Durham University

Literature Review for Condition Monitoring for Power Electronics Reliability (Draft)

By
Dawei Xiang

February 2008

Contents

1. Introduction

The COMPERE project aims to prove the feasibility of condition monitoring of power semiconductor devices in converters and to further understand the device deterioration and fault development mechanisms.

As an initial step of research, a literature survey has been carried out by Durham University concentrating on two problems. The first problem is the failure of power electronic converter systems including failure consequences and corresponding fault handing techniques. The main concerns in this area are how a sustained power device fault influences the system and how the COMPERE technology pursued can benefit the system. The second problem is about the state of arts of condition monitoring techniques for power electronic converter systems that have been investigated. It is hoped that the literature review could provide a base for our research and guide our further study.

2. Failure of Power Electronic Converter Systems

Semiconductor device faults have been previously considered for different types of power electronic converter systems including motor drives, new and renewable energy systems and FACTs (Flexible Alternate Current Transmission Systems), as shown in Table 1.

Table 1. Literature on power electronic failure in different systems

Researched systems	Literature
Drive system	DC drive [13] PWM VSI fed IM drive [3,5,9,12,15,16-18,24,35-37,46] PWM VSI fed SM drive [1] PWM VSI fed SMR drive [2,4] PWM VSI fed PMSM drive [14,34,38,39,49] Cyclo-converter fed AC drive [6,7,10,22,23,41,42,44,45]
New and renewable energy system	Wind power [25,26,60,61]
FACTs	APF [21,47,48] HVDC [27,33] STATCOM [8]

In Table 1, drive system failures are the most researched. These are usually for safety-critical systems, such as in aircraft, marine propulsion, electric vehicle/hybrid electric vehicle (EV/HEV) and rolling mills. For these applications, an accidental shut-down will lead to catastrophes and serious economic losses.

For power tracking and mechanical stress mitigation, power electronic technology is used in many new and renewable energy systems; protection and control methods are studied under grid faults [60-61]. Wind turbine systems are generally required to remain connection with the grid during a network fault for the stability and safety of the whole power system. However as individual units are of a small capacity; a generator shut-down caused by a power electronic device failure is acceptable in many utility applications. Although this perhaps indicates that condition monitoring may not be critical, the difficulty to access for maintenance means that condition monitoring may still be valuable.

FACTs are another important area for application of power electronic technologies. Research begins to address the failure consequences in HVDC, active power filter (APF) and STATCOM. This is important due to the size of the system and impact of a failure.

2.1 Failure Consequences

A power semiconductor fault in a converter causes a series of symptoms in the system, e.g. over-current, over-voltage, harmonics and/or pulsing torque. The fault consequence depends on the fault scenario and post-fault handing measures.

2.1.1 Operation with Sustained Faults

Paper [3] describes a systematic investigation into the various fault modes of a voltage-fed PWM inverter system for an induction motor drive, Figure 1. After identifying all the fault modes, a consequence analysis has been made using mathematic modelling and simulation for the key fault types, namely, input supply single line to ground fault, rectifier diode short circuit, inverter transistor base drive open, and inverter transistor short-circuit conditions. The study has been used to determine stresses in power circuit components and to evaluate satisfactory post-fault steady-state operating regions. The results are useful for better protection system design and easy fault diagnosis, Figure 2. They could be used to improve system reliability by using fault tolerant control.

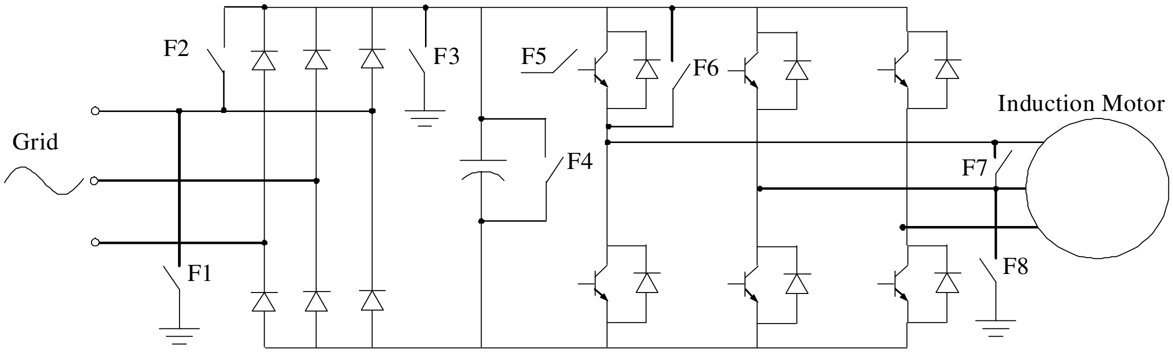


Fig. 1. A voltage-fed PWM inverter system indicating the possible failure modes

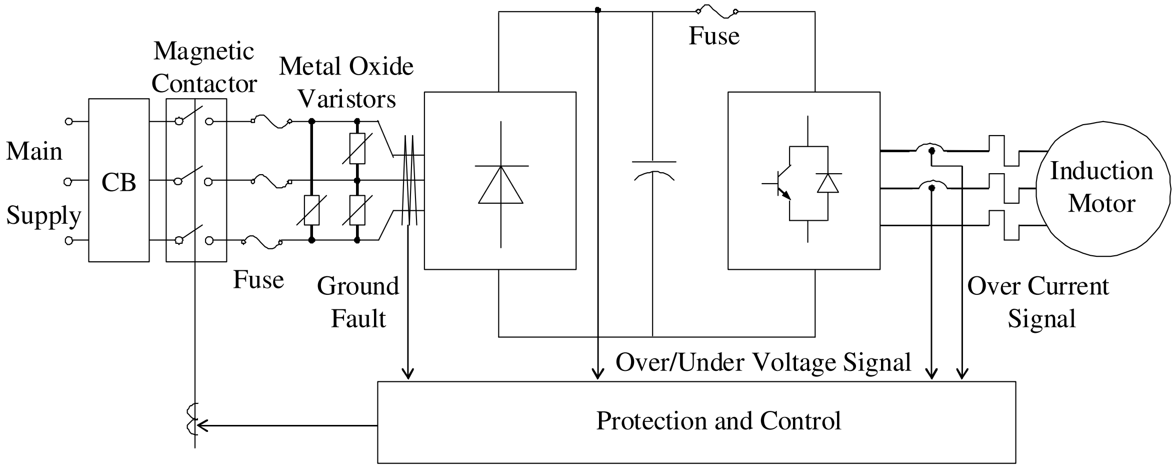


Fig. 2. A typical protection system for a voltage-fed inverter drive.

A voltage-fed inverter induction motor drive system, as shown in Fig. 1, can develop various fault modes that are outlined in Table 2.

Table 2. Various Fault modes of a PWM inverter system for induction motor drives

Fault Mode	Fault Consequence
F1: Input supply single line to ground fault	F1 is equivalent to diode rectifier single-phase operation. • More than 50% over-current in the diode rectifier. • Pulsating torque appears in the machine due to DC link voltage fluctuation.
F2:Rectifier diode short-circuit fault	F2 may cause faulty or healthy input phase fuse to blow. • If the faulty phase fuse blows, then diode rectifier will operate in single-phase mode like F1. • Else if the healthy phase fuse blows, the system will shut down.
F3: Earth fault on DC bus	Immediate shutdown of the drive
F4: DC link capacitor short-circuit fault	Immediate shutdown of the drive
F5: Transistor base drive open fault	F5 leads DC current inject into the machine, which results in: • pulsating torque in machine, • maximum average torque reduction.
F6: Transistor short-circuit fault	There are three different cases in this situation. **Case 1**: The fault occurs when the healthy (opposite) switching device of the same phase is conducting. The large short-circuit current will destroy the healthy device. DC link shoot-through will ultimately be cleared by the inverter input fuse. **Case 2**: The fault occurs when the healthy switching device of the same phase is not conducting. And only the drive of the

	healthy device in the faulty leg is suppressed immediately but maintaining the usual drive for other devices. In such a case, the phase currents rise to a dangerous level due to DC offset as discussed before. The machine speed drops sharply due to large braking torque. **Case 3**: The fault occurs when the healthy switching device of the same phase is not conducting. And all the drives are suppressed by instantaneous over-current protection. The machine will be short-circuited by stator diode bridge and the machine shuts down after a dynamic braking process. The protection system, therefore, saves the inverter from any further damage. The drive is de-energized and cannot be restarted without opening the faulty phase.
F7: Line to line short circuit at machine terminal	Immediate shutdown of the drive
F8: Single line to ground fault at machine terminal	Immediate shutdown of the drive

This is a very important paper for drive system failure consequence analysis. However, the open-circuit fault of the freewheeling diode in PWM inverter has not been analyzed in this paper; this is shown in our study to be a serious failure mode that is likely to happen in practice. Furthermore, for a drive system with active front-end converter instead of diode rectifier, more fault modes introduced by switch devices in the active front-end converter should be taken into consideration. It's noted that the case 1 of F6, which might be the most serious fault for a drive system, always leads a system to be shut down after a series of transient events. If condition monitoring technology is applied in the power electronic converter, an 'active' fault-tolerant control based on the power device fault prognosis might prevent the system from being turned off, which is one of the advantages of COMPERE and could be valuable to be investigated.

By using the fault isolation and fault-tolerant control techniques, it's possible to keep the system operating under some faulty conditions with reduced performance[1-8]. Many studies focused on this issue, which will be discussed later in detail.

Most intelligent power modules (IPM) and discrete switching devices with modern gate drive circuits have integrated active protection function [62-63]. Once device operating under a fault condition such as over-current, over-voltage, under-voltage or over-temperature is detected, all gate signals in the converter will be blocked. Then the whole system is shut-down by a pre-defined emergency procedures safely.

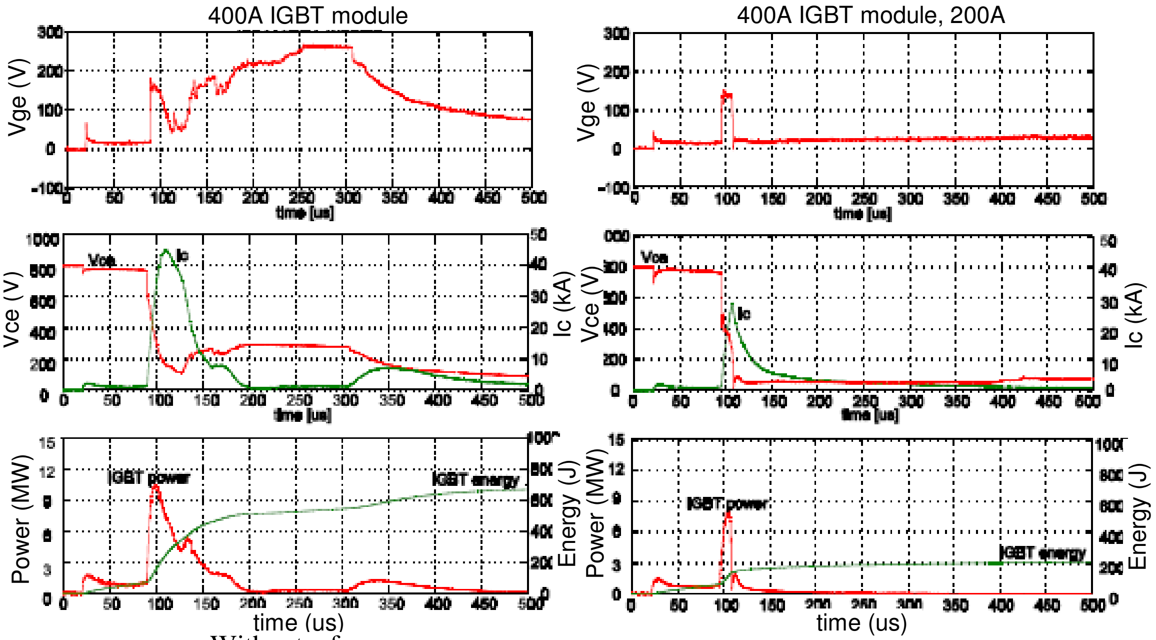
2.1.2 Severe Transient Faults

Despite the active protection, a high-power IGBT still has a small risk of exhibiting a violent rupture in the case of a fault, and one solution is to protect the converter with high-speed fuses. [30, 31]

Modern IGBT converters have low stray inductance and no reactive di/dt limitation in order to constrain over-voltages. If a failure occurs, then the stored energy of the DC link capacitor bank may be instantaneously released. The IGBT wire bonds vaporise and most of the energy is changed to plasma energy. If the plasma is confined into a small volume by modular design, then an explosion with the formation of debris with very high kinetic energy happens resulting in substantial structural damage to the converter and the surrounding elements. Serious injuries to exposed personnel cannot be excluded.

The explosion strength of high power IGBT modules is one of the important factors that decide on converter equipment reliability in extreme circumstances [29]. The explosion strength of a device is represented by the peak value of the collector current (so called "peak case nonrupture current") that cannot be exceeded.

Short circuit tests are made with a 1200V, 400A standard single switch IGBT module with and without a high-speed fuse [31]. The results are shown in Fig. 3.



a. Without a fuse

b. With a fuse

Fig. 3 Shot-circuit test of a 1200V, 400A IGBT switch with and without a fuse

In both cases the IGBT is gated on after 20 µs. Initially the current, driven by a charged capacitor, rises to 2 kA and then stabilises at 1 kA as the transconductance of the IGBT is changed by the temperature rise. After 90 µs the die is destroyed and providing a short-circuit path and a high di/dt which is limited only by the parasitic stray inductance. The current in Fig. 3a rises to 45 kA whereas the current in Fig. 3b is interrupted and limited

to 28 kA by the fuse. Fig. 3a shows that without a fuse the current decreases rapidly again after it has reached its maximum, partly because the DC-link is discharged and partly because of the arc in the module. The rupture happens after 310 µs when 550 J has been dissipated in the switch. Fig. 3b shows that only 200 J is dissipated in the switch when it is protected by a fuse, so it is far from a rupture.
Without a fuse, Fig. 3a, the gate-emitter voltage rises over a long period and exposes the driver circuit to a peak voltage of 270 V, whereas it is only exposed to 130 V for 20µs when the fuse protection is used, see Fig. 3b. The conclusion of the short-circuit tests is that a fuse may prevent a rupture of an IGBT switch and furthermore makes it much easier to protect the driver circuits from being destroyed by overvoltage.

2.2 Fault Handling Technologies for Power Electronic Systems

Usually a device failure causes over-current, over-voltage, harmonics and/or pulsating torque in the system. For the safety of the system, corresponding actions (including fault protection, fault diagnosis, fault isolation and/or fault-tolerant control) must be taken to mitigate the negative influence of a device failure.

2.2.1 Fault Detection and Diagnosis

After a power device fault, the fault information including the fault type, fault location and fault time are important for the system post-fault handling, such as fault protection, isolation, fault-tolerant control and even system maintenance. Therefore, the fault detection or diagnosis technology has been researched in the past [9-26, 34].

The most researched fault diagnosis techniques are based on the converter current features. Initially, Spee and Wallace [34] proposed a fault tolerant system for a brushless DC motor. In that drive, the fault diagnosis is obtained from the comparison between the measured and predicted currents for fault conditions. Debebe et al. [9] suggested the use of a rule-based expert system for fault diagnosis in a voltage-source inverter. To determine the faulty devices in the inverter, an interactive session between the user and the expert system is employed. Kastha and Bose [3] studied the behaviour of an asynchronous machine fed by a voltage source PWM inverter during the fault occurrence. That study was made for key fault types normally verified on the industry applications. Blaabjerg et al. [11] introduced a technique to determine the output currents in a voltage-fed PWM inverter by using a single current sensor in the dc link. Such a solution was shown to be efficient for the global protection of the system but inadequate to identify faults. Ran et al. [12] presented a methodology to detect intermittent misfiring in a voltage-fed PWM\ inverter induction-motor drive. Their technique is based on the time-domain response of the stator currents. Recently, Peuget et al. [14] introduced two techniques to identify the fault mode of voltage-fed PWM inverter. The first one uses the analysis of the current-vector trajectory to identify fault modes. The second one determines the fault condition of the inverter from the instantaneous frequency of the current vector. More recently, Mendes and Marques [15] suggested using the average motor currents Park's vector monitoring for diagnosing voltage-fed inverter faults in AC drives. It's noticeable that techniques based on current pattern do not permit to identify whether the fault has occurred in the inverter or in the machine. In addition, most of the diagnosis techniques above suggested take at least one fundamental period between the fault occurrence and the fault detection, which might be too long for post-fault actions. Recently, four detection techniques have been introduced for fault diagnosis in voltage-fed asynchronous machine drive systems based on measurement of voltages at key points of the drive systems [17], as shown in Fig. 4.

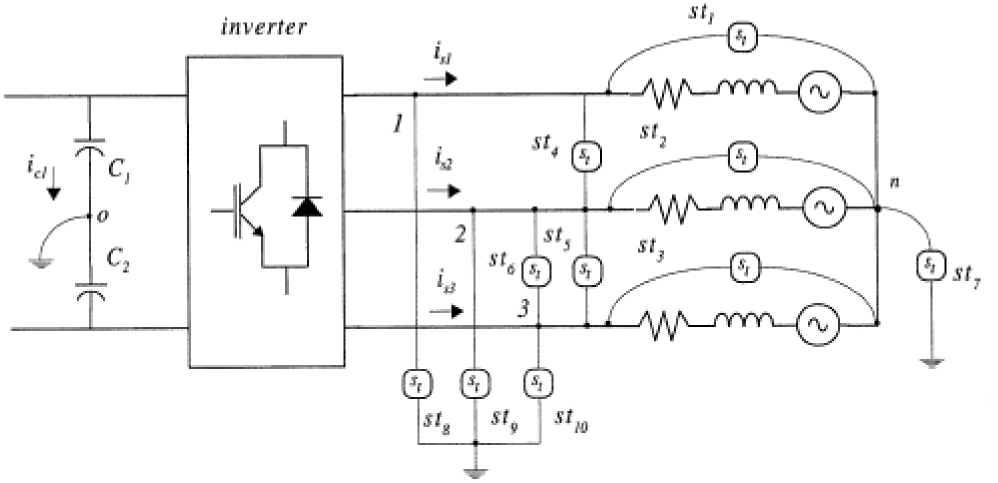


Fig. 4 Possible location of the voltage sensors

The detection techniques employ a direct comparison of the measured voltages to their reference voltages obtained from the PWM reference signals. They can be classified as follows:

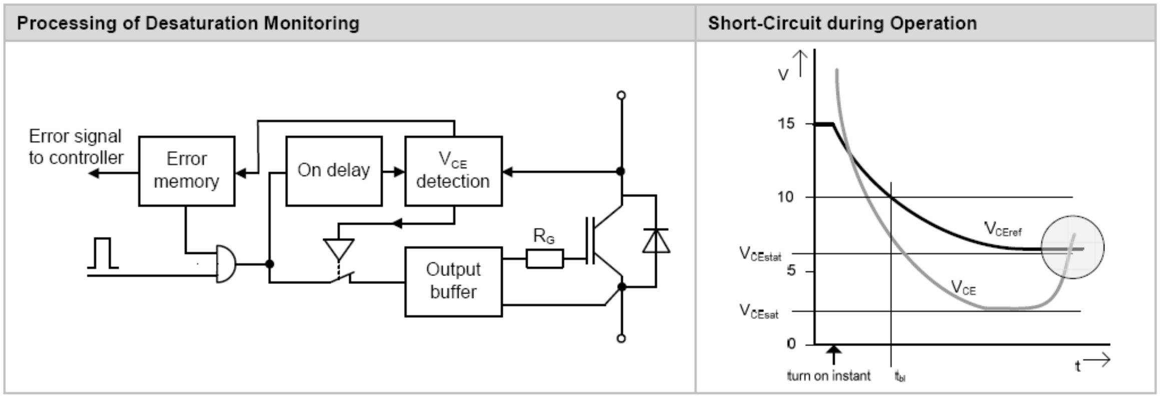
- Technique T1—inverter pole voltage measurement.
- Technique T2—machine phase voltage measurement.
- Technique T3—system line voltage measurement.
- Technique T4—machine neutral voltage measurement.

The detection of the fault condition is achieved by comparing the voltage measurements to their respective references. The fault condition is detected within one fourth of the fundamental cycle. These fault detection techniques need to incorporate extra voltage sensors in the system. However, this is justified when it is necessary to increase the reliability of those systems.

At the same time, some advanced algorithms such as expert systems, fuzzy logic and neural networks have been applied in power electronic converter fault diagnosis [9, 10, 13, 15, 18, 20, 25, 26]. Although the validities of different algorithms have been demonstrated by simulation or experiment research, the real-time requirement of fault detection and the algorithm complexity should be taken into consideration for practical industry application.

The existing intelligent power module (IPM) and advanced drive circuit have integrated fault detection function based on various sensor technologies.

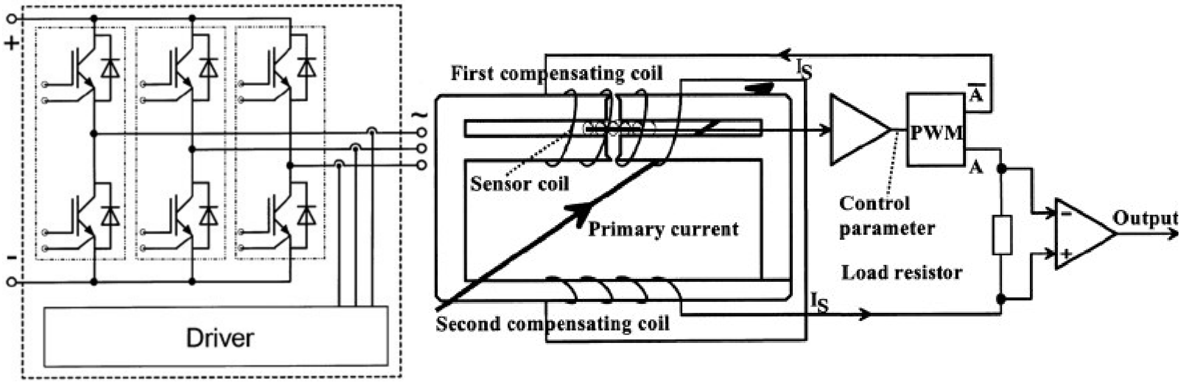
SEMIKRON IGBT Driver-SEMIDRIVER™ has the short-circuit detection function [62]. Detection of the short-circuit current is done via desaturation monitoring. As illustrated in Fig. 5, for detection of a short-circuit current, the collector-emitter voltage (V_{CE}) of an IGBT can be utilized because it rapidly increases as a result of desaturation caused by the device short circuit fault.



Technical Advantages of SEMIKRON Driver Electronics	User Benefits
V_{CE} trip level varied to suit the IGBT in use	Adaptable to various IGBT technologies and applications.
Adjustable delay time for the V_{CE} signal.	Prevents false short-circuit signal to the V_{CE} monitoring circuit.

Fig. 5 Short-Circuit detection technique of SEMIKRON Drive

The SKiiP (SEMIKRON IGBT IPM) features the following integrated sensors to detect the converter faults: compensated current sensor per phase, temperature sensor on ceramic substrate, sensing of DC link voltage [63].



a. 3-fold Skiip block diagram b. Skiip compensated current sensor

Fig. 6 SKiiP compensated current sensor

SKiiP integrates one current transformer per power section (phase) to measure the AC output current. Current transformers are working according to the compensation principle. The magnetic field caused by the load current is detected by a magnetic field sensor. This is not a Hall element but a small coil with a high permeable core. Due to the properties of this sensing element there is no offset failure and the operation is almost temperature independence. An electronic circuit keeps evaluating the value of the field sensor and feeds a current into the compensation coil in order to keep the effective magnetic field to zero. The compensation current gives an image of the load current and is evaluated across a burden resistor with an electronic circuit.

The integrated temperature sensor in SKiiP is a semiconductor resistor with a linear proportional characteristic to the temperature (PTC characteristic). The sensor is soldered onto the ceramic substrate close to the IGBT and freewheeling diode and indicates the actual substrate temperature. The sensor is insulated. An evaluation circuit realized on the integrated driver provides a normalized, analogue voltage signal of the actual ceramic substrate temperature value. The ceramic substrate temperature is very close to the heat sink temperature.

With the option "analogue DC-link voltage-sense", a normalized, analogue voltage signal of the actual DC-link voltage level is available at the DIN 41651 connector of the gate driver in SKiiP. The measurement is realized by a high impedance differential amplifier. The circuit is designed, manufactured and tested according to standard EN50178 (VDE0160).

2.2.2 Protection against Faults

In most circumstances, the active techniques are adopted in a power electronic converter to prevent catastrophic consequence at the system level upon a device failure. [62, 63]

SEMIKRON IGBT Driver-SEMIDRIVER™ has active protection functionality including short-circuit detection and Soft Turn-Off [62]. The detection of a short-circuit fault as well as response signal processing in the electronic monitoring stage takes time. To prevent electrical components from being subjected to unwanted stresses and to achieve a high degree of reliability, it is always an advantage to terminate the short-circuit current as quickly as possible. To this end, the turn-off signal should be applied to the driver stage of the IGBT with the shortest possible delay. However in short-circuit conditions the IGBT's peak current can increase to extreme values and lead to the generation of a high di/dt during turn-off. Due to stray inductances that are always present in the power circuit, a high voltage spike will be produced. The voltage spike can be reduced by soft-turn-off. In the event of a short-circuit fault, the soft turn-off circuit automatically increases the IGBT turn-off time. This reduces the di/dt and, consequently, the voltage spike across the collector and emitter of the IGBT, enabling the use of higher DC-bus voltages. This in turn means an increase in the final output power.

According to the handbook of SEMIKRON IPM, the gate drivers of SKiiP have the following comprehensive protection and supervisory functions [63]:

- Interlock and dead time
- Short pulse suppression
- Input pulse shaping

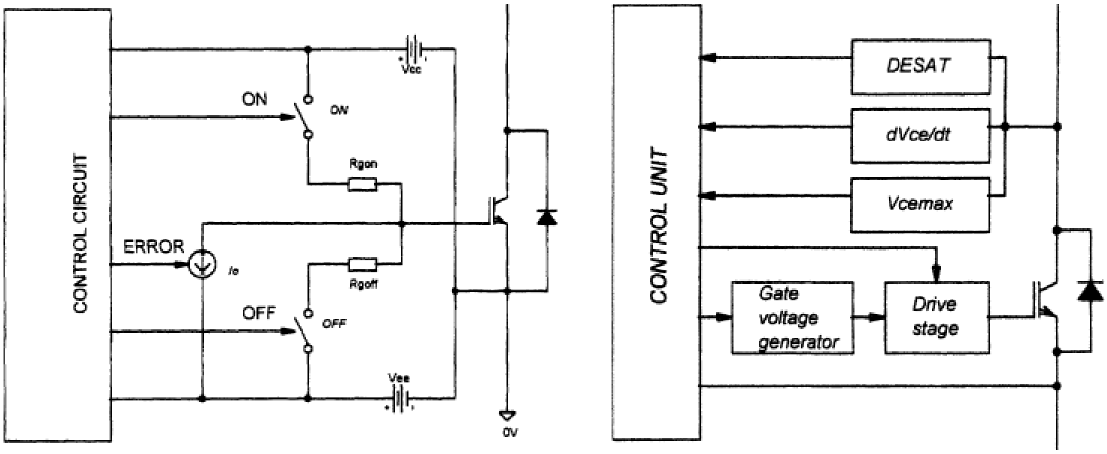
- Input signal clamping
- Under voltage monitoring of the (internal) supply voltage on primary side
- Transient over voltage and inverted polarity protection by suppressor diode
- Over temperature protection
- Short circuit and over current protection (by current sensor and Vcesat monitoring)
- Line to ground fault protection
- Over voltage protection of the DC link voltage

The integrated current sensors per AC terminal can be used for AC current control. In addition they are used to protect the SKiiP system against over currents. The over current protection reacts independently of the temperature level and provides a reliable protection of the SKiiP system. If the AC output current is higher than the maximum permissible level of 125 % I_C, the IGBTs are immediately switched off and switching pulses from the controller are ignored. The error latch is set. The output "ERROR OUT" is in HIGH state. In addition a V_{CEsat} monitoring circuit is implemented to protect the phase leg against internal short circuit ("shoot through protection").

The temperature of the ceramic substrate is monitored by an integrated temperature sensor. The over temperature trip threshold has been chosen at T = 115 ± 5 °C. At that temperature the IGBTs are switched off and switching pulses from the controller are ignored. The error latch is set. The outputs "Overtemp. OUT" and "ERROR OUT" are in HIGH state.

The under voltage protection of the primary side monitors the internal 15VDC which is provided by the internal DC/DC converter. If the operating DC link voltage is higher than VCCmax the IGBTs are turned off and switching pulses from the controller are ignored. The error latch is set. The output "ERROR OUT" is in HIGH state.

The gate voltage has great influence on the characteristics of IGBTs. An Active gate drive protection is reported in [65]



a. A conventional gate driver b. A typical active gate driver topology

Fig. 7 The conventional and active gate drivers

A fully active gate driver may effectively control the collector current slope and the IGBT may work under all conditions including overload or short circuit at the highest bus voltage. The active gate driver consists of several functional blocks. Over-current protection is usually based on desaturation of the IGBT at high collector current, and it is well known detection method.

Topology of an active gate driver is depicted in Fig 7. The dV_{ce}/dt and V_{cemax} control circuit is based on direct measurement of the collector emitter voltage via nonlinear RCD network. The feed-forward gate voltage shape generator provides direct control of the collector emitter over-voltage in case of arm short circuit fault. All these functions of the active gate driver provide safe operation under all possible working conditions including overload and short circuit at the highest bus voltage.

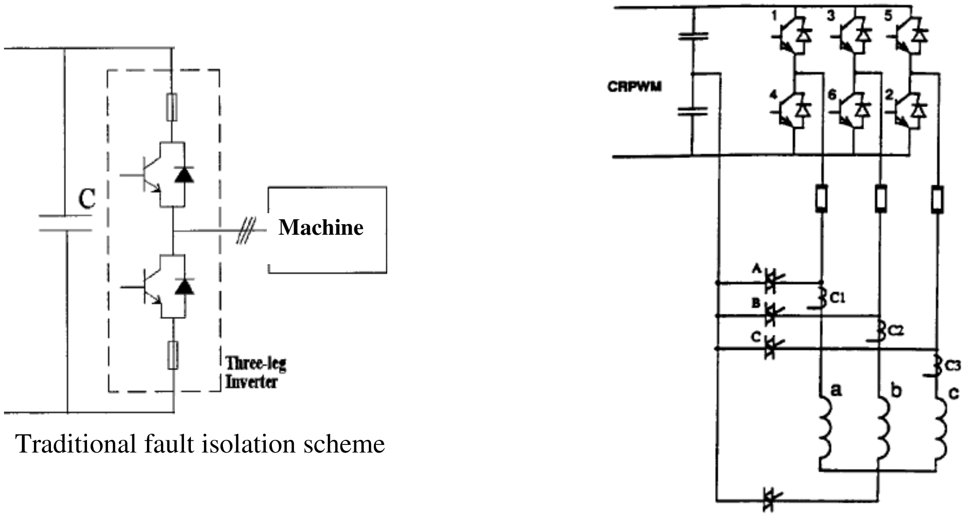
Despite the active protection, a high-power IGBT still has a small risk of exhibiting a violent rupture in the case of a fault, and one solution is to protect the converter with high-speed fuses. [29-31]

There may naturally be a reluctance to use fuse protection in IGBT converters because it takes up extra space, it is an extra cost, it introduces extra losses and finally a fuse will add some extra stray inductance. The last issue might be critical because it will increase switching losses and over-voltage during turn-off. These drawbacks may, however, be counterbalanced by the advantages such as no rupture, lesser problems with certification and no need for a special explosion chamber in the design. It is explained in paper [31] what the motivation for using high-speed fuses in medium-size and large dc-link IGBT converters is. It is not possible to give one simple answer to that question because it might depend on a number of factors, including how the converter is constructed and manufactured. Experiments show that a fuse can prevent an IGBT-module rupture in the case of a short-circuit. The fuse furthermore helps to protect the IGBT driver circuit against over-voltage. In this paper, the problem of adding inductance is treated, the inductance of existing high-speed fuses are measured, and possible future low-inductance fuse designs are proposed.

Of course, careful selection of the right fuse for a power electronic equipment is necessary and more and more sophisticated calculation and simulation are required [64]. It is reported in [30] that the medium power IGBT converters can be protected against case explosion by fast fuses correctly selected according to I^2t values. However, in high power converters it is necessary to take into account the possibility of IGBT module explosion. There are no fast fuses adequate to the highest rating IGBT modules and such fuses would be very expensive. A designer of high power IGBT converters must incorporate protection against structural damage of the equipment by providing the separating walls mentioned above. This solution will lead to cost saving if is introduced instead of complex over-current protection. An introduction of a disc shape construction with press-pack technology for high power IGBT modules enables dual side cooling and limits consequences of their explosions.

2.2.3 Fault Isolation and Fault-tolerant Control

In some safety-critical applications, the power device can be isolated after a fault and the system can operate continuously under special fault-tolerant control without being fully shut down. Many research works have been carried out in this area. [5, 34-61]



Traditional fault isolation scheme

Proposed fault isolation scheme

Fig. 8 Topologies for isolation a short circuited inverter switch

Paper [36] presented an approach to faulty switch isolation in an inverter drive. Traditional method to isolate a short-circuited switch is to simply shoot-through or short circuit the faulty leg of the inverter by turning on the other switch in the same inverter leg. With this method, two fuses per inverter leg are required, Fig. 8. However, because of the over-current limit of the switches and the clearing characteristics of the fuses, a new short-circuited switch may be created even though the original fault has been cleared. In such cases, there is no means to isolate the newly created short-circuited switch. Hence, the motor cannot be operated and must be shut down to remove the fault.

The working principle of proposed isolation method is that: once a failure indicating a short circuit signal is sensed, the other switch in the same leg is blocked and the triac of the appropriate phase is instead triggered on. This results in the short circuit of the capacitor of half DC supply. The energy stored in the capacitor will then blow out the fast active fuse and isolate the shorted switch of the inverter.

The approach utilizes low cost thyristor/fuse technology to isolate the shorted switch thereby permitting continued operation either by connecting the phase previously experiencing the fault back to the centre point of the DC bus or, when insufficient voltage is available, by connecting the neutral back to the centre point of the dc bus and simply operating with the two healthy phases. After fault isolation, the motor is under two-phase control, which has reduced driving terminal voltage as well as reduced current regulation capability.

Paper [37] considers variable frequency variable voltage operation of a three-phase induction motor in single-phase mode for two common faults of a three-phase inverter, i.e., open base drive and device short-circuit. The motor performance has been extensively analyzed in single-phase mode and remedial strategies have been developed to neutralize large second and other lower order harmonic pulsating torques. In a single-phase open loop volts/Hz control mode of a faulty three-phase inverter, it has been demonstrated that odd harmonic voltages at appropriate phase angles can be injected to neutralize the low frequency pulsating torques so as to permit smooth drive operation. It has been shown that the pulsating torque can be further reduced by load dependent flux programming rather than operating with constant rated flux.

There have not been studies on the impact of fault tolerant operation on the DC link capacitor of the drive, which no doubt will present a constraint.

The investigation of fault-tolerant control techniques for PMSM drives is arousing lively interest, to extend their use to applications where high reliability is a key feature, such as aircraft and automotive auxiliaries. Paper [39] describes a study and an experimental verification of remedial strategies against failures in the inverter power devices. The basic idea of this design consists in incorporating a fourth inverter pole, with the same topology and capabilities of the other conventional three poles. This minimal redundant hardware, appropriately connected and controlled, allows the drive to face a variety of power device fault conditions while maintaining a smooth torque production. The achieved results also show the industrial feasibility of the proposed fault-tolerant control, which could fit many practical applications.

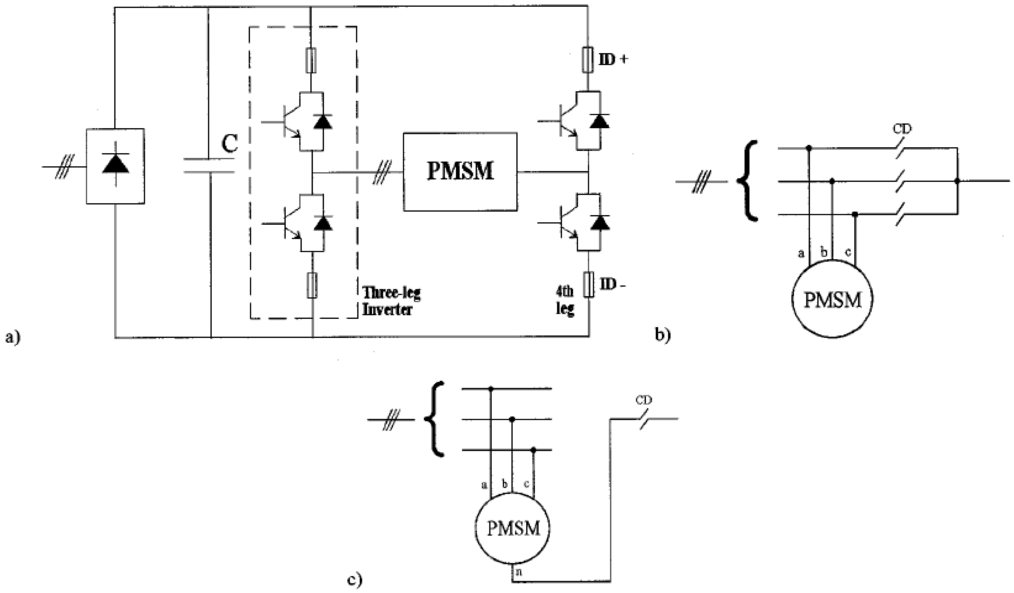


Fig. 9 Fault-tolerant drive schemes

As shown in Fig. 9, the cost introduced by this fault-tolerant technology is some isolation devices (e.g. fuses), connecting devices (e.g., a TRIAC or a pair of back-to-back thyristors), an additional inverter leg and some control software modifications. The rating increasing of the power devices might be considered for one of the fault-tolerant methods presented in this paper. The fault isolation and fault-tolerant control methods described in this paper are practical not only for PMSM drives but also can be applied for other drive systems by some adequate modifications.

Two possible modes of operation of an induction motor drive under inverter fault, utilising only four possible voltage vectors, in different ways are researched in paper [5].

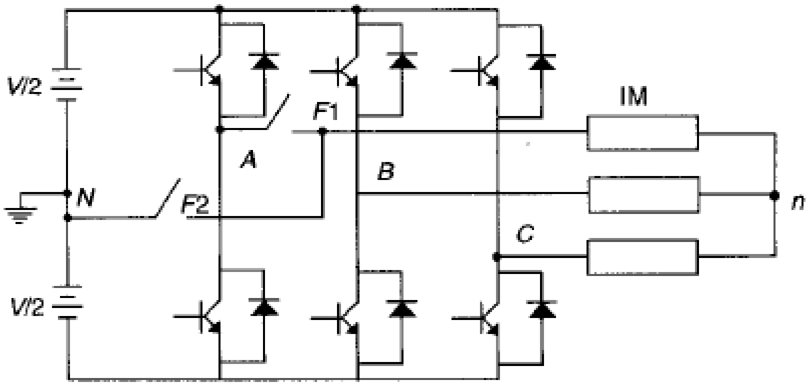
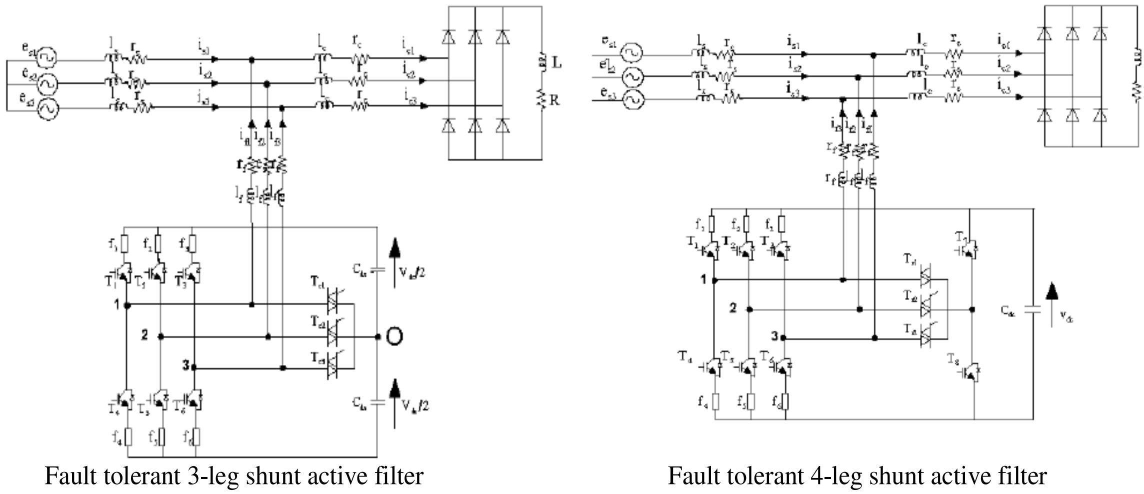


Fig. 10 AC drive reconfiguration [5]

Paper [48] developed a fault tolerant-control (FTC) system based on reliability analysis dedicated to an active power filter. Once a fault has been detected and isolated, all possible structures of the system that preserve pre-specified performance are analyzed and the highest reliability indicate the optimal structure.



Fault tolerant 3-leg shunt active filter

Fault tolerant 4-leg shunt active filter

Fig. 11 Two different fault tolerant control strategies for APF

The features, cost, and limitations of the fault tolerant three-phase ac motor drive topologies that have been presented in the literature were reviewed and compared in detail in paper [43]. This review of the alternative topologies and control methods makes it clear that there is significant cost associated with providing fault tolerant operation. All of the topologies require additional components in the form of silicon switches and/or fuses to provide this capacity in the presence of a fault that would otherwise not be present in a standard three-phase inverter drive. In conclusion, a careful assessment of the likelihood of each type of fault and the required post-fault capacity is necessary to determine which topology is best suited for each application.

Currently, the research of fault-tolerant control not only concentrates on the traditional two-level converter. Multi-level converter topologies, which are inherently suitable for fault tolerant operation with better reliability, are attracting more and more attention in academic and industry [50-59].

Redundant modules and topology configuration redundancy stand out as two fault-tolerance techniques that are suitable for multilevel converters respectively applied in naval ship propulsion systems [59]. The paper presents a unique design for flying capacitor type multilevel inverters with fault-tolerant features. Instead of sacrificing some of the line-to-ground voltage converting levels, the proposed design can guarantee consistent line-to-ground converting levels when a single-switch-fault per phase occurs.

3. Review of Condition Monitoring for Power Electronics

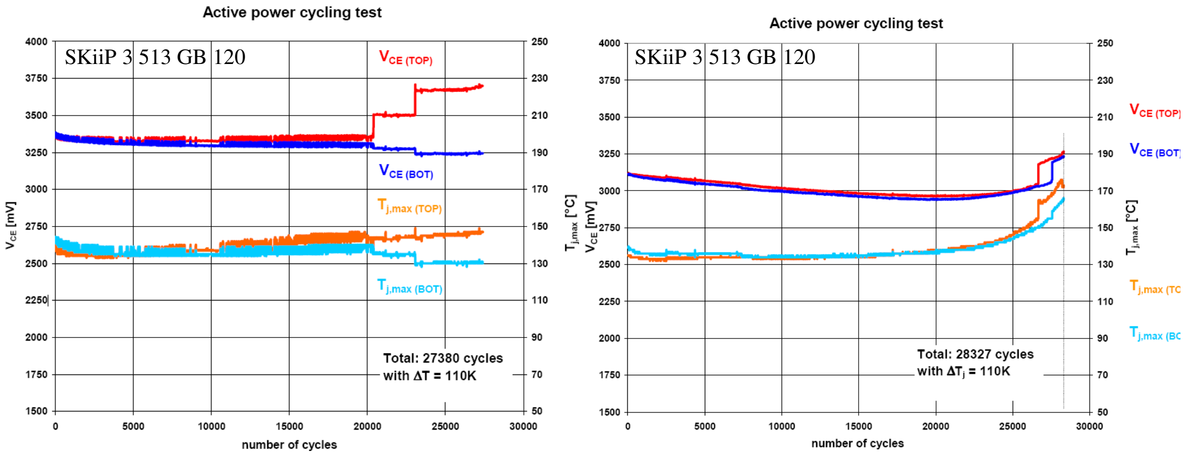
Reference [66-74] describe recent work on condition monitoring technology aiming to improve the power electronics reliability.

According to previous research, some condition variables, such as collector emitter voltage V_{ce}, device on-state resistance R_{on}, thermal resistance R_{th} and gate signals have been correlated to the health of a power device. Moreover, some special techniques i.e. sensor-tech and system identification have been applied for condition monitoring of power electronics as well.

3.1 V_{ce} or R_{on} Based Condition Monitoring Technology

Power devices such as IGBT, MOSFET always work like a switch, which has two states: on and off. During the on-state, there is a small voltage drop between collector and emitter V_{ce} while conducting a current I_c. R_{on} defined as the on-state resistance of device, describes the electrical characteristic of a semiconductor. Research shows that there are changes in R_{on} (or V_{ce}) of device after a long-term power cycling operation, which has been utilized to monitor the bond wire lift failure [66, 68-69 and 71].

Fig. 12a shows the results of an active power cycling test of a SKiip3 IGBT module with 14 chips in parallel per switch[68]. The jump in the collector-emitter saturation voltage V_{cesat} in Fig. 12a is caused by the final failure: bond wire contact loss in one or more of the parallel switched IGBT chips. In contrast to the power cycling test in Fig. 12a, Fig. 12b shows an active power cycling test with a different behaviour in the end-of-life phase. Starting around 21500 power cycles, the collector emitter saturation voltage V_{cesat} and the maximum junction temperature T_{jmax} show a continuous increase, due to a rise in thermal resistance caused by degradation of the soldering. Though the final failure detected in Fig. 12b is also bond wire lifting off; it is, unlike the lift-off in Fig. 12a, a secondary failure following on the primary mechanism of solder fatigue. Depending on the values for the accelerating factors (e.g. T_{jmax}, ΔT_j) used in the end-of-life testing, it is possible to distinguish between two primary end-of-life failure mechanisms: solder fatigue and bond wire lift-off. In both cases, however, the bond wire lift-off with its characteristic steps in the graph of the forward voltage drop V_{cesat} is the terminal failure mechanism.



a. Bond wire lift failure

b. Solder fatigue failure

Fig. 12 Two different behaviours of power cycling test for power module

In the integrated power module diagnosis unit patented by Ford Motor Company in 1996 [66], the on-state voltage across the device as well as the current through the device are monitored periodically. As shown in Fig. 13, for a specific device current, the measured on-state voltage across the device is compared against a value obtained from a look-up table. The difference or the deviation is an indication of the integrity of the bond wires and the level of deterioration to power cycling.

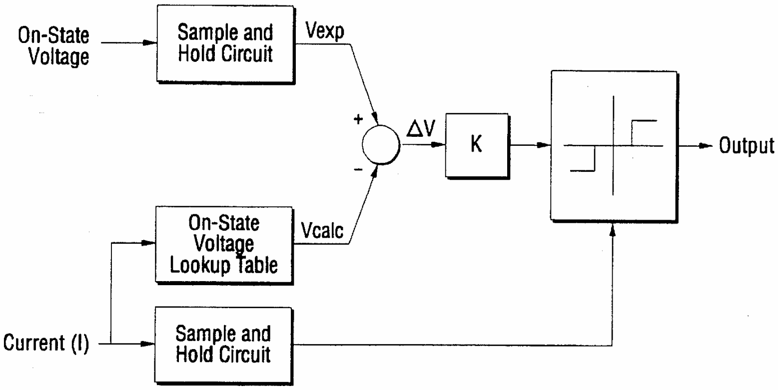


Fig. 13 Power cycling failure diagnosis in the integrated power module diagnosis unit

A quasi real-time IGBT failure prognostic system based on monitoring the abnormal V_{cesat} variation at specific currents and temperatures is developed in paper [69], which is designed to improve the reliability of power module in the electrical vehicle.

Except these existing current, voltage and temperature sensors in a normal AC drive system, three extra voltage sensors are placed at the positions a, b, and c, respectively, as shown in Fig. 14. They can directly obtain the V_{ce} on three bottom leg IGBT chips, V_a, V_b and V_c. The V_{ce} on three upper leg IGBT chips can be obtained from V_{dc} and V_a, V_b, V_c, respectively.

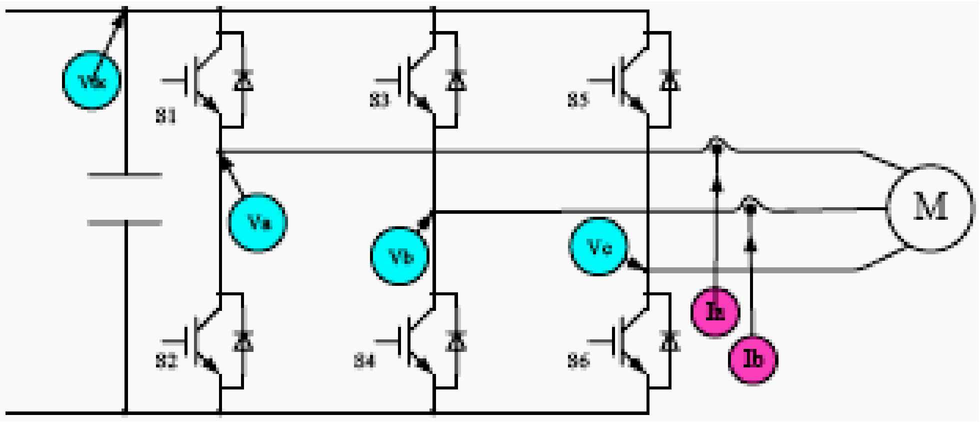


Fig. 14 Senors topology for Vcesat monitoring system [69]

The algorithm is based on monitoring the abnormal V_{cesat} variation at the specific current and temperature conditions. The basic idea is: an IGBT will be considered as being seriously "degraded" if its measured V_{cesat} increases by more than ±15% from its "normal" reference value. In practice, a prognostic subroutine was inserted to the vehicle control system immediately after the key-on and/or key-off of each vehicle use period to collect the necessary data for "normal" reference. The check-up routine typically lasts no more than a fraction of a second and does not change the normal operation of the vehicle.

A so called "loss-related health monitoring" method is reported in paper [71], which is based on the monitoring of MOSFET on-resistance (R_{on}) using an embedded digital controller. It is shown that available converter operating information can be processed to detect a significant (e.g. 2x) change in the power MOSFET R_{on}.

3.2 R_{th} Based Condition Monitoring Technology

The information of power module and sink temperatures at a certain load current value captured and stored on a day-to-day basis have been used to predict any change in the module's thermal resistance or possible degradation of the cooling system [66].

The block diagram describing the transistor stack failure diagnosis approach is shown in Fig. 15. The junction temperature T_j, case temperature T_c, sink temperature T_s and device current are monitored periodically. Using this information by diagnosis in accordance with Fig.15, the junction to case thermal resistance (R_{thcs}) and case to sink thermal resistance (R_{thcs}) and junction to sink thermal resistance (R_{thjs}) could be calculated. These would be stored to study the trend and determine if the solder interfaces (silicon die to substrate or the case to sink interface at the thermal grease or the thermal pad layer) are degrading over time.

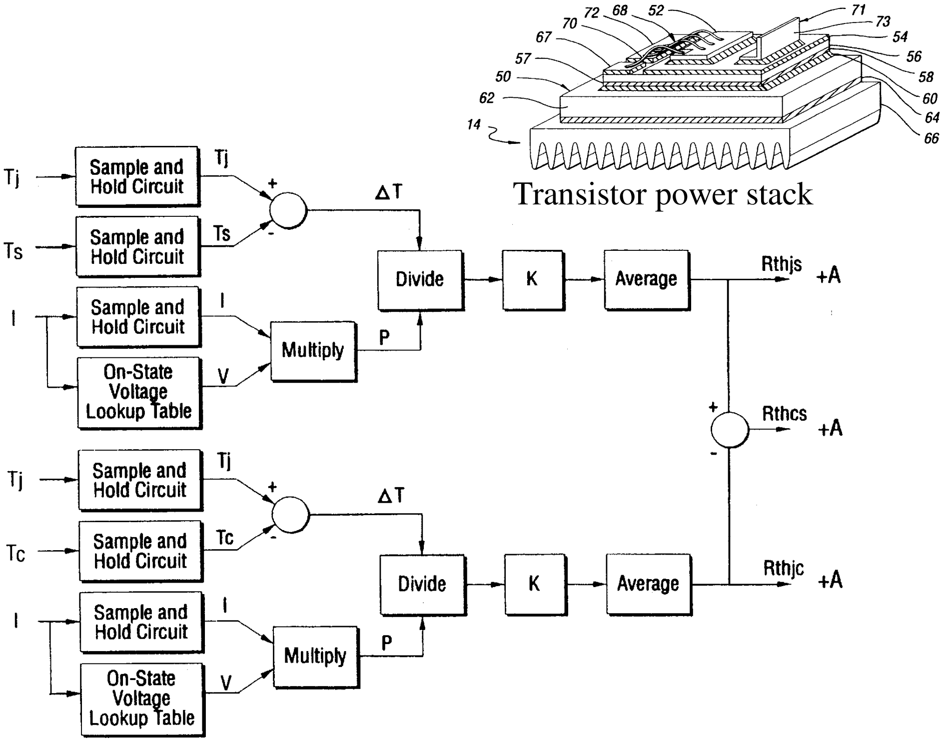


Fig. 15 Transistor power stack failure diagnosis

3.3 Gate Signal Based Condition Monitoring Technology

An IGBT failure detection method during a short-circuit fault is proposed based on the comparison of the gate voltages in fault free and faulty condition [72]. The key issue in this work is to analyze the gate voltage signal in order to generate the reference signal under faulty condition. This analysis is based on degradation of electrical parameters (C_{gd}: capacitor between gate and drain) of IGBT due to the destructive effect which modifies particularly the gate charge signal.

Experimental results in Fig. 16 show the significant variation in the IGBT gate charge in presence of IGBT failure by short circuit. In this way, a detection window can be defined from the beginning of phase 1 to the end of phase 2 for an early detection. On the other hand, to give greater robustness to fault detection it is possible to set thresholds that contemplate the variation of the electrical parameters of the IGBTs caused by natural aging.

Although the very fast protection requirement (about 500 ns) may mitigate the practice of this technology, this paper demonstrates a possibility to detect an electrical fault for IGBT. It is reported that the depletion region is more vulnerable to an electrical fault, whose aging mechanism should be investigated further. If the critical short-circuit ability of a power device can be monitored during a normal operation at early stage, the catastrophic fault could be avoided with lower real-time requirement.

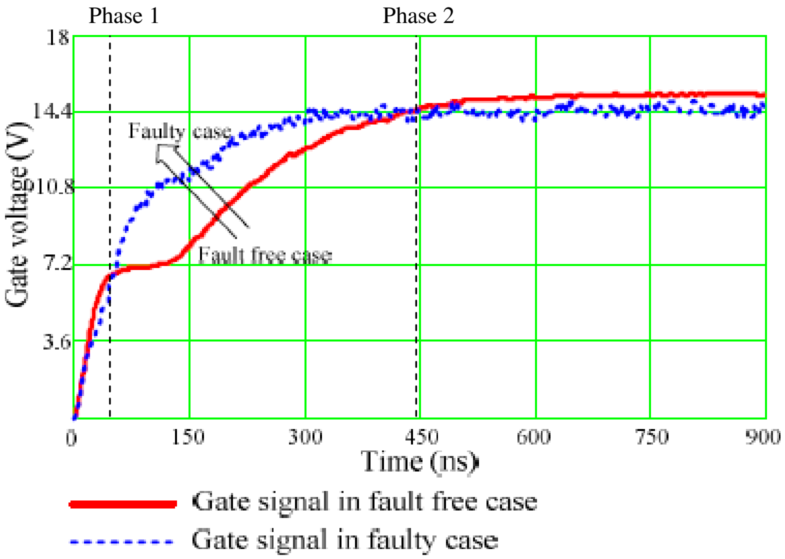


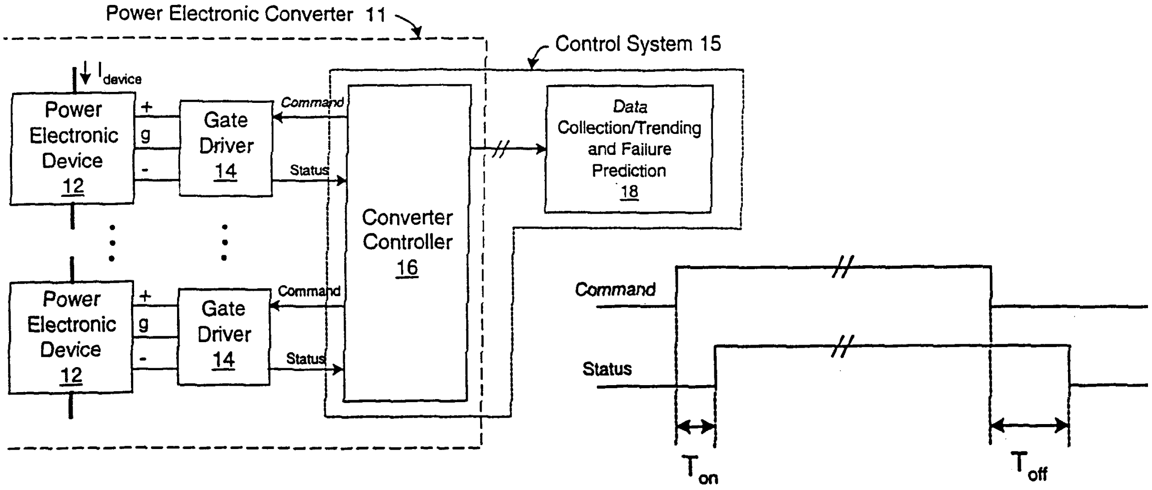
Fig. 16 Fault detection based on gate voltage monitoring

3.4 Switch Time Based Condition Monitoring Technology

The known degradation of modules of semiductors impinge on the switching characteristics of a device in several ways[67]. Typically, power semiconductor devices are comprised of many devices in parallel: either as individual segments on the silicon die (as in a GTO), or as many dies connected together in a single package (as with most large IGBT modules). Partial failure of the device, where some of these segments or dies cease to function, can result in longer transition times (that is turn-on and/or turn-off time) for a given amount of device current. Higher device junction temperature can result in prolonged switching times, and can be caused by several factors related to degradation including: higher leakage current, higher on-state voltage due to bond wires lifting, and higher thermal impedance due to die delamination, for example. On system-level, loss of converter cooling will also increase device temperature and will increase the switching times of the devices in a converter as a group.

In the gate driver of each device there typically exists one or more power supplies that incorporate electrolytic capacitors. Over time, these capacitors experience a decrease in capacitance and increase in equivalent series resistance (ESR) and temperature. Such degradation reduces the strength of the transitions of the devices. Likewise, the gate driver often has several power electronic devices (e.g. MOSFETs) operating in its output circuitry. A failure of one or more of these devices will also prolong the switching times of power electronic device.

A method for monitoring the health of power electronics was invented by GE Company, which uses the switching time to determine a diagnosis condition of the power electronic device and/or the gate driver [67]. Under typical operation of a power electronics converter, hundreds or even thousands of switching events can be measured every second. The regression of these measurements will produce a very high-resolution, time-averaged and noise immune signature for each power electronic device/ gate driver pair.



a. Health monitoring system

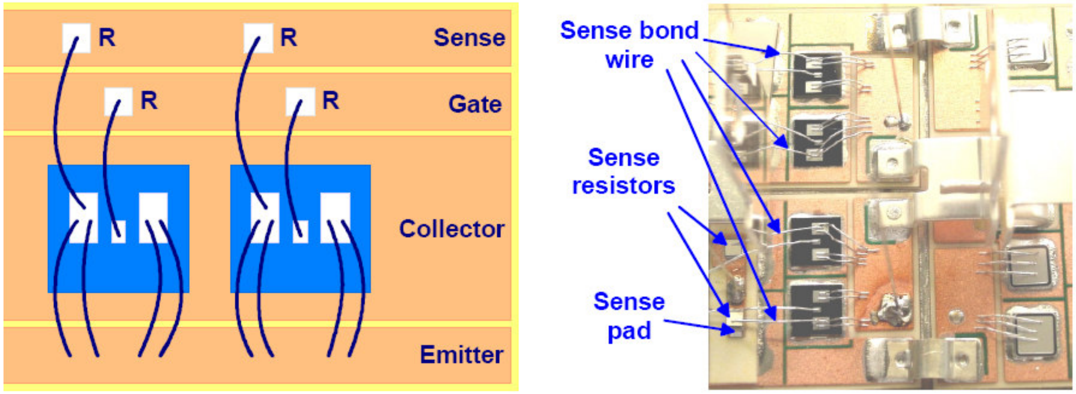
b. Example of switch time measurement

Fig. 17 Condition monitoring method based on device switch time

3.5 Sensor Based Condition Monitoring Technology

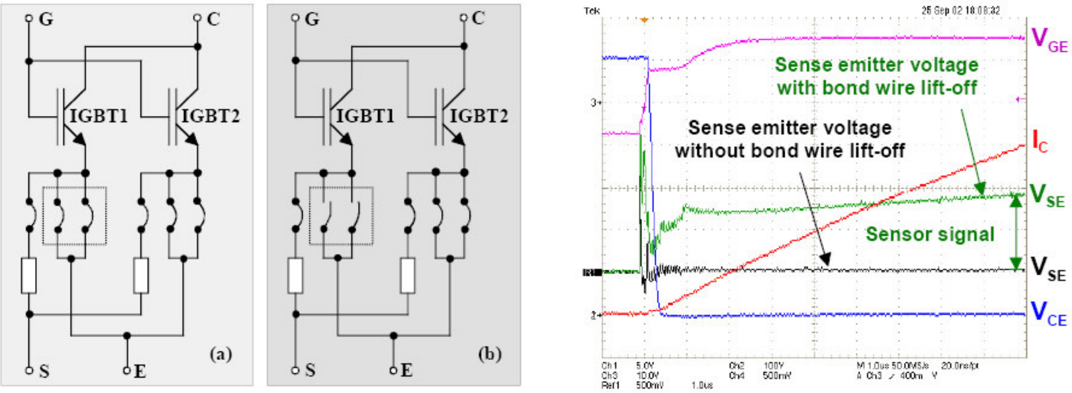
An approach is presented by SEMIKRON for detecting bond wire lift-off in power semiconductor devices while they are in operation [68]. The aim is to improve the reliability of power electronic system. The diagnostic functionality presented makes use of specific bond assemblies and integrated subcircuits, e.g. as part of the gate drive in IPMs, and serves to detect bond wire lift-off in power devices in any localisation, such as emitter, sense or gate failure inside single chip or parallel-connected systems.

Some modification of the assembly and of the DCB layout is called for. As can be seen in Fig. 18a, the IGBT collector is conventionally contacted to the DCB substrate by soldering, whereas the emitter and gate are contacted by bond wires. The modification suggested is the use of an additional contact area (labelled Sense) on DCB substrate. This bond wire does not conduct the emitter current in normal operation because of its higher impedance, but it does make sure the chip retains some controllability and is not damaged even if all the standard emitter-bonds lift off. The extra bond wires to all the IGBT emitters are separated into groups by means of low ohmic resistors which are either placed on the DCB or integrated monolithically into the IGBT. The midpoint of the resistor sub networks (Sense) is fed into control circuitry which can be part of the gate driver. Fig.18b shows a practical implementation of this assembly structure for a module with four IGBTs in parallel. The equivalent electrical network is represented in Fig.18c. If the bond wire contact to the IGBT emitter is lost as a result of bond wire lift-off, controllability of the affected chip will nevertheless be maintained, as the resistor network implemented will take over the role of ensuring a low ohmic coupling between the IGBT emitter and the controlling gate driver. The resulting feedback in the emitter branch is advantageous because it automatically means that IGBT1 has a considerably reduced being strong enough and close to the emitter potential, is analysable. Fig.18d indicates the different characteristics of the sense emitter voltage V_{SE} with and without bond wire lift-off. The sense signal is about 0.9 V and relatively independent to the values of actual sense resistances and of the collector current. Comparator can be used by the monitoring circuitry to evaluate this sensor signal.



a. Modified DCB layout

b. Modified IGBT module



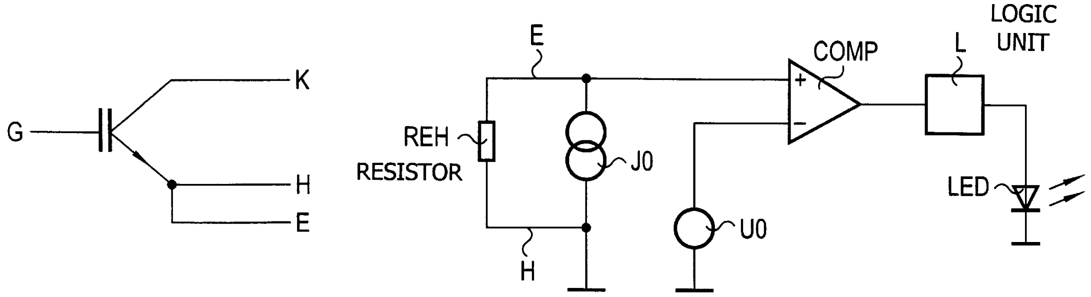
c. Equivalent circuit without and with emitter bond lift-off at IGBT1

d. Measurement results-Sense signal

Fig. 18 Detection of emitter bond wire lift-off for IGBTs in parallel

There are corresponding solutions for emitter wire lift-off detection in a single IGBT-chip and gate bond wire lift-off detection. The monitoring circuits are also reported in the paper [68] as well.

In US patent [74], SIEMENS presented a method for early failure recognition in power semiconductor modules which employs a measurement across a resistor between a bonded emitter terminal and a bonded auxiliary emitter terminal that identifies the degradation of the bond point which triggers an early warning signal so that the power semiconductor module can be changed before failure and the overall reliability of an electronic power system can thereby be increased.



a. IGBT having an auxiliary emitter

b. Schematic diagram

Fig. 19 SIEMENS invented sensor based condition monitoring technology

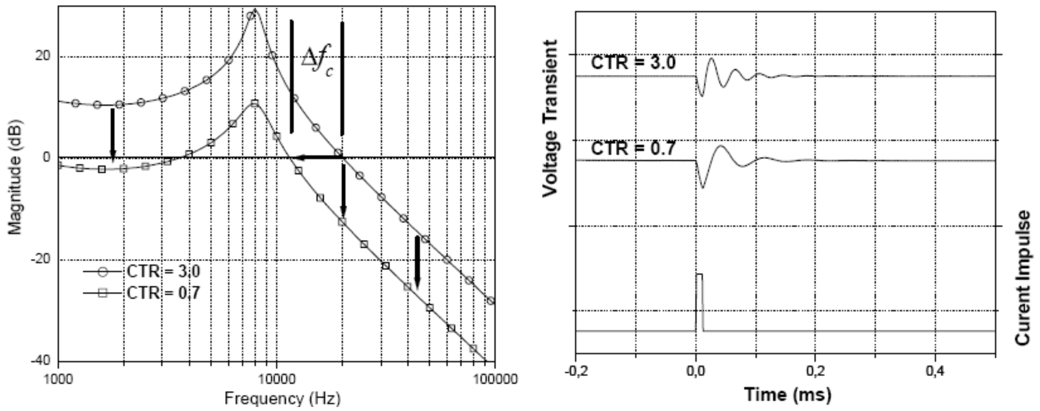
The sensor based condition monitoring technology for power electronics is reliable and accurate. However, there is no doubt that the modification of the assembly and of the DCB layout will increase the complexity and the cost of the power device chip or module.

3.6 System Identification Based Condition Monitoring Technology

As a system, any degradation of a power device in a power electronic system will affect the system response theoretically. Therefore, it is possible to diagnose the internal failure of power devices based on the system identification method. References [70, 73] and [71] reported the applications of system identification for power electronics condition monitoring.

Paper [70] outlines a non-invasive method for the detection of failure precursors for optical isolators used in switch-mode power supplies (SMPS). The method relies on the transfer characteristics of the closed loop operation of the power supply circuit to evaluate gain, rather than direct measurement of current at the isolator terminals.

The opto-isolator is one of a few high failure-in-time (FIT) rate items in the SMPS. The degradation progression for this component is a relatively slow decrease in CTR (Current Transfer Ratio) over time, which initially does not affect steady state operation of the circuit. Only when the CTR falls below a critical threshold value does the circuit cease to regulate and the output voltage begin to drift upward. However, well before this failure point, the health of the optical coupler can be measured from the observation of the crossover frequency. This frequency will decrease as CTR is reduced (see Fig. 20)



a. Shift in Crossover Frequency due to Decreased CTR

b. Voltage transient response to load current impulse with two different CTR

Fig. 20 Condition monitoring CTR for opto-isolator

It was recently shown that hardware-efficient system identification is possible for switching power converters containing a digital control loop. [71] The proposed monitoring system can be used to detect degradation of converter stability margins, leading to system failure. The diagram for a forward converter system identification process including digital pre-filter and post-filter can be found in Fig. 21.

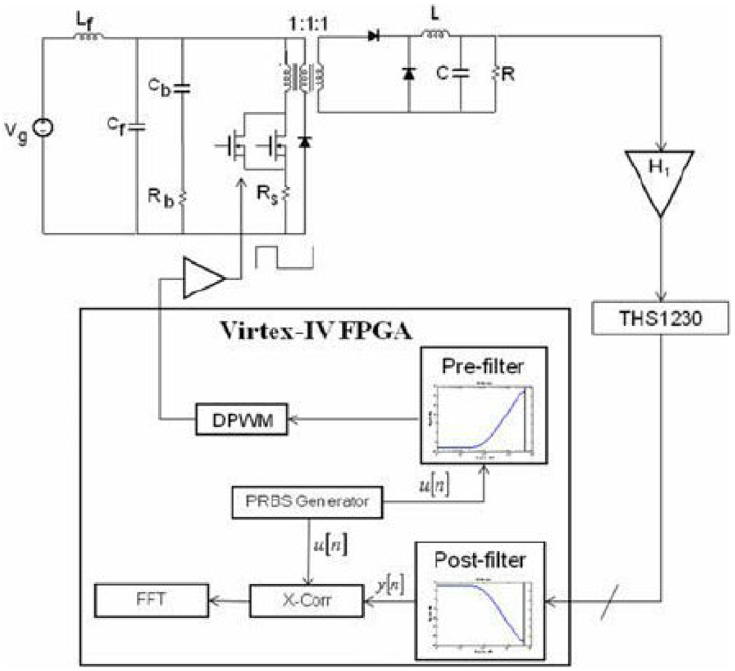
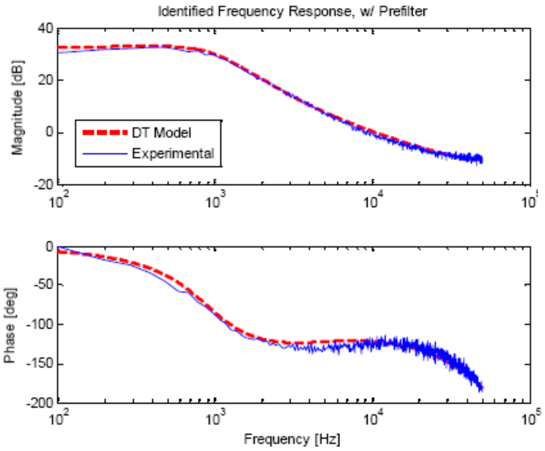


Fig. 21 System identification subsystem including input pre-filter and output post-filter



a. Magnitude and phase of
system identification results

	C=330 μF			C=800 μF		
	Without PF	With PF	DT Model	Without PF	With PF	DT Model
Crossover [kHz]	5.96	8.60	8.81	4.79	4.79	4.83
Phase Margin	39.4°	58.1°	54.7°	33.7°	61.1°	55.4°
-180° Crossing [kHz]	21	49	50	20	49	50
Gain Margin [dB]	26.03	12.34	12.23	27.32	19.66	18.3

b. System stability margins for
two different output filter capacitances

Fig. 22 Experiment results for two different output filter capacitances

The techniques are verified experimentally on a 90 W 50-15V forward converter with FPGA control. In this experiment, only output filter capacitance was varied to force changes in stability margins, possibly indicative of degradation or failure of capacitors on a voltage bus. The method also applies to other variations in the system leading to potential instabilities and can be used to provide early warning to local or system level controllers.

The identification-based condition monitoring technology can be implemented without any additional sensing points other than those required for operation of the converter and with minimal additional digital hardware. However, the accurate correlation between some specific failure modes and the system characteristics and the advanced signal process algorithms for high-frequency noise attenuation are very important for the practicability of this technology.

3.7 Comparison of Different Condition Monitoring Technologies

All the condition monitoring technologies discussed previously are compared in Table 3.

Table 3 Comparison of different condition monitoring technologies for power electronics

Method	Application	Advantages & Disadvantages	Organizations
V_{ce} or R_{on}	Bond wire lift-off	**Advantage:** Well known relationship between V_{ce} or R_{on} and the bond wire lift-off failure **Disadvantage:** Small Vce needs high accuracy	Ford [66, 69] University of Colorado [71]

R_{th}	Solder degradation	**Advantage:** The solder degradation process can be monitored before an end-of-life failure of bond wire lift-off. **Disadvantage:** Junction temperature estimation difficult	Ford [66]
Gate signal	Short-circuit capability deterioration	**Advantage:** More failure i.e. (electrical feature degradation) detectable **Disadvantage:** High real-time requirement	CENIDET[72]
Switch time	Device and gate drive degradation	**Advantage:** Gate drive failure detectable **Disadvantage:** Short switch time measurement needed	GE [67]
Sensor-tech	Bond wire lift-off	**Advantage:** Reliable and accurate **Disadvantage:** DCB Layout modification Increasing complexity and cost	SEMIKRON[68] SIEMENS [74]
System identification	Opto-isolator and output filter capacitor degradation in SMPS	**Advantage:** No additional hardware modification Excellent adaptability **Disadvantage:** Difficult correlation Complicate algorithm	Ridgetop Group[70,73] University of Colorado [71]

4. Summary

As discussed in the previous chapters, a lot of work has been carried out in the power electronics system fault and its condition monitoring area. Some key points can be summarised as follows.

1) Among fault studies of various power electronic systems, the drive systems applied in safety-critical applications are the main concern, in which an unexpected shut-down may lead to severe accident and/or economic losses.

2) By means of adequate protection and/or fault tolerant-control, most power device faults can be safely isolated and there’s no further catastrophic consequence in a system, while shut-down or operation with reduced performance (e.g. over-current, harmonics,

pulsating torque etc.) is inevitable. In some severe circumstances, repute faults can occur, which may be protected by fast acting fuses.

The semiconductor device faults so far treated most often are short-circuit and open-circuit faults. For the sake of condition monitoring for power electronic systems, the effect of device characteristics deterioration, such as V_{ce} and/or dv/dt changes, could be taken into consideration in further study.

3) The fault consequences have been studied in detail in some references. However, most of them focused on the over-current and pulsing torque problems caused by a device fault. Little research has been reported concerning the over-voltage problem caused by a initial device fault, which may damage other healthy devices in a cascaded mode. It is suggested that a further study on this problem could be carried out.

4) Although the existing drive and/or IPM integrated sensors can detect a device fault accurately and rapidly, some fault diagnosis methods based on the features of system current and voltage could be borrowed for the study of condition monitoring technology for power electronics.

5) There are many ‘active’ and ‘passive’ protection techniques adopted in modern power electronic converters. However, a COMPERE technology can further improve the reliability and reduce the requirement of protection. Especially for safety-critical application and high power converter, in which the protection becomes more complex and difficult, the COMPERE technology will be a good solution for these applications.

6) Since it is possible to get the operational information of semiconductor device prior to a fault, the condition monitoring technology is important for the power electronic systems, especially for the safety-critical applications. Comparing with the existing protection and fault-tolerant control techniques which could prevent the system from a catastrophic fault and an unexpected shutdown, the application of condition monitoring in power electronic systems has many advantages including prevention of severe transient, reduction of isolation and re-connection of devices and condition based maintenance, which means better performance at lower cost. It is suggested that an ‘active’ fault-tolerant control method based on the power device fault prognosis be investigated in further study.

7) The condition monitoring technology for power electronics is attracting more and more attention from industry and academic and some research works have been done based on different condition variables. In spite of existing studies, the device failure mechanism, condition variable correlation and efficient condition monitoring method are still needed for more reliable, accurate and low-cost application in order to improve the reliability of power electronic systems.

Reference

Fault consequences

[1] Ronkowski M., Iwan K., Szczesny R., “Simulation of converter-synchronous machine drives in normal and fault operation”, Fifth European Conference on Power Electronics and Applications, 1993, pp. 177-178

[2] A. A. Arkadan and B. W. Kielgas, “Switched Reluctance Motor Drive Systems Dynamic Performance Prediction under Internal and External Fault Conditions”, IEEE Trans. Energy Con., vol. 9, no.1, Mar., 1994. pp. 45-52

[3] D. Kastha and B. K. Bose, “Investigation of fault modes of voltage-fed inverter system for induction motor drive”, IEEE Trans. Ind. Applicat., vol. 30, July/Aug. 1994, pp. 1028–1038

[4] Gameiro, N.S., Marques Cardoso, A.J. , “Analysis of SRM drives behaviour under the occurrence of power converter faults “, IEEE International Symposium on Industrial Electronics, June 2003 pp. 821- 825

[5] J. Klima, “Analytical investigation of an induction motor drive under inverter fault mode operations”, IEE Procedings Electric Power Applications, Vol. 150, No. 13, May 2003, pp. 255-262.

[6] Alcaso, A.N., Marques Cardoso, A.J., “Power Supply Harmonic Filter Behaviour in a Twelve-Pulse LCI Drive System under Power Converter Faults”, IEEE 36th Power Electronics Specialists Conference, 2005, pp. 2893 – 2897

[7] J. Pontt, J. Rodriguez, F. Cáceres, I. Illanes, J. Rebolledo, “Cycloconverter Behavior for a Grinding Mill Drive under Firing Pulses Fault Conditions”, Proceedings of the IEEE Industry Applications Society 2005 Annual Meeting, Hong Kong, Oct, 2005

[8] Zhong Du, Bin Chen, Chong Han, Zhaoning Yang, Wenchao Song, “STATCOM ETO Failure Analysis”, IEEE 5th International Power Electronics and Motion Control Conference,14-16 Aug. 2006

Fault detection and diagnosis

[9] K. Debebe, V. Rajagopalan, and T. S. Sankar, “Expert systems for fault diagnosis of VSI fed ac drives”, in Proc. IAS’91 Conf., 1991, pp. 368–373

[10] Martscotti A., “Neural network approach to static converter faults diagnosis”, Proceedings of the IEEE International Symposium on Industrial Electronics, 10-14 July 1995, pp. 375-380

[11] F. Blaabjerg, J. K. Pedersen, U. Jaeger, and P. Thoegersen, “Single current sensor technique in the dc link of three-phase PWM-VS inverters: a review and a novel solution”, IEEE Trans. Ind. Applicat., vol. 33, Sept./Oct. 1997, pp. 1241–1253

[12] Kenneth Scot Smith, Li Ran and Jim Penman, “Real-Time Detection of Intermittent Misfiring in a Voltage-Fed PWM Inverter Induction-Motor Drive”, IEEE Transactions on Industry Electronics, Vol. 44, No. 4, Aug. 1997

[13] Marques Cardoso, A.J. Mendes, A.M.S., “Converter fault diagnosis in variable speed DC drives by Park's vector approach”, Proceedings of the IEEE International Symposium on Industrial Electronics, 7-11 July 1997, pp. 497-500

[14] R. Peuget, S. Courtine and J. P. Rognon, “Fault detection and isolation on a PWM inverter by knowledge-based model”, IEEE Transactions on Industry Applications, Vol. 34, No. 6, November/December 1998, pp. 1318-1325,

[15] A. M. S. Mendes and A. J. Marques, “Voltage source inverter fault diagnosis in variable speed ac drives, by the average current Park’s vector approach”, in Proc. IEEE International Electric Machines and Drives Conference, 1999, pp. 704–706

[16]Kral C., Kafka K., “Power electronics monitoring for a controlled voltage source inverter drive with induction machines”, IEEE 31st Power Electronics Specialists Conference, 18-23 June 2000, pp. 213 - 217

[17] R. Ribeiro, C. B. Jacobina, E. Silva, "Fault Detection of Open-Switch Damage in Voltage-Fed PWM Motor Drive System”, IEEE Trans on Power Electronics, Vol. 18, No. 2, March 2003, pp 587-593

[18] Lobos T., Sikorski T., Leonowicz Z., “Time-frequency analysis of complex space-phasor in power electronics”, the 21st IEEE Instrumentation and Measurement Technology Conference, May 2004, pp. 2115- 2119

[19] Jayabalan R., Fahimi B., “Monitoring and fault diagnosis of cascaded multiconverter systems in hybrid electric vehicles”, IEEE Conference on Vehicle Power and Propulsion, 7-9 Sept. 2005, pp. 5

[20] Murphey, Y.L., Abul Masrur, ZhiHang Chen, BaiFang Zhang, “A fuzzy system for fault diagnostics in power electronics based brake-by-wire system”, NAFIPS 2005, 26-28 June 2005 pp. 326 -331

[21] H. El Brouji, P. Poure and S. Saadate, "A fast and reliable fault diagnosis method for fault tolerant shunt three-phase active filter”, 2006 IEEE International Symposium on Industrial Electronics ISIE'06, 9-13 July 2006, ETS-Downtown Montreal, Quebec, Canada

[22] J. Pontt, J. Rodríguez, E. Cáceres, I. Illanes and C. Silva, “Cycloconverter Drive System for Fault Diagnosis Study: Real Time Model, Simulation and Construction Power Electronics Specialist Conference, PESC'06, Jeju, Korea, June 2006

[23] Illanes, I., Pontt, J., Rodriguez, J., “Model-Based Fault Diagnosis Applied to 6-pulse Cycloconverter”, IEEE Power Electronics Specialists Conference, 17-21 June 2007, pp. 684-689

[24] Masrur M., Abul Chen, ZhiHang, Zhang Baifang, Lu Murphey Yi, “Model-Based Fault Diagnosis in Electric Drive Inverters Using Artificial Neural Network”, IEEE Power Engineering Society General Meeting, 24-28 June 2007, pp. 1-7

[25] Wang Zhe Guo, Qingding, “The Diagnosis Method for Converter Fault of the Variable Speed Wind Turbine Based on the Neural Networks”, Second International Conference on Innovative Computing, Information and Control, Sept. 2007, pp. 615-615

[26] Zhang Hui, Ren Jing, Zhong YanRu, Chen Jian, “Fault Diagnosis of Power Electronics in Renewable Energy equipment Based on Fuzzy Expert System”, IEEE International Electric Machines & Drives Conference, 3-5 May 2007, pp.864-867

Fault Protection

[27] M.L.Woodhouse, J.P.Ballad, J.L.Haddock, P.A.Rowe, "The control and protection of thyristors in the English terminal cross Channel valves”, International Conference on Thyristor and Variable Static Equipment for Ac and Dc Transmission - IEE Publication No. 205, 1981

[28] Retiere N., Roye D, “Vector based considerations upon inverter protection schemes”, Seventh International Conference on Power Electronics and Variable Speed Drives, 21-23 Sep 1998, pp. 568-573

[29] S. Januszews, M. Kociszewska-Szezerbik, “Some observation dealing with the failures of IGBT transistors in high power converters”, Reliability of Electron Devices, Failure Physics and Analysis Volume 38, Issues 6-8, June-August 1998, Pp 1325-1330

[30] Stefan Januszewski, Krzysztof Zymmer, “Over-current protection coordination in converters with IGBT transistors”, EPE '99, Lausanne

[31] Flemming Abrahamsen, Frede Blaabjerg, Christian Klumpner, “Low-inductive fuses in DC-link Inverter Applications”, PCIM 2000

[32] Musumeci S., Pagano R., Raciti A., Belverde G., Melito A., “A new gate circuit performing fault protections of IGBTs during short circuit transients”, . 37th Industry Applications Conference Annual Meeting, 2002, pp. 2614-2621

[33] Darwish H.A., Taalab A.M.I., Rahman M.A., “Performance of HVDC converter protection during internal faults”, IEEE Power Engineering Society General Meeting, 18-22 June 2006, pp. 7

Fault isolation and tolerant control

[34] Spee R. and Wallance A.K., “Remedial strategies for brushless dc drive failures”, IEEE Tran. Ind Appl., 1990, 26, (2), pp. 259-266

[35] T. H. Liu, J. R. Fu, and T. A. Lipo, “A strategy for improving reliability of field-oriented controlled induction motor drives”, IEEE Trans. Ind. Applicat., vol. 29, Sept./Oct. 1993, pp. 910–917

[36] J. R. Fu, T. Lipo, “A strategy to isolate the switching device fault of a current regulated motor drive”, Conference Record of the IEEE Industry Applications Society Annual Meeting, Vol. 1, 1993, pp.1015-1020

[37] Kastha, D. Bose, B.K., “Fault mode single-phase operation of a variable frequency induction motor drive and improvement of pulsating torque characteristics”, IEEE Transactions on Industrial Electronics, Vol. 41, No. 4, Aug 1994, pp. 426-433

[38]; Mecrow B.C., Jack A.G., Haylock J.A., Coles J., “Fault-tolerant permanent magnet machine drives”, IEE Proceedings-Electric Power Applications, Nov. 1996, pp. 437-442

[39] Silverio Bolognani, Marco Zordan, Mauro Zigliotto, “Experimental fault tolerant control of a PMSM drive”, IEEE Transaction on Industrial Electronics, Vol. 47, No.5, October 2000, pp. 1134-1141

[40] Lianxiang Tang Boon-Teck Ooi, “Managing zero sequence in voltage source converter”, 37th IAS Industry Applications Conference, 2002, pp. 795- 802

[41] A. N. Alcaso, A. J. M. Cardoso, “Asymmetrical Operation of a Twelve-Pulse LCI Drive System With Power Converter Faults”, Proc. of the IEEE Power Electronics Specialists Conference, (PESC’04), CD-ROM, Aachen, Germany, June 20-25, 2004

[42] A. N. Alcaso, A. J. M. Cardoso, “Remedial Operating Strategies for a Twelve-Pulse LCI Drive System”, Proc. of the IEEE International Conference on Industrial Technology (ICIT’03), CD-ROM, Maribor, Slovenia, December 5-8, 2003

[43] B.A. Welchko, T.A. Lipo, T.M. Jahns, S.E. Schulz, “Fault tolerant three phase AC motor drive topologies: a comparison of features, cost, and limitations”, IEEE Transactions on Power Electronics, Vol. 19, No. 4, July 2004, pp. 1108-1116

[44] J. Pontt, J.Rodríguez, “High-Power LCI Grinding Mill Drive under Faulty Conditions”, Proceedings of the IEEE Industry Applications Society 2004 Annual Meeting, 2004

[45] J. Pontt, J.Rodríguez, K. Tischler, N. Becker, J. Rebolledo, “Operation of High Power Cycloconverter-Fed Gearless Drives under Abnormal Conditions”, Proceedings of the IEEE Industry Applications Society, Annual Meeting, 2004

[46] R. L. A. Ribeiro, C. B. Jacobina, E. R. C. da Silva and A. M. N. Lima, “Fault-tolerant voltage-fed PWM inverter AC motor drive systems”, IEEE Transactions on Industrial Electronics, Vol. 51, No. 2, April 2004, pp. 439-446

[47] H. El Brouji, P. Poure and S. Saadate, "Study and comparison of fault tolerant shunt three-phase active filter topologies”, IEEE 5th International Power Electronics and Motion Control Conference, 13-16 August, 2006 Shanghai, P.R.China

[48] P. Ponce, P. Weber, D. Theilliol, S. Saada, “Fault-tolerant power electronics converter: reliability analysis of active power filter”, IEEE International Symposium in Industrial Electronics, Vigo, Span, 4-7 June, 2007

[49] Richardeau F., Mavier J., Piquet, H., Gateau G., “Fault-tolerant inverter for on-board aircraft EHA”, European Conference on Power Electronics and Applications, Sept. 2007, pp. 1-9

[50] G. Sinha, C. Hochgraf, R. H. Lasseter, D. M. Divan, and T. A. Lipo, “Fault protection in a multilevel inverter implementation of a static condenser”, in Proc. IEEE Industry Applications Society Conf., vol. 3, Orlando, FL, 1995, pp. 2557–2564

[51] Shengming Li, Longya Xu, “Fault-tolerant operation of a 150 kW 3-level neutral-point clamped PWM inverter in a flywheel energy storage system”, IEEE Thirty-Sixth Industry Applications Conference Annual Meeting, 30 Sep-4 Oct 2001

[52] B. Francois and J. P. Hautier, “Design of a fault tolerant control system for a N.P.C. multilevel inverter”, in Proc. IEEE International Symp. Industrial Electronics, Italy, 2002, pp. 1075-1080

[53] C. Turpin, P. Baudesson, F. Richardeau, F. Forest, and T. A. Meynard, “Fault management of multicell converters”, IEEE Trans. Ind. Electron., vol. 49, pp. 988–997, Oct. 2002

[54] F. Richardeau, P. Baudesson, and T. A. Meynard, “Failures-tolerance and remedial strategies of a PWM multicell inverter”, IEEE Trans. Power Electron., vol. 17, pp. 905–912, Nov. 2002

[55] Frédéric Richardeau, Philippe Baudesson, and Thierry A. Meynard, “Failures-tolerance and remedial strategies of a PWM multicell inverter”, IEEE Transactions on Power Electronics, Vol. 17, No. 6, November 2002, pp. 905-912

[56] P.W. Hammond, “Enhancing the reliability of modular medium-voltage drives”, IEEE Trans. Ind. Electron., vol. 49, pp. 948–954, Oct. 2002

[57] S. Wei, B. Wu, F. Li, and X. Sun, “Control method for cascaded H-bridge multilevel inverter with faulty power cells”, in Proc. IEEE Applied Power Electronics Conf., vol. 1, Miami, FL, Feb. 2003, pp. 261–267.

[58] Xiaomin Kou, Corzine, K.A., Familiant Y.L., “A unique fault-tolerant design for flying capacitor multilevel inverter”, IEEE Transactions on Power Electronics, July 2004, pp.979- 987

[59]Brando G., Dannier A., Del Pizzo A, “Failure adapted techniques to improve service dependability in systems using fault-tolerant converters”, IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, 2007, pp. 64-69

[60] Alan Mullane, Gordon Lightbody and R. Yacamini, “Wind-Turbine Fault Ride-Through Enhancement”, IEEE Trans. Power System, Vol. 20, No.4, Nov. 2005, pp. 1929-1937

[61] Dawei Xiang, Li Ran, Peter J. Tavner and Shunchang Yang, “Control of a Doubly Fed Induction Generator in a Wind Turbine During Grid Fault Ride-Through”, IEEE Trans. Energy Conversion, Vol. 21, No. 3, SEPTEMBER 2006, pp. 652-662

[62]http://www.semikron.com/internet/webcms/objects/pdf/semidriver_semikron_IGBT_driver_electronics.pdf

[63] http://www.semikron.com/internet/webcms/objects/a_part/A06_det_eng.pdf

[64] D. Tournier JL. et. al., “Evaluation of Thermal and Electrical Behaviour of Fuse in case of paralleling and/or high Requirement”, EPE 99, Lausanne

[65] Grbovic, P.J., ”The Gate Drive Requirements for New Generation of High Current Low Voltage IGBTs Employed in Motor Converter”, Power Electronics and Drives Systems, International Conference on PEDS, 16-18 Jan. 2006, pp. 687 – 693

Condition Monitoring Technologies for Power Electronics

[66] Sankaran et al. (Ford Motor Company), “Integrated power module diagnostic unit”, US Patent, Number: 5528446, June 18, 1996

[67] Ryan, Michael John (General Electric Company), “Method and apparatus for power electronics health monitoring”, US Patent, Number: 6405154, June 11, 2002

[68] Lehmann, Netzel, Herzer and Pawel, “Method for Electrical Detection of Bond Wire Lift-off for Power Semiconductor”, IEEE ISPSD, 2003

[69] Xiong Y., Cheng X., Shen Z.J., Mi C., Wu H., Garg V., “A Prognostic and Warning System for Power Electronic Modules in Electric, Hybrid, and Fuel Cell Vehicles”, IEEE Industry Applications Conference, Oct. 2006, pp.1578 -1584

[70] Judkins, J. B., et.al., “A prognostic sensor for voltage-regulated switch-mode power supplies”, IEEE Aerospace Conference, March, 2007

[71] M. Jeffrey; D. Arseny, S. Mariko, Z. Regan, M. Dragan, “Online Health Monitoring in Digitally Controlled Power Converters”, IEEE Power Electronics Specialists Conference, 17-21 June 2007, pp. 112 – 118

[72] Rodriguez M. A., Claudio A., Theilliol D., Vela L. G., “A New Fault Detection Technique for IGBT Based on Gate Voltage Monitoring”, IEEE Power Electronics Specialists Conference, 17-21 June 2007, pp. 1001-1005

[73] Judkins Justin, Goodman Douglas, Vonhout Sonia, “Practical considerations for power electronics system and actuator prognostics implementations”, IEEE Autotestcon, 17-20 Sept. 2007, pp. 553-560

[74] Farokhzad, Babak (SIMENSE Company), “Method for early failure recognition in power semiconductor modules”, US Patent, Number: 6145107, November 7, 2000