Implementation of diagnostics functions in the IGBT drivers, part 1. – Diagnostics

J. Knobloch, B. Klima, Z. Nouman, M. Pochyla

Abstract -- **The paper deals with possibilities of power IGBT transistor diagnostics directly in driver of voltage source inverters. It is necessary to implement the diagnostics circuits as close as possible to the power IGBT transistor due to high demands on drive reliability and failure predictability in many applications.**

Possibilities of diagnostics quantities measurements are discussed in the paper. The measurements of transistor chip temperature, voltage overshoot size, off-state voltage, on-state saturation voltage, measurement of inverter output current, gate charge measurement and driver secondary side supply voltages are discussed. Possibilities of IGBT diagnosis and IGBT technical state based on measured data are also discussed.

The paper also proposes some hardware solutions for obtaining mentioned information and methods of using measured data in IGBT downgrading progress monitoring, failure prediction and drive maintenance planning.

Index Terms—**diagnostics, IGBT driver; power transistor**

I. Introduction

The present trends are oriented to spread controlled electrical drives, which means that the reliable power electronic inverter is needed. The Controlled electric drives are more and more used in applications with high reliability requirements in electric traction, automotive and aerospace applications.

The power voltage source inverters- usually use IGBTs or MOSFETs. In the future it is also possible to expect SiC transistors in these applications.

Online diagnosis is used to increase operational reliability. High effort is put on development of diagnostics methods implemented into inverters with standard design without usage of special hardware. The advantage of this solution is preservation of convenient price. Phase currents and output pole voltage analysis are used for individual transistor failure detection [2][3][11]. Short circuit or open circuit is usually diagnosed. The sensitivity of these methods doesn't allow to monitor continuous state of power transistor.

Fig. 1 shows the standard configuration of common three-phase voltage source inverter. It usually contains line rectifier, DC-bus with electrolytic capacitors and three-phase inverter with six power IGBTs. Each of IGBTs has its own driver, which has to switch on/off the transistor correctly, handle the transistor overcurrent protection by limiting of saturation voltage. The driver also provides error information to the inverter controller in case of some protection circuit is tripped.

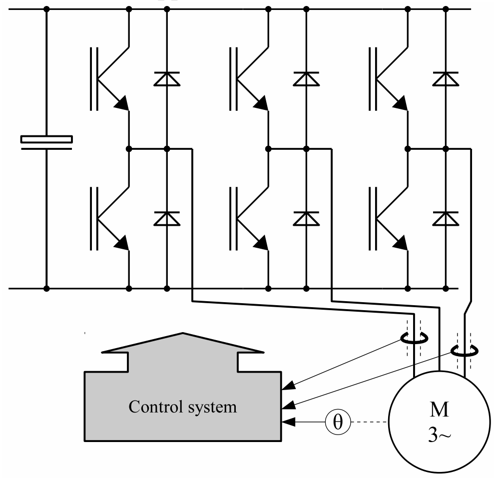

Fig. 1. Sketch of the standard three-phase voltage source inverter

Many of known methods deal with failure detection of individual power device. In this situation there is not possible to monitor downgrading process of IGBT and predict the failure. Often it is too late, when failure occurs. In many cases, it is possible to continue in drive operation if one transistor doesn't switch, however with limits.

If we want to obtain a possibility of transistor failure prediction, it is necessary to watch long-time progress of downgrading parameters and to extrapolate them and predict the time to reach their critical values. From standard feedback sensors (phase currents, DC link voltage) it is very difficult to watch processes which take place in power transistor.

This is the reason for finding new methods for detailed monitoring of power transistor quantities directly in the driver. The secondary side of the driver is the place, which is

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closest to the power transistor. For these purpose it is necessary to develop a special driver, where measurement of these quantities will be possible.

If we are able to watch and evaluate transistor parameters, it would be possible to predict the failure and also plan a drive maintenance.

The total failure of a transistor can be caused by impact of some other event (for example short circuit on the inverter output causes high peak thermal stress). Inverter output short circuit is protected by using anti-saturation circuit. This protection circuit usually switches-off the transistor and when the short circuit is eliminated, the transistor can continue in normal operation. However the parameters of this transistor can partially change and the partial damage may occur. When similar short circuit event comes in future, total destruction of the transistor may occur.

The continuous change of the transistor parameters can be also caused by impact of long-period thermal and mechanical stresses during normal operation. Switching process of power IGBT is described in [7].

Usual measured quantities in standard drives are output currents, DC-bus voltage, drive position and speed. The diagnostic quantities are often compared with preset threshold value and its overpassing is detected. For example voltages of power supplies for control electronics, driver secondary side supply voltages, transistor saturation voltage are measured.

The DC bus voltage, mentioned above, has many ripples. These ripples affect inverter output voltages. Therefore the DC-bus voltage non-stability is usually compensated by inverter controller. However, the DC bus high frequency voltage ripple due to inverter switching can serve for diagnostics of DC-bus capacitor and its capacity losing.

In the reference [2], there are the methods for transistor failure detection based on analysis of measured output currents described. There is an overview of transistor short circuit detection methods, interrupted gate circuit and occasional gate failures detection methods. These methods do not require any additional hardware.

Comprehensive description of present IGBT drivers functions is given in [1]. There are discussed other possibilities of some advanced driver functionality. Some ideas will be introduced in the following text.

The reference [12] deals with minimizing transistor power losses using switching-on and switching-off process intelligent control.

The way of transistor chip measurement is described in [4] a [5]. The possibility of chip temperature direct measurement using infrared sensor is limited. The present fastest IR sensors have time constant approximately 6 µs. [15].

II. Power Transistor Diagnostics in the Driver

The main idea of proposed quantitative power transistor diagnosis is to move a diagnostics circuits close to the inverter power semiconductors. It means to transfer the diagnostics circuits into the transistor driver. In this place it is possible to watch some operation processes and evaluate some parameters of the transistor.

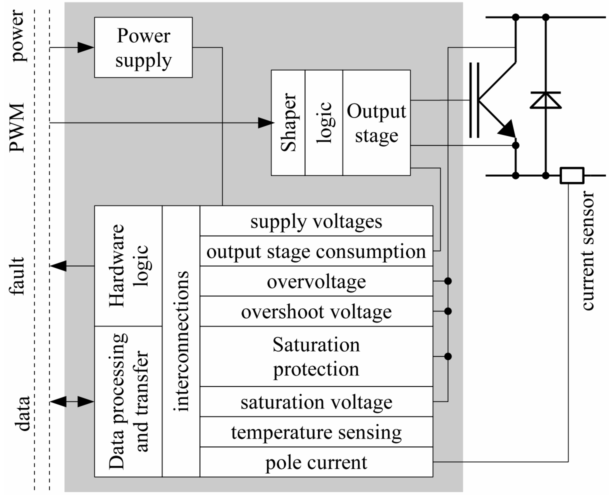

Fig. 2. Sketch of the proposed driver

Regarding to complexity of proposed diagnostics in the driver, the data communication of the IGBT driver and inverter controller is required. The measured data are transferred into inverter controller for their evaluation. The questions of hardware implementation and communication interfaces are described in the second part of this paper. Except of data, transferred from drivers into inverter controller, can be also written into the driver to configure driver and its protections systems. Inverter controller has information from all six drivers and other diagnostics data (DC-bus voltage, cooler temperature etc.)

This concept makes possible to use a low cost current sensors without necessity of galvanic insulation, because the inverter outputs are at the same potential as emitters of upper IGBT transistors. Then it is possible to eliminate galvanic insulated current sensors, or the standard current sensors can be backed up with redundant current measurement in drivers.

III. Circuit Design for Measuring Parameters

In followings paragraphs are discussed advanced methods for intelligent transistor control, its protection and diagnostic

A. *Programmable anti-saturating protection*

Anti-saturation protection functionality in driver is usually used in two basic modes. One-shoot mode or regenerative mode can be used. In the proposed driver it is possible to implement hybrid mode of the anti-saturation protection, i.e. regenerative mode with limited count of attempts of the new switching in following modulation periods. Programmable logic allows implementation of following features of anti-saturation protection:

- The attempts count repeatedly the transistor to switch-on is monitored and saved in memory
- The allowed switching-on attempts count can be preset.
- The allowed switching-on attempts count is automatic, according to transistor current, transistor chip temperature. In case of overcurrent it is necessary to use soft-switching-off of the transistor.

The switching-off softness is settable in dependence on saturation voltage, which depends on flowing current through the transistor.

B. Voltage overshoot measurement

Voltage overshoot arises when transistor is switched-off. It is affected by slope of decreasing of transistor collector current and by parasitic inductance. Its amplitude can be affected also by active clamping.

For voltage overshoot measurement peak detector is used. It allows to determine overshoot peak value avoiding to aliasing errors when transistor voltage is sampled. Configuration of such circuits is shown in fig.3

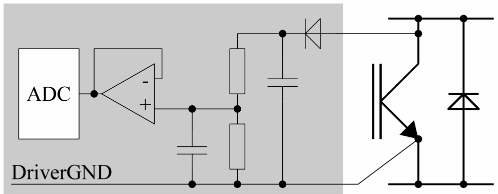

Fig. 3. Overshoot peak detector sketch of the proposed driver

C. Driver supply voltage measurement

The IGBT driver supply has usually positive and negative voltage. In the most drivers only the information about sufficient supply voltage is monitored. In the drivers usually the sum of positive and negative voltage is evaluated. This approach can mask a failure on first of the voltages if that is compensated by the second one. The voltage must be high enough in order to switch the transistor reliably. Low supply voltage leads into incorrect switching on with possibility of de-saturation and the transistor damage.

In our concept the voltage is measured by analog-digital converter (ADC). The positive and negative voltages are measured separately. In addition, the ripple and the mean value are evaluated.

Many drivers are supplied by small pulse transformer. In supply circuits, there are usually electrolytic capacitors, or LC filter. Here, the information about the capacitor condition is present in the voltage ripple.

D. Output stage power consumption measurement

The driver output stage is directly connected to the power transistor gate. Its consumption depends on charge supplied in the gate. Measured data can provide information about the power transistor and output stage condition. Another possible detectible fault is gate circuit resistance rise. It can represent the individual chip gate failure in the module with more parallel chips.

For example, the concept is outlined in Figure 4.

E. Current measurement

According to [2] the current de-saturation detection can be used to measure the current, which is common for overcurrent protection. The use of dv/dt detection between Kelvin's emitter and power emitter seems to be interesting method for overcurrent protection. It exploits a parasitic inductance present in power module.

In our concept we assume usage of the branch current sensor, which can be either a shunt, or any Hall principle based sensor. Both sensors are without voltage insulation because they are at the same potential as the driver.

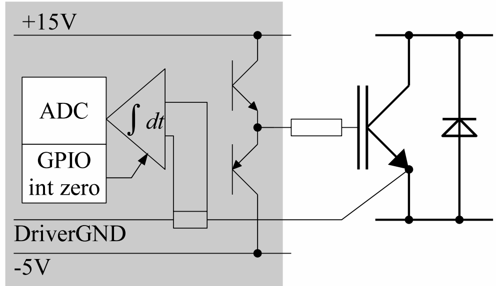

Fig. 4. Peak detector sketch of the proposed driver

F. DC-link voltage measurement

Measurement of this quantity in drivers is difficult, but not impossible. For measurement of the voltage a special sensor is necessary. Alternating component of the voltage together with output current carries information about the electrolytic capacitor condition.

G. Chip temperature measurement

The switching process causes the temperature variations at the power transistor chip. It depends on power dissipation, silicon plate thermal capacity and isolation layer thermal resistance. The temperature variation leads to mechanical stress on the chip due to thermal expansion effect.

A few publications [4] [5] deals with peak chip temperature measurement. Direct measurement is possible by using an infrared temperature sensor. [15] However this have still a long response time due to the speed of switching process. This type of sensor is still faster than a thermistor in the copper of power transistor module.

IV. Failure Prediction Methods

Many already published papers deals with system behavior prediction, which is based on captured data. We will describe a few approaches to predict system behavior. In all cases we need enough measured data.

Common approaches are using the least mean square method. With this method we obtain the approximation formula that can be extrapolated to obtain the data in the future. Usually time is an independent variable. When the power transistor condition is solved, we obtain exponential or polynomial characteristics. This approach can be usable.

Papers [9] a [10] shows for example polynomial, which is compared with a Kalman's algorithm. Here authors predicting a rotor bar break. In that case the polynomial approach is not usable, because it is complex problem. Next paper [8] describes advantages of Kalman filter to predict of system behavior.

Device for vibration based prediction of bearing failure is described in [16]. In that case exponential extrapolation is used. This document explains the averaging of the data and their compress, which makes possible to forget the less important values.

V. Conclusion

Current power transistor drivers are sophisticated, but still simple devices. Of course, exceptions already exists. [13]. This is the reason why current drivers do not offer a complex diagnostic capabilities.

Next development will lead to experimental design and its realization. Most probably the FPGA device to fast process control will be used.

The benefit of this approach is a possibility to measure variables that can't be measured in standard systems. Transistor condition based on measured data trend can be predicted.

For example determination of peak junction temperature is an interesting task for future.

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VII. Biographies

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