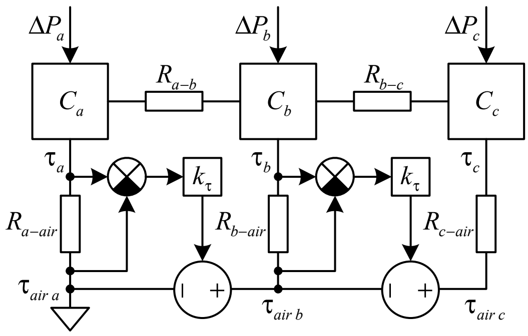

Fig. 4. Thermal model of the heatsink.

TABLE I. PARAMETERS OF THERMAL MODEL

Parameter	Value, Units
$C_a = C_b = C_c, \frac{\text{J}}{\text{kg}\times\text{K}}$	296
$R_{a-b} = R_{b-c}, \frac{\text{K}}{\text{W}}$	2
$R_{a-air} = R_{b-air} = R_{c-air}, \frac{\text{K}}{\text{W}}$	1.34
$k_\tau, \frac{\text{K}}{\text{W}}$	0.154
t_{sw}, μs	1
f_{PWM}, kHz	16
ΔV_{sw}, V	2
V_{DC}, V	540

TABLE II. MODELING RESULTS

Cost function	Results	
	Total losses, W	***Maximum temperature, °C***
PCDPWM	213.4	99.65
Switching losses minimization	199.9	95.22
Minimization of losses in phase *c*	213.5	96.69
Switching losses minimization with minimization of phase *c* temperature	202.5	94.22

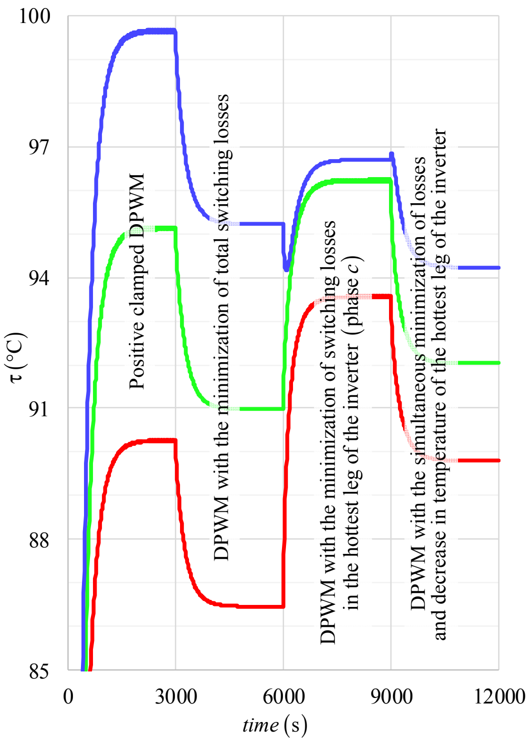

Fig. 5. Temperature of the IGBT modules for various cost functions (red — phase *a*; green — phase *b*; blue — phase *c*).

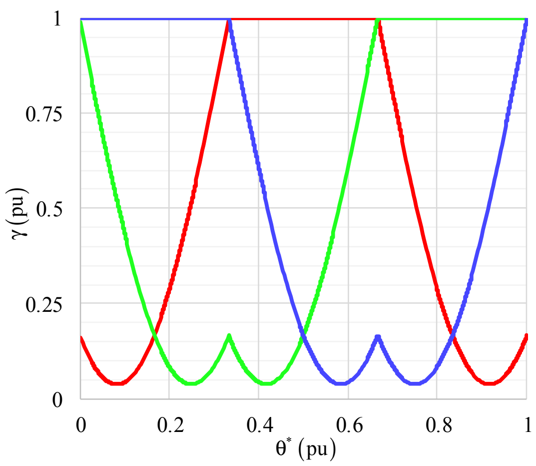

Fig. 6. DPWM duty cycles for positive bus bar clamping (red — phase *a*; green — phase *b*; blue — phase *c*).

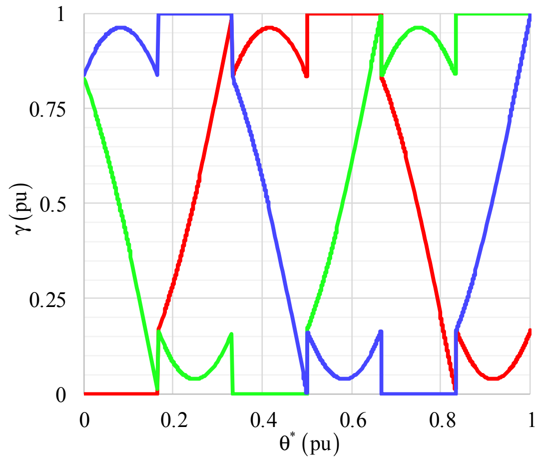

Fig. 7. Duty cycles for the strategy with the minimization of the total switching losses (red — phase *a*; green — phase *b*; blue — phase *c*).

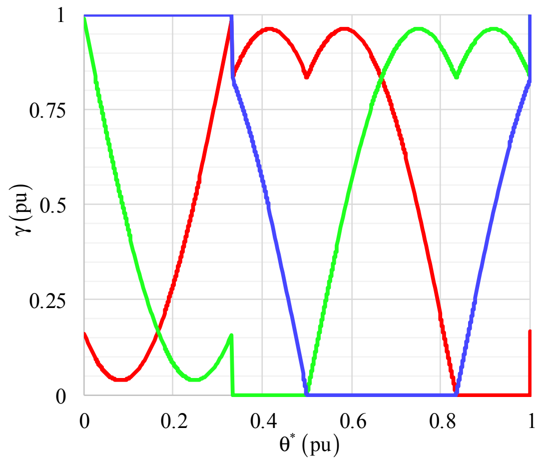

Fig. 8. Duty cycles for the strategy with the minimization of the switching losses in phase *c* (red — phase *a*; green — phase *b*; blue — phase *c*).

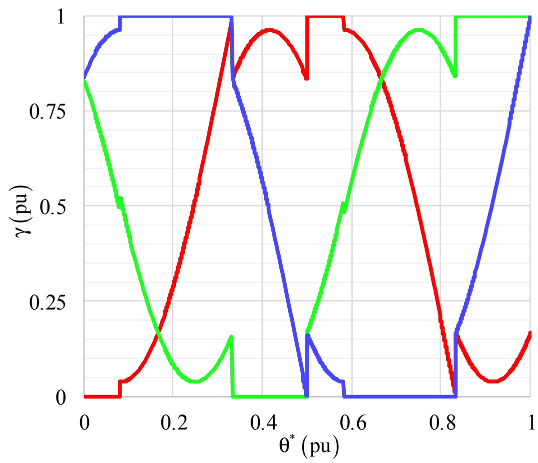

Fig. 9. Duty cycles for the proposed strategy with the simultaneous minimization of the total switching losses and temperature of the hottest leg of the inverter (red — phase *a*; green — phase *b*; blue — phase *c*).

VI. CONCLUSIONS

The increase in the output power of power converters in addition to active thermal control by means of special algorithms comprises the topical issue of power electronics. In this case study, the suggested method helps to enhance the conventional DPWM strategy, minimizes switching losses, and redistributes the losses to the coldest IGBT module.

The proposed method adopts a predictive control technique with a cost function that contains the total losses of the inverter and the losses in the hottest module of the inverter. The minimization of losses in this phase is implemented only when the negative impact on the total losses is not high. This helps to reduce the maximum temperature of the IGBT modules in the power converter by 1.53% (for the particular configuration of the heatsink) in comparison with the conventional switching losses minimization strategy, while the total losses are increased by 1.3% compared to the conventional DPWM strategy, with the minimization of switching losses.

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