Thermal Stabilization of Power Devices for Compressor Drive with Start/Stop Operation Mode

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***Abstract* — This paper deals with the thermal stabilization of the power devices which was implemented in the compressor drive of the subway trains. This drive operates in start/stop mode, thus the thermocycling problems in the IGBT modules can occur. The algorithm of thermal stabilization is given and tests were conducted with the real power converter. The thermal images and temperature curves show the efficiency of the thermal stabilization algorithm in comparison to an ordinary solution.**

Keywords* — *Thermal management of electronics; Temperature control; Thermal stability; Pulse width modulation inverters; Variable speed drives.

I. Introduction

For many years the pneumatic system of the subway trains was filled by the compressors with the DC motor drives [1, 2]. The pneumatic system is used for the train braking and door opening. Approximately 8 years ago Knorr-Bremse Company started to supply modern compressors with induction motors to the Moscow subway. The major advantages of AC induction drives are much longer time between maintains of the drive and significantly greater reliability in comparison with the DC machine drive due to the absence of brushed contacts. Most of the problems with reliability happened due to increase of the supply voltage level. The DC rail voltage should not exceed the range from 550 to 950 V according to the basic regulations for subway power supply in Russia [3]. But with the growth of the energy consumption during the last 10 years due to intensification of the traffic, the idle voltage of the DC rail was increased to 1100 V. This helps to keep it not less than 550 V under raised load. Since that time the frequency of the malfunctions in the DC motor drives of the car compressor has increased noticeably.

The minimal operation temperature for the equipment in subway is –20°C. The equipment should be as much reliable as possible. Thus, the power converter was designed with Mitsubishi intelligent power modules (IPM), which performs excellent reliability in various power-electronic converters designed by R&D group of power converters of Electric Drives Department of Moscow Power Engineering Institute. The power converter was designed and it contains step-down DCDC, which provides stabilized voltage to the inverter, 3-phase voltage source inverter and dV/dt-filter. The only problem that can significantly reduce the reliability and life time of the power converter was start/stop operation mode, which results in thermocycling of the IGBT devices. The drive works for approximately 5 minutes and fills the pneumatic system with compressed air. After that the drive stops until the pressure in the system reduces while the train is braking or opens and closes the doors. Thus, the chips of the IGBT suffer from sequential heating, cooling and heating again. A method to avoid thermocycling of the power-electronic devices is considered in this paper.

II. Problem of Thermocycling

The problem of thermocycling is well known in drives with start/stop operation mode or in drives which operate at extremely low speeds. During the operation cycle or the fundamental frequency cycle the crystal of the IGBT heats and cools for several degrees or tens of degrees, while the base plate temperature remains approximately constant due to bigger thermal capacity and respectively higher thermal time constant. The change of the crystal temperature results in the change of its size though the size of the base plate stays unchanged. This leads to degradation of the solder layer and mechanical destruction and stratification of the solder layer. At last the malfunction of the power-electronic device occurs.

To overcome this problem two different methods can be implemented. First is to use special IGBT modules, which are designed for traction applications [4, 5]. This may be Semikron spring contact IGBT modules, but these modules are not so reliable in case of short circuit currents in comparison to

Mitsubishi IPMs. Another solution is to use special heating algorithm in off state to stabilize the crystal temperature regardless of the operation mode.

III. Compressor Power Converter

The structure of the power converter is presented in Fig. 1. It contains step-down DCDC with LC-filter, inverter and dV/dt-filter. In normal operation mode the DCDC converter produces 540 V for the inverter supply. Inverter forms the motor voltage using V/f-constant control strategy with space-vector PWM and current limiting function in case of start up with high backpressure in the compressor. The drive is controlled with the only signal “on/off” from the pressure sensor in the pneumatic system. The motor rated power is 7.5 kW and the rated current is 15 A. The rated current in the DCDC filter inductance is approximately 15 A. So, the rated currents in the phase and in the DCDC converter are the same.

To keep the losses in IGBT on the same level as in operation mode, the following algorithm was proposed. During the stopped state the inverter legs should be shorted and the DCDC should stabilize the rated current, which now will flow through the inverter bypassing motor windings.

The algorithm takes into account the following problems. An additional state to discharge the capacitor of the LC-filter is needed. It is necessary to discharge it before shorting the inverter legs to avoid high discharge currents. The DC voltage can be applied to the motor windings from the inverter to dissipate the energy stored in the capacitance. The discharge process and its duration should be controlled by the DC link voltage sensor. After that the top and bottom switches can be turned on safely (see Fig. 2a).

Another problem is that it is not possible to switch all transistors on during the heating process, because it is not guaranteed that the current will split equally in all three phases. Also the commutation losses will be reduced too. Thus, the phase change algorithm should be implemented. During heating mode the inverter will be fed from the DCDC converter with LC-filter with the current loop, and will have the properties of the current source. That is why at any time at least one leg of the inverter should be switched on and during their change their control should be overlapped like shown in Fig. 2b.

The step-down DCDC converter operates as a current source. The output voltage is zero, thus the duty cycle for the high-side IGBT is very small. The PI controller was used and the minimal duty cycle was limited in order to prevent the transistor to operate with overlap of the switching on and off transients. The structure of the control system of the DCDC converter is shown in Fig. 2c.

IV. Experimental Setup

The power converter is fed from the high-voltage DC voltage source. The supply voltage can be changed by turning the handle of autotransformer. For the sake of simplicity, the induction motor was replaced with the 3-phase RL-load of 7 kW of active power. The phase current reaches 10.5 A. The current through the DCDC switch was at the rated value 14 A.

The layout of the power devices and temperature sensor is shown in Fig. 3. The thermal sensor is a LM135Z chip [6], which is directly calibrated in °K. Its signal is used by control system for thermal protection. To visualize the temperature map a thermal camera Testo 880 was used.

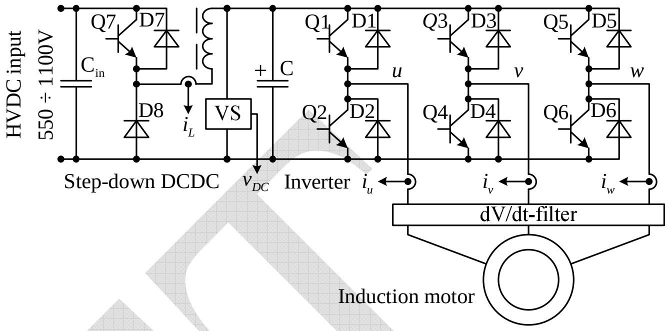

Fig. 1. Power converter of the compressor induction motor drive.

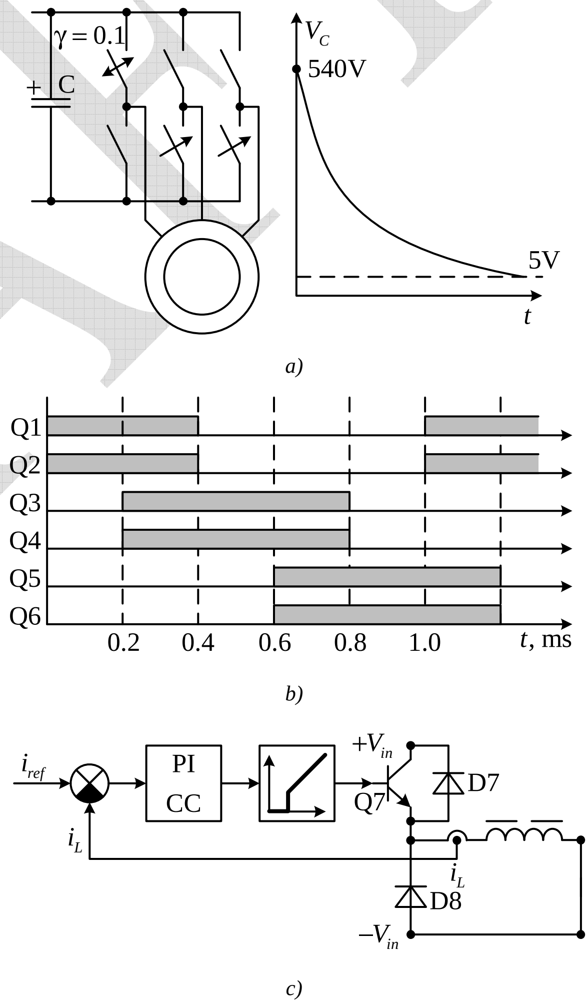

Fig. 2. Diagrams for the control system in the heating mode (a — discharge process; b — inverter commutation sequence; c — DCDC control system structure for heating operation mode).

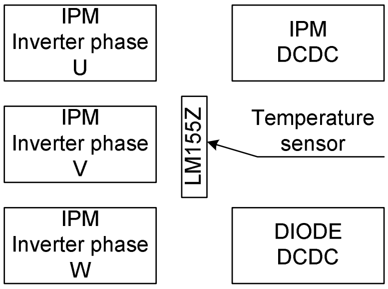

Fig. 3. Layout of the power-electronic devices in the power converter.

The experiments were carried out using the following four steps sequence:

- The power converter was switched on into operational mode. The RL-load was fed for 31 minutes. This was needed to heat up the power converter to its steady temperature.
- The converter was stopped for 5 minutes by a higher level control system. Heating mode is enabled at this time.
- The power converter was switched on again for 5 minutes.
- The power converter was switched off. Heating mode is disabled.

At the end of each stage the thermal image of the power-electronic devices was shot with the thermal camera.

V. Experimental Results

The experimental curve of the difference between radiator and ambient temperatures is presented in Fig. 4. The air cooled heatsink of the converter is a massive aluminum plate with the vertical cooling fins. It is sufficient to operate at ambient temperature up to 60° C even if the train is stopped during taxi when leaving or arriving the depot for a long time under the summer sun. Its dimensions are mainly defined by the size of the standard case for the undercar equipment. Thus, the difference in this experiment is not exceeding 10° C. The transient shows that during the heating operation mode the temperature stopped rising, because the losses were decreased. Actually the decrease of the losses happens due to several factors:

Switching losses in step-down DCDC became smaller, because the switching frequency decreased. This happens because the control system limits the minimal duty cycle of the step-down switch. Thus, some of the PWM cycles were totally skipped. The inductance current is shown in Fig. 5, the commutation frequency varies and it is much smaller than 10 kHz.

A small growth of the temperature of the inverter switches during the heating mode (Fig. 6b in comparison with Fig. 6a and Fig. 6c) happens due to the change of the switching losses. The switching is performed using sequence from Fig. 2b. The state machine for this sequence operates in inverter PWM timer interrupt, thus the commutation frequency is six times smaller.

But on the other hand, in normal operation mode the value of the phase current was smaller than it should be with the induction machine in the load.

Thermal images were shot at the end of each operation mode during 30th, 35th, 40th and 45th minutes and they are shown in Fig. 6.

The thermal stabilization algorithm works well, though it can be adjusted to increase losses by several percent. But the crystals of the power devices loose less temperature than if they are turned totally off. It can be seen from the curve from Fig. 4 that if they are turned off the temperature decreases with a high derivative. Crystal itself suffers from much more deviation of the temperature. The losses in the power devices of a single inverter phase can be evaluated by the following estimation [7, 8]. The power module parameters and operation conditions:

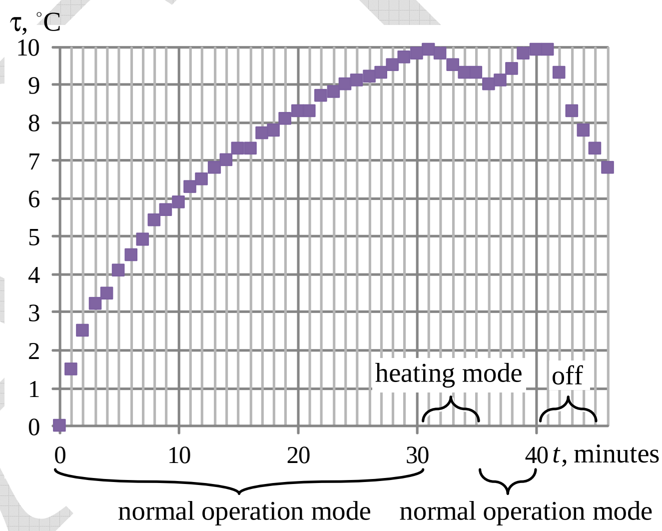

Fig. 4. Difference between radiator and ambient temperatures in various operation modes.

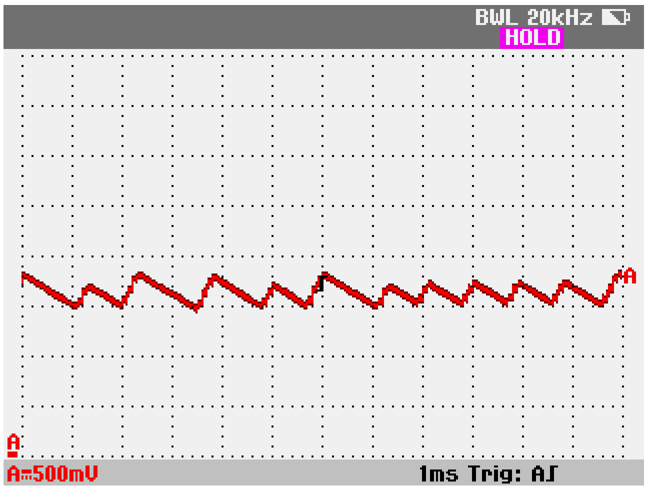

Fig. 5. DCDC inductance current in the heating mode (4.27 A per division, 1 ms per division).

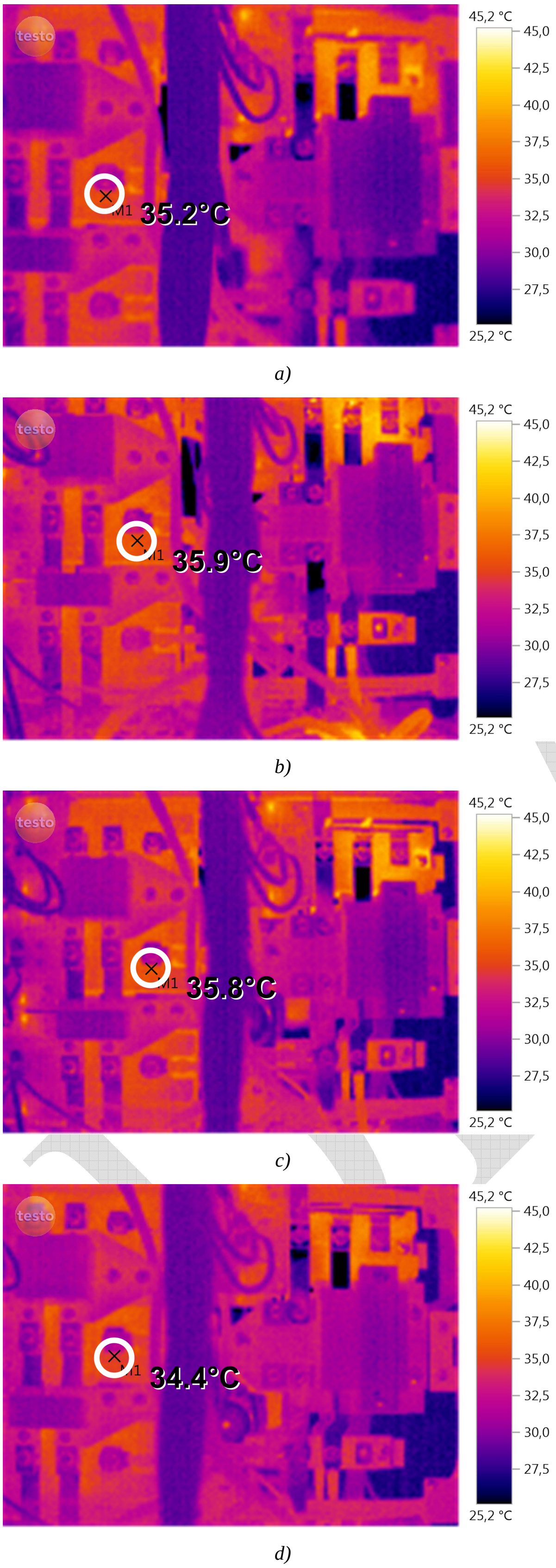

Fig. 6. Thermal images of the power-electronic devices of the converter: a) t=30 min; b) t=35 min; c) t=40 min; d) t=45 min.

$$\begin{aligned}
&R_{th(j-c)Q} = 0.27\ °\text{C/W};\\
&R_{th(j-c)D} = 0.51\ °\text{C/W};\\
&R_{th(c-h)} = 0.06\ °\text{C/W};\\
&\Delta V_{ce} = 2\ \text{V};\\
&\Delta V_{ec} = 1.6\ \text{V};\\
&t_{C(on)} = 0.4\ \mu\text{s};\\
&t_{C(off)} = 0.6\ \mu\text{s};\\
&t_{rr} = 0.2\ \mu\text{s};\\
&V_{DC} = 540\ \text{V};\\
&I_{peak} = 21\ \text{A};\\
&f_{PWM} = 5\ \text{kHz};\\
&\cos(\varphi) = 0.71;\\
&D = 0.95.
\end{aligned} \tag{1}$$

where $R_{th(j-c)Q}$ — junction to case thermal resistance of the IGBT, $R_{th(j-c)D}$ — junction to case thermal resistance of the freewheeling diode, $R_{th(c-h)}$ — case to heatsink thermal resistance (including resistances case to fin and fin to heatsink via thermal paste), ΔV_{ce} — collector-emitter voltage under rated current, ΔV_{ec} — emitter-collector voltage under rated current, $t_{C(on)}$ — turn on switching time, $t_{C(off)}$ — turn off switching time, V_{DC} — switching voltage, I_{peak} — peak current value, f_{PWM} — PWM frequency, $\cos(\varphi)$ — power factor of the load, D — modulation rate.

The conducting losses in each IGBT are:

$$\Delta P_{cl\ IGBT} = I_{peak}\Delta V_{ce}\left(\frac{1}{8}+\frac{D}{3\pi}\cos(\varphi)\right) = 8.3\ \text{W}, \tag{2}$$

and in the freewheeling diode:

$$\Delta P_{cl\ FWDi} = I_{peak}\Delta V_{ce}\left(\frac{1}{8}-\frac{D}{3\pi}\cos(\varphi)\right) = 1.8\ \text{W}. \tag{3}$$

Switching losses in the IGBT:

$$\Delta P_{sl\ IGBT} = \frac{1}{\pi\sqrt{2}}\frac{I_{peak}V_{DC}f_{PWM}\left(t_{C(on)}+t_{C(off)}\right)}{2} = 6.5\ \text{W}. \tag{4}$$

The freewheeling diode recovery losses:

$$\Delta P_{rl\ FWDi} = \frac{1}{8}I_{peak}V_{DC}t_{rr}f_{PWM} = 1.4\ \text{W}. \tag{5}$$

Total losses:

$$\left.\begin{aligned}
\Delta P_{IGBT} &= \Delta P_{cl\ IBGT} + \Delta P_{sl\ IGBT} = 14.8\ \text{W};\\
\Delta P_{FWDi} &= \Delta P_{cl\ FWDi} + \Delta P_{sl\ FWDi} = 3.2\ \text{W}.
\end{aligned}\right\} \tag{6}$$

With the respect to the thermal resistance the temperature difference between crystals and case reaches:

$$\tau_{IGBT-case} = \Delta P_{IGBT} R_{th(j-c)Q} = 4\ °C;$$
$$\tau_{FWDi-case} = \Delta P_{FWDi} R_{th(j-c)D} = 1.6\ °C, \quad (7)$$

for the IGBT and freewheeling diode. The difference between case and heatsink temperatures:

$$\tau_{case-heatsink} = 2\left(\Delta P_{IGBT} + \Delta P_{FWDi}\right) R_{th(c-h)} = 2.2\ °C. \quad (8)$$

With the respect to deviation of the heatsink temperature during the off state and summarizing temperature differences the deviation of the crystals temperature is approximately 10 °C. This difference may be significantly bigger if the size of the heatsink were smaller.

VI. Conclusions

This paper describes a thermal stabilization system for the power devices in three phase inverters used for compressor drives in railway. The designed control system with thermal stabilization is currently implemented in more than 500 power converters which are in operation since 2008 on the trains of the Moscow subway. The conducted experiments showed that in this particular case there is no need in thermal stabilization due to very small deviation of the crystal temperature. The drive may operate for more than 25 years with deviation of crystal temperature of 10 °C per cycle. But this approach to the thermal stabilization may be used in other power converters with different parameters of the heatsink and operation cycle.

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