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POWER SEMICONDUCTOR DEVICES TEMPERATURE MONITORING SYSTEM

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Abstract: The temperature measurement system, for parallel monitoring of temperatures of the power semiconductors devices in power converters is presented in the paper. The system was implemented in a power electronics converter for rapid recognition of the power losses level generated by individual power components. This information is important when evaluating system efficiency, current flow symmetry, and allowable output power in a given inverter configuration. The proposed system utilizes parallel multi-channel temperature measurements with digital temperature sensors operating on separate serial 1-Wire buses. FPGA device collects data from the temperature sensors and sends them through wireless interface to a PC terminal. The structure of the system as well as particular devices are described in the paper. Selected results of experimental investigations which show proper operation of the system are presented as well.

Keywords: Digital temperature sensor, temperature measurement, 1-Wire bus, semiconductor power devices.

1. INTRODUCTION

Power semiconductor devices are crucial components in power electronic converters. Their condition has high influence on the converter performance and can cause converter malfunction in a bad case. One of the important parameters, which give information about their condition and which can be easily observed on-line, during converter operation, is temperature of the power semiconductor devices. The power semiconductor devices frequently operate in thermally stressful conditions. The increasing junction temperature of a power semiconductor device is directly related with increasing power losses and can lead to semiconductor failures. Rising temperature also has influence on decreasing the region of safe operating area of the semiconductor switch. Monitoring of the temperature is therefore important for optimal operation and for reliability reasons. If the switch temperature (junction or case) is known during the operation of a converter, real-time control systems could be developed to improve the system reliability.

The most popular methods used to estimate the temperature of power semiconductor devices using thermo-sensitive electrical parameters are discussed in [1]. The methods are the collector-emitter voltage under low current levels, the threshold voltage, the voltage under high current levels, the gate-emitter voltage, the saturation current, and the switching times. All these methods have different characteristics in terms of sensitivity, linearity, accuracy, calibration needs, and possibility of characterizing the thermal impedance or the temperature during the operation of the converter. The collector-emitter voltage measured during conduction of low currents is the most suitable method of the chip temperature estimating [1].

A analysis of a suitable and temperature sensitive electrical parameters (TSEP) for SiC power MOSFET condition monitoring is presented in [2]. The drain current switching rate and its temperature dependency have been measured and analyzed for different SiC MOSFETs showing that at lower switching speeds, i.e. using higher gate resistances, it can be a suitable TSEP for condition monitoring [2]. The impact of temperature on the switching speed indicates that the current switching rate is a effective TSEP for higher current rated devices but there is necessary sacrifice in switching speed for enabling the ability of estimating the junction temperature. In particular case it may be a disadvantage.

There are attempts to calculate the IGBT junction temperature using special device model in Simulink [3], where a RC thermal network with temperature dependent thermal conductivities and heat capacitances is used. Authors in [4] propose use of the IR camera for junction temperature evaluations in a power IGBTs. It seems interesting and can be useful in practice but it is a relatively expensive solution and needs special software to recognize separate temperatures of each monitored switch. Additionally, an automatic control may be complicated.

Temperature measurements of power semiconductor devices is important in many applications. In the presented solution, the multipoint temperature monitoring system is implemented in the laboratory rig allowing for rapid development of switching power converters. The system allows to recognize asymmetries in the tested converter current flows and gives possibility to test the converter maximal output power. If any of the monitored switches gets too warm, automatic turn-off of the converter may occur or sound signal can be generated. The system is based on the DS18B20 digital temperature sensors which communicate through separate 1-Wire buses for faster temperature scanning of all sensors.

2. TEMPERATURE MONITORING SYSTEM

2.1. Digital temperature sensors

A digital temperature sensors are available in many variations, varying in accuracy, temperature range, casing, and serial interface used. When measuring the temperature of semiconductor power devices, a measuring range up to 120 °C is required, which is met by the DS18B20 digital temperature sensors from Maxim-Dallas. It communicates via a 1-wire bus which is convenient and simplifies the connection net. These sensors are frequently used in many reported industrial and other systems [5-7]. The DS18B20 digital thermometer provides 12-bit resolution of the temperature measurements and has an internal alarm function with nonvolatile user-programmable upper and lower trigger points [8]. The measurements range is from -55°C to +125°C (±0.5°C minimum accuracy from -10°C to +85°C and ±2°C from +85°C to +125°C [8]) which is enough for the presented purpose. The DS18B20 generates an 8-bit CRC (Cyclic Redundancy Check) value and provides this value to the bus master to allow validate the transfer of data bytes. The DS18B20 sensors communicate over a 1-Wire bus that requires only a single data line for communication with a microcontroller. Just a single connection line delivers not just serial data but also the power supply in particular time moments (parasite power mode). It is possible because of an internal capacitor which is charged from the data line and delivers the energy to the sensor during the time of a single bit operation. After each bit transferred through the 1-Wire bus, the microcontroller must set logical "1" for the specified time period to allow charging of the internal capacitor. Parasite power is useful for applications that require remote temperature sensing or that are space constrained. In parasite power mode, the 1-Wire bus and the internal capacitor can provide sufficient current to the DS18B20 for most operations as long as the specified timing and voltage requirements are met [8]. However in the presented project, ”parasite power” capability is not used. During laboratory tests it was revealed that normal supply with a separate power supply wire gives much more robust solution in electromagnetic interference environment. Such EMI environment occurs in the described system, because the sensors are located very close to the high frequency switching power converter.

The 1-Wire bus frame consists of the special time slots representing the logical low and high levels. Any communication starts from the RESET pulse, after which responding device sends the PRESENCE pulse. It is depicted in Fig. 1. Figs 1-3 have been recorded in the presented system. All data and commands are transmitted least significant bit first over the 1-Wire bus. It is also visible in Fig. 1 presenting short frame carrying two commands: 0x0CC – “Skip ROM” and 0x044 – “Convert T”. The whole set of available commands is described in [8].

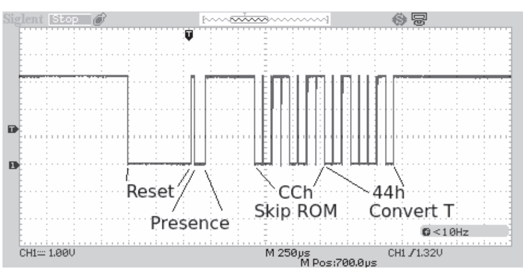

Fig. 1. The 1-Wire command frame, 0x0CC – “Skip ROM”, 0x044 – “Convert T”

The transmitted sequence 0x0CC, 0x044 (Fig. 1) starts the temperature conversion process in DS18B20 sensor connected to the 1-Wire bus, if there is just single sensor connected to the bus. If there are more sensors connected to the bus, each sensor must be addressed before it can start the conversion, it is presented in Fig. 3 and the conducted operations with necessary execution time are presented in Table 1. The addressing process is extended in time, because each sensor has a unique 64 bit serial number which should be send to every sensor that should start the conversion. In such case the single temperature conversion consists of the following steps: firstly “Match ROM” command should be sent to the sensor, after that the 64 bit serial number, then the sequence starting the temperature conversion, then wait for conversion complete, start again communication with the sensor and read internal registers called “Scratchpad” containing the conversion result. The beginning of the 0x0BE “Read scratchpad” operation is depicted in Fig. 2. The whole process of single sensor measurement takes about 800 ms at the maximal 12 bit resolution and because of that a sequential measurement with all sensors one by one will give results shifted in time. The more sensors are used (in operation on just one 1-Wire bus) the more shifted the results are. In the presented solution this is not the case.

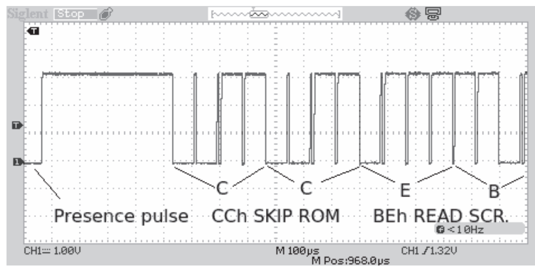

Fig. 2. The 1-Wire command frame, 0x0CC – “Skip ROM”, 0x0BE – “Read Scratchpad”

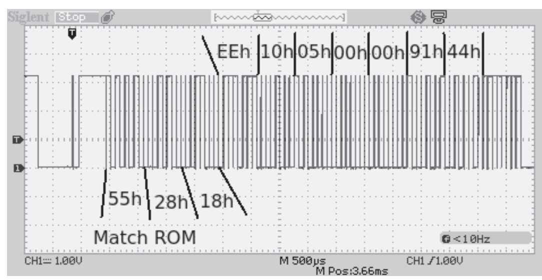

Fig. 3. The 1-Wire full frame, 0x055 – “Match ROM”, 64 bit serial number = 0x09100000510EE1828, 0x044 – “Convert T”

Table 1. 1-Wire operations for starting the temperature conversion process if more than a single sensor is connected

µC mode	Data (LSB first)	Comments	Execution time
Tx (transmit)	Reset	µC issues reset pulse	> 480 µs
Rx (receive)	Presence	Sensor responds with presence pulse	> 480 µs
Tx	0x055	µC issues “Match ROM” command	> 488 µs
Tx	64-bit ROM code	µC sends DS18B20 ROM code	> 3,9 ms
Tx	0x044	Master issues “Convert T” command	> 488 µs

The single conversion process is shorter in time in the case if just a single temperature sensor is connected to the 1-Wire bus. Because of that, in the presented project each temperature sensor is connected to the individual 1-Wire bus and the buses operate in parallel to achieve faster overall system temperature scanning time. It is very important in the presented system because all temperature sensors can be triggered at the very same moment and temperature conversion results are obtained at the same time from all used sensors. It gives better overall control (thanks to information about devices' temperatures) over all monitored semiconductor devices and allows for faster response (max. 1 s) in case of rising temperatures.

2.2. FPGA implementation

The presented project incorporates the digital FPGA (Field-Programmable Gate Array) for implementation of the individual 1-Wire buses for each temperature sensor. Thanks to that, the overall sampling period of all sensors is independent on number of sensors. If the sensors operate on a single bus, each sensor adds 0,8 s to the overall sampling period. As a development board for this purpose the DE0-Nano with Cyclone IV EP4CE22F17C6N FPGA is used. The simplified block diagram of the temperature measurement system is presented in Fig. 4. There are six digital temperature sensors (T_1 – T_6, Fig. 4) connected through individual 1-Wire buses to the DE0-Nano board. The board communicates with PC through Bluetooth wireless interface using HC-05 module. The HC-05 module sends standard UART signals through the wireless Bluetooth interface and allows for control of the incoming data using serial port terminal. From the PC side the implemented interface is visible as a virtual serial COM port.

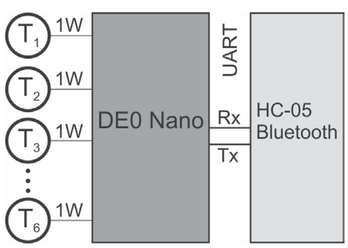

Fig. 4. The simplified block diagram of the temperature measurement system

The algorithm of the FPGA system operation consists of few steps. Firstly all sensors starts process of temperature conversion at the same time (in the moments of the system temperature sampling, about every 800 ms). The sampling period is short enough in the system (it is assumed that the sampling period should not be higher than 1 s). Then (between temperature samples) conversion results are collected by processor implemented in the FPGA and are sent to the PC through the Bluetooth interface. The temperature values from the DS18B20 sensors are set to be 12 bit. The six temperature values are transferred using asynchronous transmission mode as ASCII codes. Besides the temperatures, a time stamp is transferred through the interface to allow distinguish moments of measurements. As a serial port terminal the CuteCom software is used under the Ubuntu Linux system. The presented measurement system allows to observe six temperatures on the terminal, but it also can automatically turn on an alarm sound if the set threshold is exceeded and then can send logical signal to the investigated power converter control circuit which then can decrease the converter output power or turn the power down. The terminal window showing measurements is presented in Fig. 5.

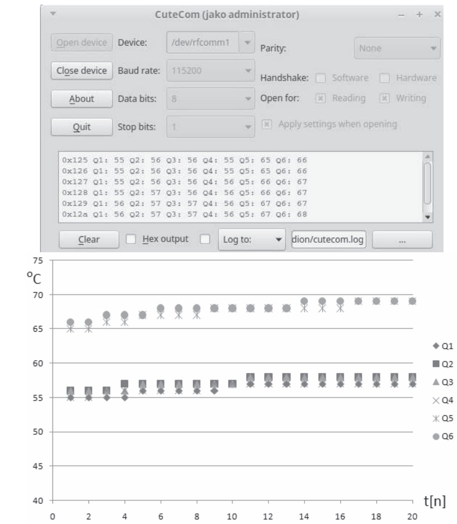

Fig. 5. The terminal window and chart showing measurements

2.3. Laboratory setup

The presented system is used for temperatures monitoring of the resonant DC/DC power converter presented in Fig. 6. It consists of four power MOSFET transistors, two auxiliary serial diodes and diode rectifier to be monitored. Each MOSFET transistor is screwed to individual radiator and on each radiator the temperature sensor is placed. The sensors are clamped to the radiators by small lamellas that are bolted to the radiators nearby the monitored devices.

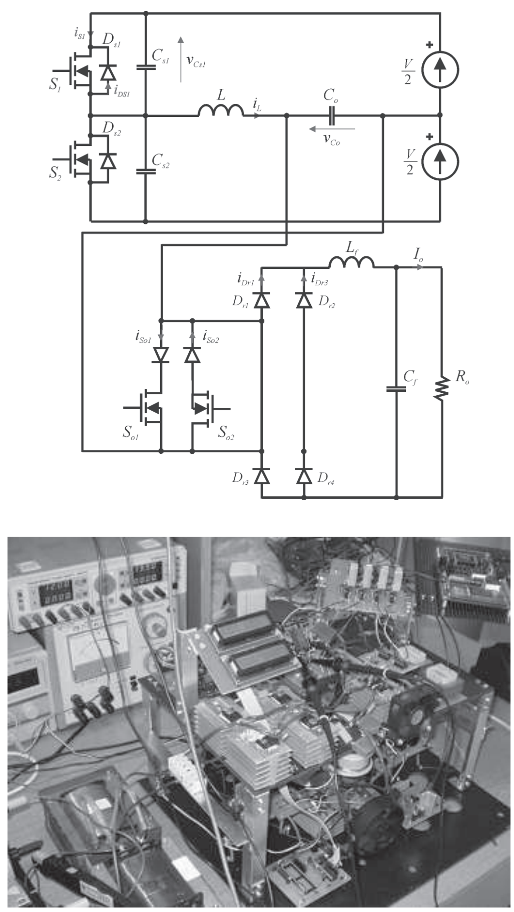

Fig. 6. The resonant DC/DC power converter

Four temperature sensors are used for monitoring temperatures of switches S_1, S_2, S_{o1} and S_{o2} (Fig. 6), and two sensors are used to monitor temperatures of the output rectifier diodes which are mounted on two separate radiators (each radiator has one temperature sensor). The auxiliary diodes connected in series with S_{o1} and S_{o2} transistors are mounted on the same two radiators as the series switches, so they do not require additional temperature sensors. During laboratory test the temperature monitoring system works well and measures temperatures up to 120°C. The higher the output power controlled by the converter is, the more electromagnetic interferences is visible in the transferred data through 1-Wire bus, but after shortening of any possible wire connections and after use of normal power supply mode (instead of the "parasite power" mode) of the sensors, the measuring system is robust and reliable and useful during laboratory investigations. The most adverse test conditions occurred during testing of a switching converter working at the switching frequency 450 kHz and output power up to 3 kW. The presented system worked properly and temperatures were controlled well.

3. SUMMARY

The article presents a multi-channel temperature measurement system useful for power electronics prototype research but it also can be used for monitoring of industrial power electronic converters. Multi-channel temperature measurement in the power electronics prototype allows for rapid recognition of the power losses level generated by individual power components. This information is important when evaluating system efficiency, current flow symmetry, and allowable output power in a given inverter configuration. In the described system, the digital temperature sensors that use the 1-Wire serial communication bus are utilized, requiring only one data line to work.

Exceeding the temperature threshold of any of the monitored element can automatically switch off the system, which prevents overheating and thermal damage. The presented temperature measurement system can detect various types of anomalies occurring in the inverter and control waveforms, as most of them involve excessive heating of the endangered power semiconductor devices.

The presented temperature monitoring system has been successfully used to monitor a resonant DC / DC converter operating at a switching frequency of 450 kHz at an output power of 3 kW.

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SYSTEM MONITOROWANIA TEMPERATURY PÓŁPRZEWODNIKOWYCH PRZYRZĄDÓW MOCY

W artykule przedstawiono system równoległego pomiaru temperatury półprzewodnikowych przyrządów mocy w przekształtnikach energoelektronicznych. Prezentowany system jest użyteczny podczas badania laboratoryjnego nowych topologii przekształtników energoelektronicznych. System ten umożliwia szybkie wykrycie nadmiernego nagrzewania jednego z monitorowanych przyrządów półprzewodnikowych i jednocześnie może automatycznie włączyć sygnał dźwiękowy oraz przesłać informację do sterownika przekształtnika. Otrzymywana informacja związana z poziomem strat mocy wydzielanej w poszczególnych monitorowanych elementach jest cenna przy badaniu sprawności układu, symetrii rozpływu prądów oraz przy badaniu dopuszczalnej mocy wyjściowej przekształtnika w danej konfiguracji. Cyfrowe czujniki temperatury wyposażone w interfejs szeregowy 1-Wire komunikują się z procesorem nadzorującym w sposób sekwencyjny. Przy większej liczbie czujników czas skanowania wszystkich wartości jest nadmiernie wydłużony. W prezentowanym rozwiązaniu zastosowano oddzielne magistrale szeregowe dla każdego czujnika. W związku z tym czas pełnego odczytu nie zależy od liczby czujników. Aby to było możliwe, wykorzystano układ FPGA z zaimplementowanymi interfejsami 1-Wire. Prezentowany system ułatwia wykrywanie wielu nieprawidłowości występujących w badanym przekształtniku i w przebiegach sterujących, gdyż większość z nich wiąże się z nadmiernym nagrzewaniem zagrożonego przyrządu mocy.

Słowa kluczowe: cyfrowe czujniki temperatury, pomiary temperatury, magistrala 1-Wire, półprzewodnikowe przyrządy mocy.