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Review on fault-diagnosis and fault-tolerance for DC–DC converters

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Abstract: The DC–DC converters operate extensively in a variety of industrial applications such as electric vehicles, renewable energy systems, aerospace applications, consumer electronics (smartphones, laptops, etc.) and energy storage solutions. The reliability of the DC–DC converters is of a greater significance. The research endeavours made in enhancing the reliability of the DC–DC converters are still very limited and dispersed. Due to the rapid growth in semiconductor technology, the DC–DC converters have an endless number of topologies, with various operating principles and functionalities. Enhancement of the reliability of all types of DC–DC converters is still a challenging task. Power switches are the most fragile components in converter circuits, which inherently fall prey to the faults occurring in the system. Hence, there is always a requirement to take appropriate remedial measures to deal with all kinds of faults. Further, in order to detect the occurrence of fault a fast fault-diagnosis and fault-tolerant strategies in the DC–DC converters is mandatory and the same has to be embedded in the converter for safety purpose. In view of the importance of the same, the fault-diagnostic algorithms and fault-tolerant strategies developed in the literature, by various researchers are furnished in a single document after conducting an exhaustive review.

1 Introduction

The DC–DC converters are extensively used to convert DC voltages efficiently from one level to another. The system reliability of these converters is very critical because even a single failure in the components of the converter will lead to defect in the entire system. In some crucial practices, the DC–DC converters must be capable of operating continuously even under faulty situations. One important application is the use of the DC–DC converters in the medical industry [1]. Another critical application is in a brake-by-wire system in the control of a car [2]. The loss of output voltage of these converters can have serious effects. To improve reliability, one popular method is the parallel redundant operation of circuits or components. However, this method is a costly option because one or more additional converters are connected in parallel to achieve the redundancy in case of failure of main converter. Therefore, reliability is assured only if appropriate fault-diagnosis and fault-tolerant methods are incorporated for the most vulnerable fault subjected components like capacitors and semiconductor switches, which permit to quit the system action in time.

Semiconductor switches and the aluminum capacitors are the two most important elements in the DC–DC converters. More than 34% of breakdowns and malfunctions are recorded due to the soldering joint failures and semiconductor failures [3, 4] and 50% is due to the aluminum electrolytic capacitors [5]. The DC–DC converters are constantly exposed to surplus stress factors such as thermal, electrical and physical stress as any other energy conversion system in power electronics. The feasible faulty components and their stress distributions involved in power electronics are shown in Fig. 1 [6, 7]. Figs. 1*a* and *b* show the source of stresses and the root cause for failure in power electronic components.

The combination of all these stress factors prompts early deterioration of converter components, thus reducing the overall lifetime of the DC–DC converters. Power semiconductor switches especially insulated gate bipolar transistor (IGBT) and meta-oxide semiconductor field-effect transistors (MOSFETs) comprise the most vulnerable components demonstrating the higher failure rates in the DC–DC converters. Power switch faults are mainly classified into open circuit faults (OCFs) and short circuit faults (SCFs).

The OCF occurs due to driver failure, which in turn dislodges the bonding wires during thermic cycling, by an SCF induced in rupture or ageing [8–16]. OCF does not create a serious problem to the core components of a converter that stands healthy and the energy transfer to load is commonly accomplished even in deteriorated state. Nevertheless, if such faults are sustained for long duration, additional damage might be experienced by the converter and in utmost cases, leads to absolute standstill. Hence the identification and detection of such failures are recommended to prevent further damage in power converters.

The SCF occurs due to either an intrinsic failure (caused by avalanche stress/overvoltage or temperature overshoot) or an improper gate-driver (caused by driver circuit malfunction or auxiliary power supply failure). SCFs, which are very severe faults in the converter that may cause further damage to additional components in the converter circuit and it, should be isolated carefully and quickly [17–19]. At present SCF protection is a basic practical integrated segment in gate-driver circuit [20, 21]. Nevertheless, the cost is high and frequently employed in high power inverter applications. Many fault diagnostic algorithms, basically reject the capabilities for SCF diagnosing. Several disputes are furnished for not examining the SC faults in the diagnosis of switch faults:

- A fast reaction of control structure is required for SC faults so that faults will segregate and prevent additional destruction to the converter.
- SC faults are frequently accompanied by OC faults, consequently, separate actions are carried out through hardware.

The basic aim of fault diagnosis and fault tolerance is to detect and to identify any kind of failures at the initial stage in order to avoid shutdowns and accordingly plan in advance a maintenance action. Developing fault diagnosis is the first step for the DC–DC converters, which prevents the catastrophic failures for the semiconductor switches in the system. The fault-tolerant strategies allow uninterrupted operation of converters, though the power switches are in faulty scenarios. Generally, fault-diagnosis strategy comprises of three tasks [22–24]:

- Fault detection
- Fault identification
- Fault isolation.

During the fault detection period, a fault alarm is activated but the faulty element and the relative fault mode remains unknown. During the fault identification period, the faulty component and corresponding fault mode that has given rise to fault alarm are identified. Generally fault detection and fault identification are called as ‘fault-diagnosis’, which is used to recognise the nature, location and type of the fault [25–27]. Such implementations rely on the abilities of the supported fault-diagnostic variables and fault-diagnostic algorithms. The fault-tolerant operation (FTO) consists of fault isolation and fault reconfiguration is the next counter measure, which is always based on hardware redundancy design and corresponding fault-tolerant control. The fault isolation is also known as remedial action, which is used to segregate the faulty devices and redesign the converter for continuous and safe operation.

Due to the growing importance and extensive research surroundings the fault diagnosis and fault tolerance of power converters, the authors feel that this is the right time to put forth a systematic perspective on the status of fault diagnosis and fault tolerant research. Thus, this paper introduces the most applicable advancements attained so far regarding the improvements of fault diagnostic algorithms and fault tolerance strategies suitable for the DC–DC converters. Special significance is given in this paper to the diagnostic techniques concentrating on OC and SC faults in non-isolated and isolated converter power switches.

2 Fault diagnostic algorithms

There is no commonly selected classification scheme developed so far for the fault diagnostic algorithm, pointed towards semiconductor faults. However, it is feasible to set up a classification scheme by taking the data required into consideration to execute the fault diagnostic algorithm. The simplified classification scheme is depicted in Fig. 2.

Fault signatures based on converter variables, which are sensed in real time are used in most fault diagnostic algorithms for the DC–DC converters. The algorithms, in this paper are classified as ‘signal processing-based algorithms’ because the fault diagnostic action is completely carried out by the analysis of fault signatures, which is taken out from the converter variables.

Other diagnostic algorithms with better robustness against false faulty alarms have been developed recently. The algorithms in this paper are classified as ‘model-based algorithms’, because the diagnostic action is aided by pre-established converter model. These algorithms use a detailed knowledge of system and are normally based on parity equations, residual generations using parameter estimation or state observers. Model-based algorithms are based on artificial intelligence techniques, such as artificial neural networks, fuzzy logic, or machine learning, to establish a trained system that once trained, can determine the specific faults. The following segments give further insight of each of the previously mentioned methods.

2.1 Fault diagnostic algorithms based on signal processing

Signal processing techniques occupy a huge part in the literature pointed towards diagnosing switch faults in converters. Certain selected fault signatures are identified as fault signatures in these algorithms, which are commonly used for regulation purposes. Capacitor voltage or DC bus current are the commonly used control variables for the fault diagnosis. As depicted in Fig. 3, either the converter output, input or internal variables are detected and treated with signal processing techniques. Signal processing techniques are extremely reliant on selected diagnostic variables. The implementation of signal processing fault diagnostic algorithms is quite easy, and there is no need for finding previous knowledge of converter parameters.

Regrettably, signal processing diagnostic algorithms may not be fully successful, because false fault alarms may be activated when the converter is mandatory to serve under extremely dynamic conditions with significant switching frequencies or oscillations in load levels, leading to false diagnostic results.

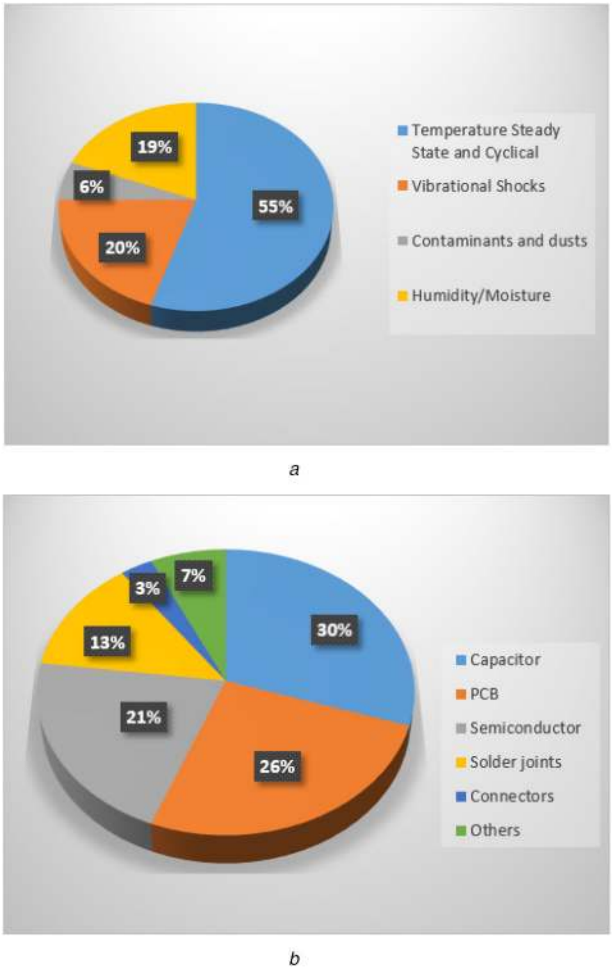

Fig. 1 *Stress distributions and failure in power electronic systems [6, 7]*
(a) Source of stress distribution, ***(b)*** Failure root cause distribution

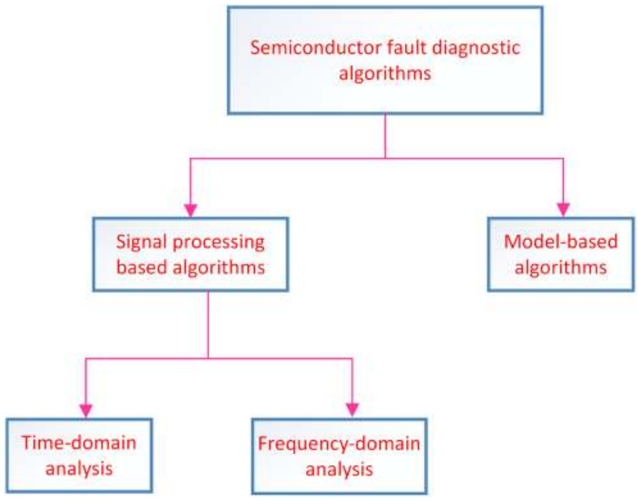

Fig. 2 *Categorisation of fault diagnostic algorithms for semiconductor switches in DC–DC converters*

Based on diagnostic parameters measured in frequency or in time domain, signal processing algorithms can be again categorised as frequency domain [28–34] and time domain analysis [35, 36].

2.1.1 Signal processing algorithms based on time domain: These algorithms execute an examination of variables in time domain selected for diagnosis purpose. Such examinations may depend on different methodologies including trend analysis,

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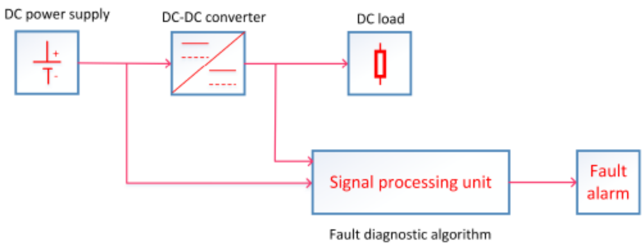

Fig. 3 *Implementation of fault diagnostic algorithm based on signal processing techniques*

magnitude analysis, statistical moments, mean values assessments, limit evaluations etc.

Based on time domain examination, definite fault diagnostic algorithms are developed to meet very particular requirements of a few converter topologies. Accordingly, for other converter topologies the extrapolation of these algorithms may be more challenging or even unattainable.

The time domain analysis in fault diagnostic algorithms mainly differs on the mythologies used and the adopted diagnostic variables to take out the suitable fault signatures. For the decision-making task the requirement of thresholds also relies on the construction of diagnostic algorithms. During the time of choosing diagnostic variables, researchers choose diagnostic variables which satisfy the following conditions:

- Additional sensor requirements are eliminated or at least minimised.
- Through the diagnostic variables, many fault signatures are implemented in proper recognition of definite faulty components or fault modes.

Earlier, the diagnostic tools employing time-domain analysis record the abnormal deviations in the measurement of converter variables using the input current peak to integral ratio [22], or the numerical moments of converter currents and voltages [37] to investigate the OC faults in converter topologies. These algorithms' implementation is absolutely simple and depends on simple analogue circuits to identify the switch faults. Nonetheless, the recognition of these algorithms is completely confirmed for FB-ZVS the DC–DC converters [22] and the cascaded converters [37], the algorithms' nature facilitates the execution in other converter topologies too by using such diagnostic strategies.

The DC bus capacitor voltage balance in multilevel DC–DC converter, is a condition in which the capacitor voltage is continuously monitored to identify the switch faults [21]. Although the algorithm is simple, but the simple act of investigation of DC bus capacitor voltage in most situations does not furnish precise information about the converter faulty components. This algorithm is implemented on a three-level flying capacitor DC–DC converter constitutes the comparison of flying capacitor voltage with two unique thresholds. Based on the comparison result, it is possible to subject a fault alarm, and at any time it is possible to detect the faulty component. The merits of the proposed method include:

- Easy implementation and economical.
- Response time is fast, that is very crucial in shoot-through and short circuit protection.
- No additional components are required; therefore there is no effect on normal converter performance and operation.
- Ability to identify multiple faults.

The transformer winding voltages are widely preferred as diagnostic variables in isolated DC–DC converter topologies. The examination of winding average voltage values have been selected to identify and detect the OC switch faults in dual active bridge (DAB) DC–DC converters using galvanic isolation [38]. The merits of this proposed method are

- Implementation cost is low.
- Fault detection speed is fast.
- Increases the reliability of DAB.

Similar fault diagnostic algorithm, based on transformer primary side voltage in isolated phase shifted full bridge (PSFB) converter is used as a diagnostic criterion to identify the OC faults, which can be easily obtained by adding an auxiliary winding [39]. This algorithm requires the establishment of an empirical threshold value. The OC faults can be identified by comparing the diagnostic variable amplitude to a predefined threshold value. After finding the faulty switch, the PSFB converter is redesigned into an asymmetrical half-bridge converter to carry the continuous operation. The following are the advantages of the proposed method:

- The implementation cost of the diagnostic circuit is very low because only a few components are added.
- The diagnostic results are correct because the detection circuits are average value based.
- The converter can reconstruct its topology and maintain the continuous DC power to the critical load when the OC fault occurs in any switch. Therefore, the reliability of the system can be increased greatly.
- Before and after the fault, the voltage stresses of the switches are steady and the voltage stresses of the rectifier diodes only have a slight increase.

In non-isolated single-ended converters, signs of inductor current slope are used as diagnostic variable to identify the power switch faults [20]. In this proposed method, two fault detection algorithms (FDAs) are working together to detect both OCF and SCF. The expected inductor current slope sign measures the differences between the measured inductor current slope sign, resulting in ensuring reliable and fast diagnostic results. The merits of the proposed method are

- Fault detection speed is relatively fast and robust.
- Low cost and economical because no additional sensors are required.

Accordingly, based on the principles of operation and on the same diagnostic variable, a series of fault diagnostic algorithms have been developed with small developments in the effect of original fault diagnostic algorithms. An FDA which can detect and identify the type of faults (SCF or OCF) is proposed in [40]. This validation allows for distinguishing SC and OC faults which were not accessible in the prior algorithm [20]. The switch command and sign of inductor current slope are used to identify the switch faults. The proposed method has two subsystems (FDA1 and FDA2) and works in parallel. FDA1 is fast and precisely compares the measured values of inductor current's slope sign and the switch command. FDA2 is robust and during a switching period of normal operation of converter, with controlled duty cycle, the inductor current cannot always decrease or increases. In OCF, after the fault detection the faulty switch can be restored with a redundant switch, whereas in SCF the reconfiguration of the converter will happen only after the faulty switch is disconnected [40].

A comparison between the delayed version of gating signals and the sign of the inductor current slope is used as fault diagnostic to identify both OCF and SCF in non-isolated DC–DC boost converter [41]. However, still the same approach can be applied to any other non-isolated single switch DC–DC converters including buck, buck–boost, Cuk, SEPIC and dual SEPIC converters. By this proposed method OCF can be detected in 14 µs and the SCF in 18 µs. The converter operates at a switching frequency of $f_{SW} = 15\,\mathrm{kHz}$ (corresponding switching period $T_{SW} = 67\,\mu s$). The ratio between detection time and switching period for an OCF and SCF are 0.2089 (14 µs/67 µs) and 0.0012 (18 µs/67 µs), respectively. The merits of this methods are

- Additional voltage or current sensors are not required.
- OCF and SCF can be detected in less than one switching period.

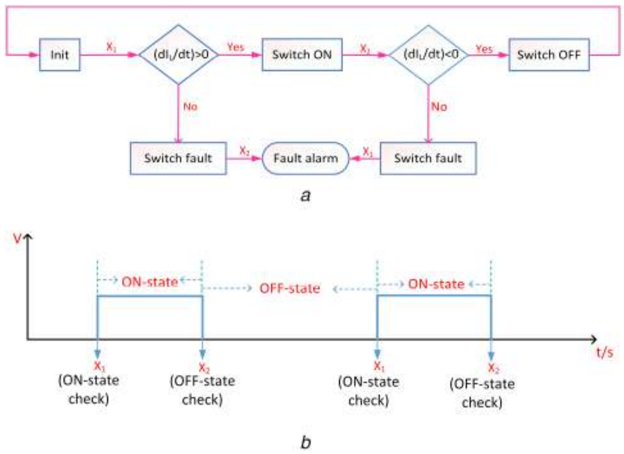

Fig. 4 *Flowchart and gating signal [42]*
(a) State machine flowchart implementation based on inductor current slope, ***(b)*** Gating signal *v* and moments used to manage the changeover among machine states

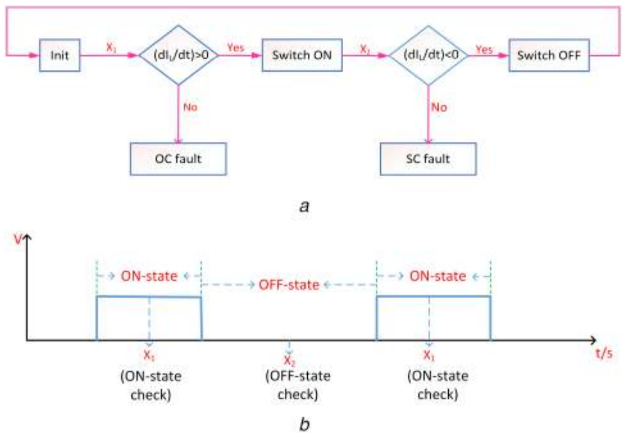

Fig. 5 *Flowchart and gating signals [43]*
(a) Flowchart accompanied by the state machine, ***(b)*** Gating signals *v* and instants

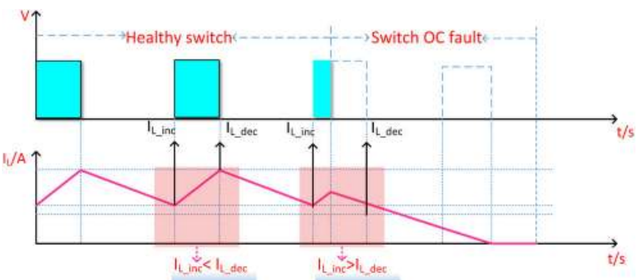

Fig. 6 *Inductor current evolution in non-isolated unidirectional buck converter, under healthy and faulty conditions*

Same strategies based on similar diagnostic principles, but with less computational efforts were developed in [42, 43]. In this proposed method, a single algorithm (instead of two parallel algorithms in [20]) is used in order to detect efficiently the faults in the switches. Depending on inductor current slope sign, the switch OCF [42] and switch OCF and SCF [43] are detected in these proposed methods. The calculated inductor current is used in two ways. One is for fault detection and the other is for control purpose. Therefore, no additional sensors are required. As a result, the cost reduces and the reliability of the overall system continues. In short by the examination of inductor current slope sign, the investigation of switch health condition is executed.

In the initial iteration, the fault diagnosis is obtained, but there is no conclusive result about the switch OCF or SCF as depicted in Fig. 4*a*. x_1 and x_2 denote the transition between states, takes into report that the data provided by gating signal *v*. At the end of gating signal *v*, every transition is activated as shown in Fig. 4*b*.

The fault identification problem in the previous algorithm [42] will be made better by choosing different instances for changeover among machine states. The flow chart accompanied by the state machine is shown in Fig. 5*a* [43], while the gating signal *v* and instants are shown in Fig. 5*b*.

The proposed fault detection method (FDM) in [43] can identify the switch faults in less than one switching period, generally around 100 ms in medium power applications. The sign of the inductor current slope is used as diagnostic criteria. The FDM can detect SCF and OCF for boost converters used in PV systems.

To meet the specifications of practical applications, certain optimised fault diagnostic strategies are developed. The amplitude of PV variables (power, voltage and current) with low-frequency oscillations provides satisfactory information to identify switch faults. An OCF-diagnosis and fault-tolerant scheme for a three-level boost converter are proposed in [44]. The output dc-link capacitor voltage and control variables used for maximum power point tracking are used as fault diagnostic variables. The merits and demerits of the proposed method are stated below.

Merits:

- This fault-diagnostic method identifies any open circuit power switch faults and provides the exact location.
- Only a few components are added to three-level boost converter for fault-tolerant reconfiguration.

Demerits:

- Nearly 30% of the power is less from the reconfigured converter when compared with the original converter.
- Higher voltage stress on the remaining healthy IGBT switches, because of dc-link capacitor voltage unbalance.

Fault diagnostic algorithms depend on the estimation of inductor current amplitude which is a powerful group in the time domain. The inductor current magnitude is sampled at critical instances in order to create a logical relationship between sampled values. This algorithm best suits for single-switch converters [45]. Inductor current absolute values are compared with sampled values at three peculiar moments which permits for detection of faults in converter switches.

With the help of gating signals information, several approaches are developed based on sampling the magnitude of inductor current at falling and rising edges. Minute changes in the fault diagnostic algorithms were made and it was successfully implemented in non-isolated bidirectional DC–DC converters [46], multi-input DC–DC converters [47], interleaved DC–DC converters [48], and in non-isolated unidirectional DC–DC converters [49]. The logical relationship between the current magnitude measured at falling and rising edges of gating signals are concerned by OCFs in converter switches as depicted in Fig. 6. The advantages of the proposed methods are

- Additional sensors are not required for fault diagnosis, because converter control variables are used.
- Minimum computational efforts required.
- Easy control and economical.

Current magnitude provides sufficient information for fault diagnostic in the parallel-connected single active bridge (SAB) DC–DC converters. In this method the output current of converter is sampled at pre-established stages, permitting for detecting the OCF and even recognition of module accommodating the faulty switch in less than two switching periods [50]. The healthy operation of converter is shown in Fig. 7*a*. The decrement in one of the peaks of output current of converter due to a single OCF is shown in Fig. 7*b*.The following are the merits of the proposed method.

- By using only one current sensor in output, the proposed fault diagnosis method detects the type and exact location of the fault in no more than two switching periods.

- The quality of the output current remains unaffected under faulty situations.

The simple action of analysing the current amplitude of the converter might indicate inefficient in more complex converters. To accommodate the requirements in complex converters, more detailed fault diagnostic algorithms have to be developed. Addressing to the same, based on the current derivative, a fault diagnostic algorithm is developed which can detect and identify the OCFs in interleaved DC–DC converters [51]. In this proposed method comparison between the expected derivative sign and the measured derivative sign on each interval is considered. Each switching period consists of six similar intervals as shown in Fig. 8. The imbalance in the derivative sign happens at interval (*d*) of period T_{SW_2} as shown in Fig. 8. The merits of this proposed method are

- This method is robust to transients and current imbalance between phases.
- No additional sensors are required.

The magnetic component voltage (transformer or inductor) is utilised as fault diagnostic criteria for PWM DC–DC converters operating in continuous conduction mode [52]. Based on the switch gate-driver signals and real time voltage measurement, characteristics of switch SCF and OCF are easily identified. From the control circuit, the gate driver signals can be obtained and by using an auxiliary winding in magnetic core, the magnetic component voltage can be measured. The combined signals will be used to detect the switch faults. The proposed method is preferable than the traditional methods [20–22, 39, 44, 45] in terms of detection time, size and cost.

A different algorithm, based on magnetic component voltage is used as fault signature to detect OC and SC faults that occur in a boost converter switch [53] is developed to increase the fault diagnostic efficiency for converters performing in discontinuous conduction mode. The inductor voltage is compared with the switching function at every switching period in this proposed method. With this action, the abnormal inductor voltage generated a fault alarm only in each fault condition. This algorithm can detect switch faults within two switching periods. The advantages of the proposed method are

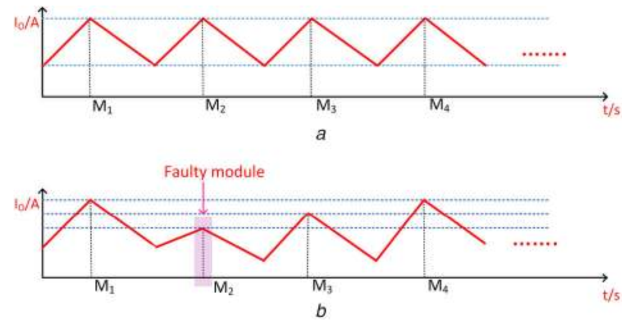

Fig. 7 *Parallel connected single active bridge output current under various conditions [51]*
(a) Healthy converter operation, ***(b)*** Faulty operation, fault in module 2

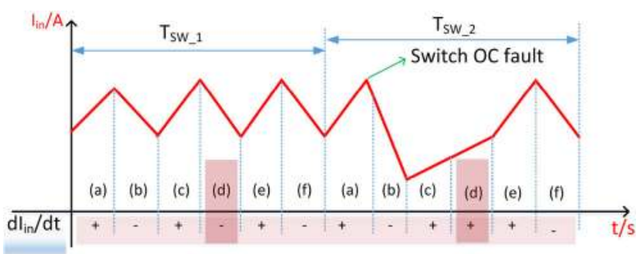

Fig. 8 *Development of input current in time for 3-phase interleaved boost converter in two switching intervals. Highlighted the OC fault by shadowed portions during the* T_{SW_2} *period [51]*

- Easy to detect switch OC and SC faults.
- Low cost to implement.

Transformer primary voltage and dc-link current are considered as fault diagnostic criteria to detect the switch SCF for PSFB DC–DC converter [54]. Once the switch SCF occurs, a high current pulse exceeds a predefined threshold value, selected empirically must appear at the dc-link side. If the dc-link current exceeds the threshold value then switch SCF occurs. Within one switching period, the faulty switch will be identified and the faulty PSFB converter is reconfigured into an asymmetrical half-bridge converter. The merits of this method are

- The diagnostic results are fast and exact.
- Continuous DC power will be provided by the converter to the critical loads when the SCFs occur in any switch. Therefore the reliability of the converter can be greatly increased.
- Voltage stresses of the diodes and the switches are maintained constant, before and after the fault.
- Remedial system cost is low because only one diode and switch are added.

The diode voltage is selected as fault diagnostic variable to determine the SCF and OCF of the diodes and switches in non-isolated DC–DC converters [55] including boost, buck, and buck–boost. The gate driver signals and diode voltage are handled in the simple logic circuit to develop indicators for diode and switch faults. To implement this algorithm, at least one voltage sensor is required for capturing the diode voltage and is responsible for fault detection in less than one switching cycle. Some of the important merits of this method include:

- Low cost.
- Fast detection capability.
- Simplicity.

A comparison between the voltage measured at each input sub-module and the voltage measured at each sub-module output is adopted as fault diagnostic criteria in modular multilevel DC–DC converters to detect the fast OCFs [56]. The advantages of the proposed method are

- This algorithm proposes a fast fault location.
- Simple and effective diagnostic method.
- Avoids complex mathematical operations.
- This algorithm minimises the fault diagnostic time.

To diagnose the switch faults, a Rogowski coil sensor is proposed in [57–60] which captures the inductor current derivative, and it contains sufficient information about switch faults in non-isolated single switch DC–DC converters. By using the Rogowski coil sensor output and the gate driver signal, the switch OCF and SCF could be detected in less than one switching cycle. Moreover, a new approach for capacitor lifetime monitoring is proposed, in which the Rogowski coil sensor voltage is employed for calculating the capacitor ESR. The advantages of this method are

- Linear response for a wide range of frequencies.
- Low cost.
- Compactness.
- Higher accuracy and reliability.

In three phases non-isolated interleaved bidirectional DC–DC converter second-order derivative of the converter is used to diagnose the switch faults [61]. By analysing the magnitude of second-order discrete time derivative of converter low voltage side current, the fault detection can be obtained. Along with the information of second-order discrete time derivative, the gating signals are also used to detect the faulty switch.

OCF diagnosis in interleaved DC–DC boost converters can be identified through the time domain analysis of reference current error waveform [62]. The unusual increase of reference current

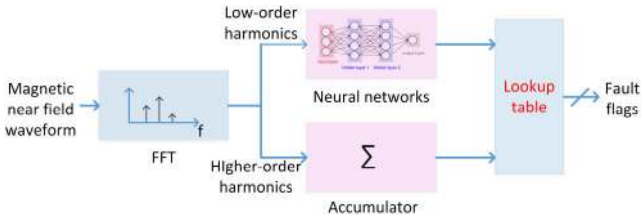

Fig. 9 *Spectral evaluation of MNF waveform fault diagnostic algorithm*

Table 1 Comparison of non-isolated converter signal processing-based fault diagnostic algorithms

Ref.	Diagnosis criterion	Application	Type of fault	Switching frequency	Maximum diagnostic time (T_{d_max})	Diagnosis speed	Cost
[37]	numerical/statistical moments of converter currents and voltages	cascaded buck converter, most DC–DC converters	OC, SC	20 kHz	$8T_S$	slow	low
[20]	inductor current slope sign	non-isolated single switch converters	OC, SC	15 kHz	$2T_S$	relatively fast	medium
[44]	PV variables (current, power and voltage)	DC–DC converters used in PV MPPT applications	OC	5 kHz	$2T_S$	relatively fast	low
[40]	inductor current slope sign	non-isolated single switch converters	OC, SC	15 kHz	$2T_S$	relatively fast	medium
[45]	inductor current evolution	non-isolated single switch converters	OC, SC	40 kHz	$1.5T_S$	relatively fast	low
[41]	inductor current slope sign	non-isolated single switch converters	OC, SC	15 kHz	T_S	fast	medium
[42]	inductor current slope sign	non-isolated single switch converters	OC	15 kHz	T_S	fast	medium
[43]	inductor current slope sign	non-isolated single switch converters	OC, SC	15 kHz	T_S	fast	medium
[51]	input current derivative sign	interleaved boost converters	OC	1 kHz	$2T_S$	relatively fast	low
[48]	inductor current evolution	interleaved boost converters	OC	1 kHz	T_S	fast	low
[52]	magnetic component voltage	buck converter	OC, SC	48 kHz	T_{SW}	fast	low
[55]	diode voltage	non-isolated single switch DC–DC converters	OC, SC	50 kHz	$1.5T_S$	relatively fast	low
[57]	Rogowski coil voltage	non-isolated single switch DC–DC converters	OC, SC	50 kHz	T_S	fast	low
[62]	reference current error	interleaved boost converters	OC	5 kHz, 10 kHz	T_S (validated through simulation)	fast	low
[61]	low-voltage side current second order derivative	interleaved bi-directional converter	OC	5 kHz, 10 kHz	$2T_S$ (validated through simulation)	relatively fast	low
[70]	MNF	buck converters	OC, SC	24 kHz	$>2T_S$	slow	high

error furnishes good fault indicators that permit the identification of power switch OCFs.

2.1.2 Signal processing algorithms based on frequency domain: The algorithms handling signal processing techniques for fault diagnosis in the frequency domain does not have much attention when compared with signal processing techniques based on the time domain, for the improvement of reliability in DC–DC converters. A large number of training sets and weighty computational efforts are required to detect the switch faults which constitute difficulty in implementation of such algorithms.

The magnetic near field (MNF) is utilised as diagnostic criteria to identify the OCFs in buck and PSFB converter [63–70]. By using a field probe, the MNF of the converter is captured. The information from MNF is extracted by using the computation of fast Fourier transform. The spectral analysis is carried out on an accumulator and neural networks to diagnose faults in the converter switches as shown in Fig. 9. The use of MNF signatures brings some special features which are stated below.

- Current and voltage sensors are not required.
- The MNF probe is used to capture the magnetic fields near the converters.
- The power stage and the diagnostic system are isolated naturally.
- The magnetic fields emitted from distinct sources can be grabbed by using one MNF probe and the measured waveforms consist of ample information for diagnosis.

2.1.3 Performance of signal processing based algorithms: A general outline of performance levels based on signal processing techniques of each fault diagnostic algorithm is compiled in Tables 1 and 2 for non-isolated and isolated converters, respectively from different aspects including diagnosis criterion, application, type of the fault, diagnosis speed, switching frequency, and cost. The data depicted in Tables 1 and 2 is based on the compilation and analysis of data which is available in the literature. T_{d_max} indicates the maximum fault detection time which determines the maximum time required to identify and detect the faulty switch. It should be eminent that detection speed is treated as

Table 2 Comparison of isolated converter signal processing based fault diagnostic algorithms

Ref.	Diagnosis criterion	Application	Type of fault	Switching frequency	Maximum detection time	Diagnosis speed	Cost
[38]	transformer windings voltages	dual-active bridge converters	OC	20 kHz	$1T_S$ (validated through simulation)	fast	low
[39]	transformer primary voltage	full bridge converters	OC	50 kHz	$100T_S$	slow	low
[21]	flying capacitor voltage	half-bride three-level converters	OC, SC	200 kHz	$<1T_S$	fast	low
[50]	converter output current	parallel-connected single active bridge converters	OC	10 kHz	$2T_S$	relatively fast	low
[53]	magnetic component voltage	half-bridge converter	OC, SC	25 kHz	$2T_S$	relatively fast	low
[56]	sub-module output voltage	modular multilevel DC–DC converter	OC	4 kHz	T_S	fast	medium
[54]	transformer primary voltage and DC-bus current	PSFB	Oc	50 kHz	T_S	fast	high
[70]	MNF	PSFB	OC, SC	135 kHz	$>2T_S$	slow	high

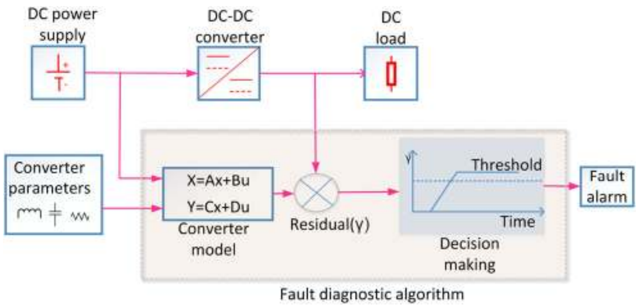

Fig. 10 *Development of model-based fault diagnostic algorithm for DC–DC converters*

slow, relatively fast, and fast, for detection delays more than two switching periods, up to two switching cycles and less than one switching period, respectively. Expenses of the recommended diagnosis circuitry and additional sensors for fault detection are treated as a criterion to analyse the techniques from the cost point of view. Based on this principle, the methods are classified into low, medium, and high-cost categories.

2.2 Model-based fault diagnostic algorithms

From the last few years, model-based fault diagnostic algorithms become very popular for DC–DC converters, because the execution of these algorithms requires significant computational efforts.

The challenges faced by signal processing based algorithms are overcome by the model-based algorithms, as these algorithms have the features of effectiveness and flexibility in determining SCF or OCF, independent of converter parameters (load level, switching frequency, conduction modes etc.). In the model-based fault diagnostic algorithms, the stability against non-linearity such as load transients or noise is also improved.

Model-based algorithms use analytic knowledge of system and generally based on state observers, parity equations, or residual generation using parameter assessment [71–76]. For the advancements of the model-based algorithms past knowledge of converter specifications (capacitances, inductances, parasitic resistances) is crucial.

Model-based algorithms depends on artificial intelligence-based methods, such as fuzzy logic, machine learning or artificial neural networks to design an intelligent system that once trained, will detect specific faults [77–83].

Generally, model-based algorithms compare the observed response of the converter (determined by the converter output signals such as current or voltage) with expected converter response as shown in Fig. 10.

Based on accurate information about converter topology, converter input signals and the converter parameters; the converter performance is emulated and modelled with utmost care. By comparing the modelled response with converter response residuals are generated.

The information furnished by residuals may be handled by different strategies, similar to signal processing based algorithms. A decision-making block, allows extraction of important information that gives a hint about the faulty switch which disturbs the converter operation. In model-based fault diagnostic algorithms, state observers are the commonly adopted tools to measure the state of DC–DC converters. One of those tools is the sliding mode observer (SMO).

An OCF detection method for modular multilevel converters (MMC) based on SMO is proposed in [75, 84]. SMOs were originally developed for MMCs, but they can further be used in associated DC–DC converter topologies. No additional sensors are needed in this method because this method uses the cell capacitor voltages and converter arm currents as inputs, which are already accessible as measurement inputs to the control system. The faulty switching device and also the faulty cell can be easily identified by using this method. When the observed circulating current deviates from the measured circulating current, then an OCF is detected in the power semiconductor device. This method can locate and detect an OCF of the power switch or a gate driver failure in <50 ms. Nonetheless, this method is not satisfactory for isolation and detection of SCF, due to fats response demand (10µs). The merits of the proposed methods are

- Fast and effective in identifying switch faults.
- Robust against measurement and parameter uncertainty error.
- This method is independent of the operating frequency of MMC.
- OC faults can be located in a very short duration of time.
- This method is easy and simple with only one SMO equation and no additional circuits are required.

Based on the modulation of particular DC–DC converter, the inductor current derivative is applied to provide analytical current emulator model for fault identification and diagnosis in boost

Table 3 Model-based fault algorithm features

Ref.	Diagnosis criterion	Application	Type of fault	Switching frequency	Maximum detection time	Cost
[75]	sliding-mode observers	modular multilevel DC–DC converters	OC	not specified	100 ms	low
[85]	inductor current emulation	synchronous boost converters	OC, SC	20 kHz	$<T_s$	low
[87]	state estimation	switching power converters	OC, SC	10–20 kHz	<10 ms	medium
[84]	sliding-mode observers	modular multilevel DC–DC converters	OC	not specified	50 ms	low
[86]	inductor current emulation	synchronous boost converters	SC	10 kHz	$<T_s$	low

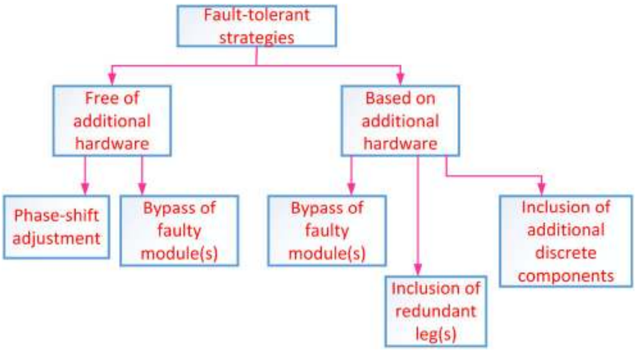

Fig. 11 *Categorisation of fault-tolerant strategies available in literature for DC–DC converters*

converter [85, 86]. However, this method can be extended to other non-isolated converters including buck, buck–boost, Cuk, SEPIC. By this method, it is possible to identify the switch fault type and faulty switch in less than one switching cycle. In addition to monitored inductor current, converter output and input voltages are the necessary diagnostic variables. The faults can be identified by analysing the measured inductor current at an instance '*n*' and the expected inductor current at similar instance '*n*'. The deviation between the expected and measured inductor current furnishes significant information to diagnose the faulty component. The merits of this algorithm are

- This method provides a fast and accurate fault detection alarm.
- Additional sensors are not required.
- This method provides FTO, which is used to operate the converter continuously after the fault condition.
- Robust to input disturbances and load variations.

A robust open circuit switch fault-diagnosis method based on real-time SMO-based is proposed for the DC–DC power converters for fuel cell applications [87]. This proposed method is tested on a multiphase floating interleaved boost converter (FIBC). Based on a nominal converter model the SMO is used to generate the residual for fault diagnosis. The significant features of the proposed method are

- Robust to the circuit parameter uncertainty and disturbance.
- This method can diagnose multiple switch faults.
- The diagnosis time is less than two switching periods.

A control scheme with open circuit switch fault-diagnosis is proposed in [88] for FIBC to ensure the reliability and maintain the control performance in all conditions. An enhanced adaptive active disturbance rejection control is developed in this proposed method to handle with parameter uncertainty and switch fault uncertainty of FIBC.

Typical fault detection and identification (FDI) by utilising a model-based state estimator is used as fault diagnosis for switching power converters [89] including a three-phase inverter, a single-phase rectifier, an interleaved boost converter, and a buck converter. This FDI algorithm strongly accomplishes the fault identification in <10 ms and fault detection in <400 µs. A real-time error residual is developed by state estimator which captures the inequality between the estimated outputs and measured outputs (currents and voltages) of a switching power converter. The fault detection is enabled when the error residual becomes non-zero. Model estimator requires a high sampling rate, so it needs powerful computational efforts. Therefore, a powerful and fast DSP tool is required to expand this algorithm. This is the major drawback to be considered of the algorithm. The major advantages of this algorithm are:

- The proposed FDI can be used to identify and detect arbitrary faults in sensors and components in an extensive class of switching power converters.
- Fast response and wide applicability.
- High flexibility.

To improve the reliability of the DC–DC converters, further, literature provides further model-based algorithms for substitute purpose. These algorithms are commonly used for converter parameters estimation like capacitances and inductances. However still, these algorithms have the potential to find the fault diagnostic moments in power switches. A small illustration of the model-based algorithms focusing on the evaluation of other converter states is furnished: algorithms based on self-tuned Kalman filters [90, 91], adaptive gradient descent [92], observers featuring adaptive estimation of parameters [93].

2.2.1 Performance of model-based algorithms: To better assess the merits and performance of model-based algorithms applicable for DC–DC converters, Table 3 creates a relative examination between the most important fault diagnostic algorithms.

3 Fault-tolerant strategies

Fault-diagnosis plays a major role in achieving the high-reliability measures for DC–DC converters. However still, fault diagnostic effort does not completely reduce the harmful effects in DC–DC converters. Therefore fault-tolerant strategies are implemented on DC–DC faulty converters which permit the continuous power conversion, with adequate quality levels after the post fault.

Yet, the fault-tolerant strategies are implemented on DC–DC converters; it does not allow the full recovery of power conversion capabilities. Even after the redesign of DC–DC faulty converter, power de-rating transferred to load and power quality degradation are frequently observed. As a consequence of reconfiguration strategies side effects will be predicted. Higher switching and conduction loss are the two common side effects experienced by fault-tolerant converter after the post-fault operation.

The fault-tolerant strategies, classification for DC–DC converters available in the literature is shown in Fig. 11.

3.1 Reconfiguration strategies free of additional hardware

A decent set of reconfiguration strategies without employing any additional hardware on DC–DC converters are provided in the literature, which takes the advantage of inherently fault-tolerant structure for some converter topologies to continue the power conversion even the post fault. Reconfiguration strategies based on free of additional hardware is basically constructed on two individual approaches:

- Phase shift adjustments.
- Bypass of faulty modules.

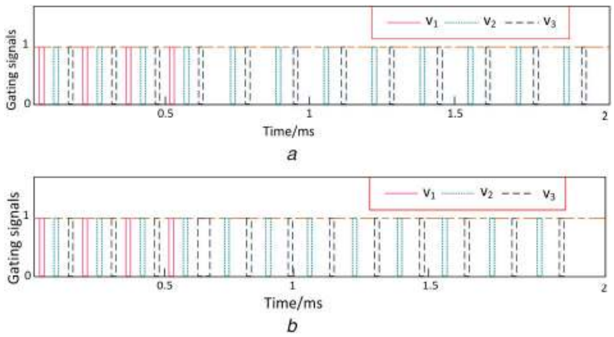

Fig. 12 *Interleaved switching pattern after OCF at t = 0.55 ms*
(a) Without reconfiguration, ***(b)*** With phase shift reconfiguration

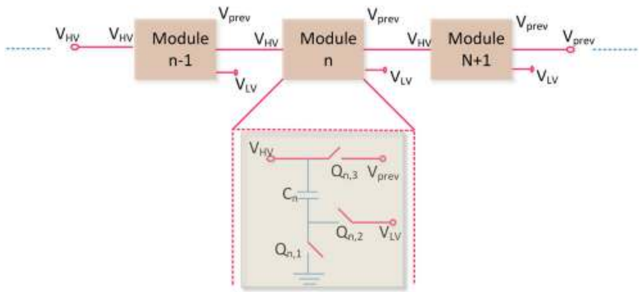

Fig. 13 *Bidirectional MMC Fault-tolerant structure [99]*

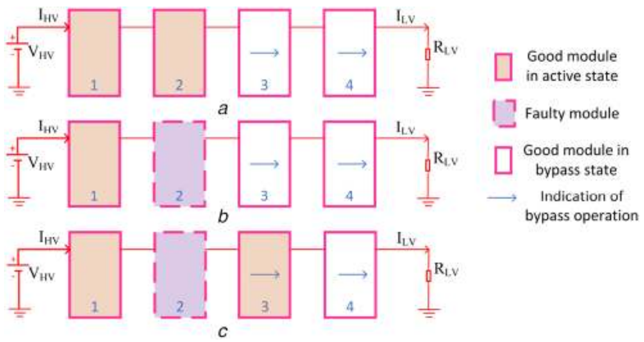

Fig. 14 *Fault bypass operation and redundancy of MMC [100]*
(a) MMC operating in normal mode with two redundant modules (3 and 4), ***(b)*** Occurrence of fault in module 2, ***(c)*** Module 2 is replaced by module 3 with the help of bypass mode

3.1.1 Phase shift adjustment: Adjustment of gating signals is introduced to faulty converters in phase shift adjustment method. This means that, the phase shift modification among the control signals are adjusted to active converter components/switches.

After finding the fault, the gating signal associated with the faulty switch, which damages the switch managed by signal q_1 as shown in Fig. 12*a* has to be removed from the switching pattern. In addition, the applied phase shift among the gating signals to the active switches is corrected. As an example depicted in Fig. 12*b* the gating signals q_3 and q_2 are altered by π rad, after $t = 0.55$ ms. The switching pattern is reconstructed by using the reconfiguration approach after the post fault period. Phase shift adjustment, a reconstructed scheme which is normally employed in converter topologies that apply a phase shift modulation method. Accordingly, phase shift adjustment contributes very good results on parallel-connected SAB converters [50], input parallel output-series (IPOS) converters [94], and interleaved DC–DC converters [48, 51, 95–98]. The major merits of the phase shift adjustment fault-tolerant strategy are

- Low implementation cost.
- Effectiveness and simplicity.

3.1.2 Bypass of faulty modules: The execution of faulty modules by bypass method is a very simple method for certain MMC topologies [99, 100], as depicted in Figs. 13 and 14. Fig. 14 demonstrates the fault bypass and presents how the converter can resist a fault and maintain its normal operation. Fig. 14 shows a three-level converter with two redundant modules. Modules 1 and 2 work as active modules during normal operation, and modules 3 and 4 acts as bypass modules, as shown in Fig. 14*a*. A fault has occurred in module 2 as shown in Fig. 14*b*. The converter uses two active modules in the system, to maintain the conversion ratio constant. Now, the location of fault has been detected by the control circuit and bypasses module 2. Thereafter, it enlist module 3 in the active state, which was in bypass state so far, as shown in Fig. 14*c*. From this point, modules 2 and 4 work as bypass modules, and modules 1 and 3 work as active modules. To execute the bypass function, all the components are required which are originally included in the structure. Faulty modules bypassing in modular converters have few merits over reconfiguring approach:

- No changes in the original control scheme.
- Implementation cost is null.

An FTO scheme is proposed in [101] for the two-level converters-MMCs (TLC-MMC), which interconnects the medium-voltage DC (MVDC) and high voltage DC (HVDC) grids. A cost-effective FTO scheme by employing low-speed mechanical disconnectors is proposed in this paper. By this proposed method, a faulty TLC can be bypassed and isolated from the TLC-MMC converter for maintenance, and the TLC-MMC converter can continuously operate with a reduced power rating.

3.2 Reconfiguration strategies employing additional hardware

Reconfiguration strategies applying additional hardware are the most reconfiguration strategies accessible in literature. Due to SC and OC faults, there will be a loss of power conversion capabilities. In order to avoid that situation, additional components are recommended in the original converter. Additional components either directly replace the faulty element or bypass the faulty element if the converter has a modular structure. Based on the topology of DC–DC converter the replacement can take place at either leg level or at the device level (IGBTs, TRIACs, and MOSFETs). Reconfiguration strategies employing additional hardware is basically constructed on three individual approaches:

- Bypass of faulty modules.
- Inclusion of additional discrete components.
- Redundant legs insertion.

3.2.1 Bypass of faulty modules: The DC–DC converters with modular structures do not provide adequate elements to establish bypass function. However, to achieve the fault-tolerant capabilities, it is necessary to include additional components in the original circuit. Additional components such as solid-state relays or thyristors are used in case of ISOP converter to bypass the faulty module [102, 103] as depicted in Fig. 15.

A fault-tolerant method for cascaded quasi *Z* source DC–DC converter, which depends on the bypass of faulty modules are proposed in [104]. If a fault appears in a particular switch of cascaded configuration, results in power conversion loss function of the entire converter. Bypass function and isolation play a major role in such aspects. An additional number of power switches should be introduced in cascaded DC–DC converters to obtain bypass function and isolation of faulty modules.

3.2.2 Inclusion of additional discrete components: This method uses additional discrete components which are different from the original components used in DC–DC converters.

The additional components used in fault-tolerant converters do not directly change the faulty switch functions. The reduction of output voltage in the full bridge DC–DC converter is the most important side effect that occurs from open circuit switch faults. To compensate the decrement in the output of the full bridge DC–DC converters reconfiguration strategy plays a major role. These fault-

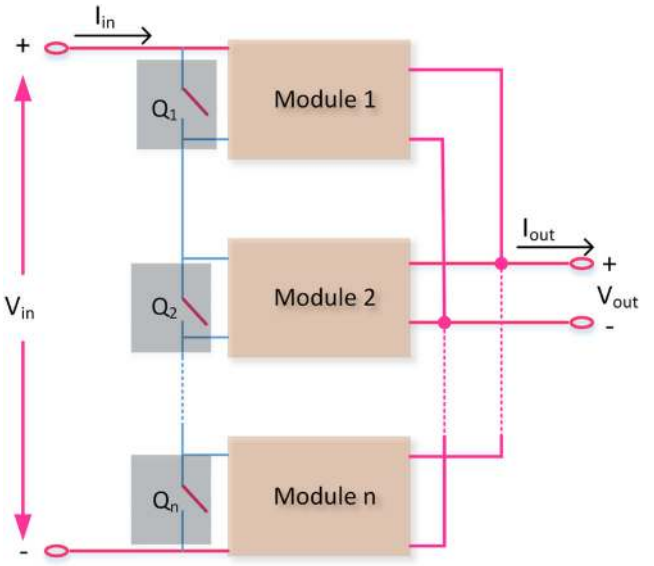

Fig. 15 *Fault-tolerant implementation in input series output parallel converter [102, 103] (Q_1, Q_2, Q_n denotes the bypass switches)*

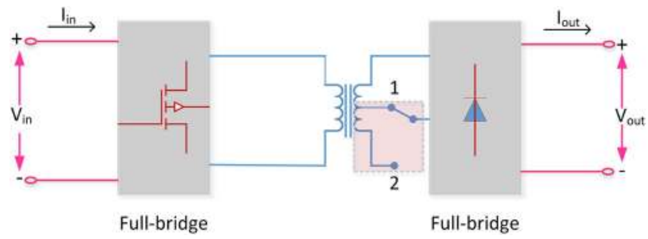

Fig. 16 *FTO of full bridge DC–DC converter depends on auxiliary winding connected in secondary winding of transformer [39]*

tolerant structures require an additional auxiliary transformer winding [39]. This is to be placed in the transformer secondary winding as shown in Fig. 16. If a faulty switch damages the transformer primary side bridge operation, then the auxiliary winding is activated. Placing an auxiliary winding for compensating the output voltage, involves high implementation cost.

Different reconfiguration strategies contribute cheaper and feasible solutions for similar problems. The Auxiliary winding is inserted in the transformer, in order to compensate the depletion of the output voltage of the converter. However, the implementation of this method requires a high cost. A simple boost converter is connected to regain the pre-fault voltage in cascade configuration either at transformer secondary-side [105] or at the transformer primary side [106]. This method provides a cheaper and feasible solution to the aforementioned one.

A voltage doubler circuit consists of two power switches and two capacitors attached to the transformer secondary side. It is another reconfiguration strategy which furnishes a solution for voltage decrement problem in multilevel series-resonant and full-bridge DC–DC converters [107, 108].

Due to a single OC-circuit fault command, there is a complete loss of power conversion capabilities in multilevel DC–DC converters particularly in non-isolated three-level DC–DC converters. The fault tolerant non-isolated three-level DC–DC converters are shown in Fig. 17, which comprises of the reorganisation of converter input.

A single OCF may completely discontinue the converter operation if there is absence of redundancy of single-switch buck converter. From the similar circuit of two individual DC–DC converter topologies, a fault-tolerant architecture is derived for a buck converter to solve this problem. With this fault-tolerant architecture, operation at either buck/boost or buck mode is possible. In simple, this fault-tolerant buck converter has one extra power switch compared to normal buck converter [109].

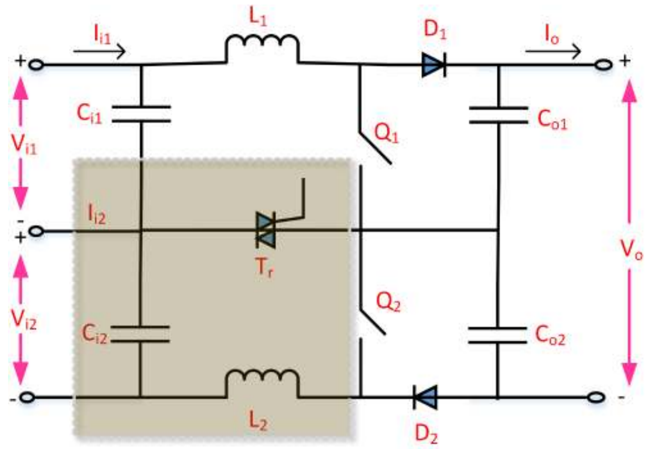

Fig. 17 *Three-level boost converter fault-tolerant structure [44] (grey emphasise box includes new components establish in three-level boost converter)*

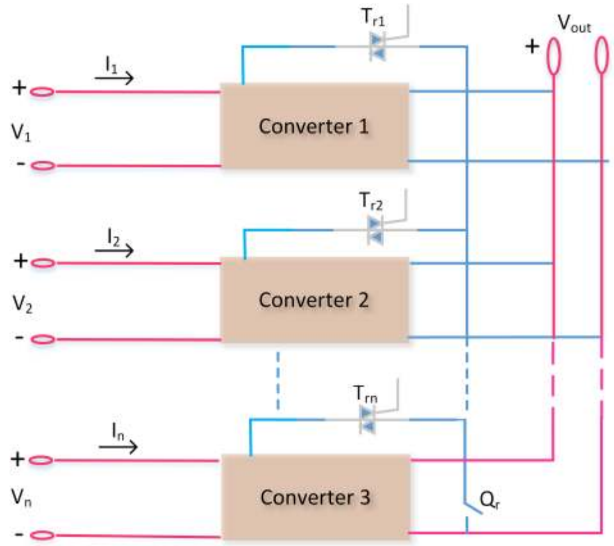

Fig. 18 *Redundant leg implementation depends on simple redundant switch [40]*

3.2.3 Redundant legs insertion: Redundant legs insertion is a type of fault-tolerant architectures that avoids the discontinuity of operation when a fault occurs. Typically, redundant legs include redundant switches and sometimes other auxiliary components whenever applicable.

The best example based on redundant legs is the fault-tolerant structure of single switch DC–DC boost converter. The redundant leg consists of just a single switch or one TRIAC and a switch [40] is associated in parallel to the original converter. The redundant leg gets activated when there is a fault in the original converter switch. The implementation of this strategy becomes cost-effective and an interesting solution when engaged in a number of single switch DC–DC boost converters as shown in Fig. 18.

3.3 Comparative analysis of converter reconfiguration strategies

The most important features of the fault-tolerant strategies applicable for the DC–DC converters are summarised in Table 4. Unique consideration should be dedicated to the column ‘reconfiguration?’. Control of switch changes that concentrates on isolated faulty modules are not taken into the account of reconfiguration. If no additional hardware is required in the converter circuit then the cost is classified as not applicable.

Table 4 Comparison of fault-tolerant approaches

Ref.	Reconfiguration approach	Application control	Reconfiguration?	New components?	Cost
[50]	phase-shift adjustment	parallel-connected single active bridge converters	yes	no	not applicable
[97]	phase-shift adjustment	IPOS	yes	no	not applicable
[51, 92, 93, 95, 96]	phase-shift adjustment	interleaved converters	yes	no	not applicable
[99, 100]	bypass of faulty module	input series output parallel	no	yes (1 per module)	low
[94, 98]	bypass of faulty module	MMCs	no	no	low
[101]	bypass of faulty module	cascaded DC–DC converters	no	yes (atleast 5)	high
[106]	inclusion of redundant components	dual-switch buck converters	no	yes (1 per module)	low
[104, 105]	inclusion of redundant components	series-resonant DC–DC converter	no	yes (4 per module)	medium
[92–103]	inclusion of redundant components	full bridge converters	yes	yes (3 per module)	medium
[44]	inclusion of redundant components	non-isolated multilevel converter	yes	yes (1 per module)	low
[39]	inclusion of redundant components	PSFB converter	yes	yes (2 per module)	low
[40, 43]	inclusion of redundant components	single-switch boost converter	no	yes (2 per module)	medium

4 Conclusions

A comprehensive review on fault-diagnosis and fault-tolerance for DC–DC converters has been carried out with the intention to provide a clear picture of the current status of the research field. Fault-diagnosis and fault-tolerance are becoming increasingly important for power electronic systems. Their application in power converters is very significant to ensure reliability. Fault-diagnosis techniques and their applications have been broadly reviewed from signal processing based and model-based algorithms, respectively. Signal-based fault diagnosis is performed from the classifications obtained from time and frequency domains.

The contribution targets on fault-diagnosis and fault-tolerance in DC–DC converters has gained its own position in the last few years. Gathering data about the fault diagnostic algorithms and fault tolerance strategies developed until now in a single document turns out to be progressively essential. Thus, this paper furnishes an up to date analysis of recent achievements attained with respect to the improvement of reliability and availability of DC–DC converters.

The solutions accessible in literature furnish an effective fault-diagnosis and tolerance methods for endless DC–DC converter topologies, permitting them to create a strong groundwork for the reliability improvement in DC–DC converters.

Lastly, the status of current research identifies the following key results and limitations.

- Advancement of power switches with better SC capabilities and faster fuses would greatly simplify the fault-isolation circuit.
- Quick identification of faults and transition from faulty state to post fault state should be addressed in detail.
- Most of the fault-tolerant strategies are only suitable for detecting single OCF or SCF. Further analysis has to be done on simultaneous multiple faults.

5 References

[1] Gerber, M., Ferreira, J.A., Hofsajer, I.W., *et al.*: 'High density packaging of the passive components in an automotive DC/DC converter', *IEEE Trans. Power Electron.*, 2005, **20**, (2), pp. 268–275

[2] Blaabjerg, F., Ma, K., Zhou, D.: 'Novel digital control topology of a high power resonant DC–DC converter for X-ray high-voltage applications'. 2012 Proc. Power Conversion Conf. – PCC'97, Tokyo, Japan, 2012, no. 3, pp. 19–30

[3] Freire, N.M.A., Cardoso, A.J.M.: 'Fault-tolerant PMSG drive with reduced DC-link ratings for wind turbine applications', *IEEE J. Emerging Sel. Top. Power Electron.*, 2014, **2**, (1), pp. 26–34

[4] Wolfgang, E.: 'Examples for failures in power electronics systems', *ECPE Tutor. Rel. Power Electron. Syst.*, 1997, **2**, pp. 1013–1018

[5] Amaral, A., Cardoso, A.: 'On-line fault detection of aluminium electrolytic capacitors, in step-down dc–dc converters, using input current and output voltage ripple', *IET Power Electron.*, 2012, **5**, (3), pp. 315–322

[6] Blaabjerg, F., Ma, K., Zhou, D.: 'Power electronics and reliability in renewable energy systems'. 2012 IEEE Int. Symp. on Industrial Electronics, Hangzhou, People's Republic of China, 2012, no. 3, pp. 19–30

[7] Wang, H., Ma, K., Blaabjerg, F.: 'Design for reliability of power electronic systems', IECON Proceedings (Industrial Electronics Conference), Montreal, QC, Canada, 2012, pp. 1423–1440

[8] Song, W., Huang, A.Q.: 'Fault-tolerant design and control strategy for cascaded H-bridge multilevel converter-based statcom', *IEEE Trans. Ind. Electron.*, 2010, **57**, (8), pp. 2700–2708

[9] Shahbazi, M., Poure, P., Saadate, S., *et al.*: 'Fault-tolerant five-leg converter topology with FPGA-based reconfigurable control', *IEEE Trans. Ind. Electron.*, 2013, **60**, (6), pp. 2284–2294

[10] Estima, J.O., Cardoso, A.J.M.: 'A new algorithm for real-time multiple open-circuit fault diagnosis in voltage-fed PWM motor drives by the reference current errors', *IEEE Trans. Ind. Electron.*, 2013, **60**, (8), pp. 3496–3505

[11] Yang, S., Bryant, A., Mawby, P., *et al.*: 'An industry-based survey of reliability in power electronic converters', *IEEE Trans. Ind. Appl.*, 2011, **47**, (3), pp. 1441–1451

[12] Rothenhagen, K., Fuchs, F.W.: 'Performance of diagnosis methods for IGBT open circuit faults in voltage source active rectifiers'. IEEE 35th Annual Power Electronics Specialists Conf., Aachen, Germany, June 2004, vol. 6, pp. 4348–4354

[13] Rodriguez-Blanco, M.A., Claudio-Sanchez, A., Theilliol, D., *et al.*: 'A failure-detection strategy for IGBT based on gate-voltage behavior applied to a motor drive system', *IEEE Trans. Ind. Appl.*, 2011, **47**, (3), pp. 1441–1451

[14] Rothenhagen, K., Fuchs, F.W.: 'Performance of diagnosis methods for IGBT open circuit faults in three phase voltage source inverters for AC variable speed drives'. 2005 European Conf. on Power Electronics and Applications, Dresden, Germany, September 2005, p. 10

[15] Sleszynski, W., Nieznanski, J., Cichowski, A.: 'Open-transistor fault diagnostics in voltage-source inverters by analyzing the load currents', *IEEE Trans. Ind. Electron.*, 2009, **56**, (11), pp. 4681–4688

[16] Cruz, S.M.A., Ferreira, M., Mendes, A.M.S., *et al.*: 'Analysis and diagnosis of open-circuit faults in matrix converters', *IEEE Trans. Ind. Electron.*, 2011, **8**, (5), pp. 1648–1661

[17] Klim, T.J., Lee, W.C., Hyun, D.S.: 'Detection method for open circuit fault in neutral-point-clamped inverter systems', *IEEE Trans. Ind. Electron.*, 2009, **56**, (7), pp. 2754–2763

[18] Lu, B., Sharma, S.: 'A literature review of IGBT fault diagnostic and protection methods for power inverters', *IEEE Trans. Ind. Appl.*, 2009, **45**, (5), pp. 1770–1777

[19] Duan, P., Xie, K.G., Zhang, L., *et al.*: 'Open-switch fault diagnosis and system reconfiguration of doubly fed wind power converter used in a microgrid', *IEEE Trans. Power Electron.*, 2011, **26**, (3), pp. 816–821

[20] Shahbazi, M., Jamshidpour, E., Poure, P., *et al.*: 'Open and short-circuit switch fault diagnosis for nonisolated DC–DC converters using field programmable gate array', *IEEE Trans. Ind. Appl.*, 2013, **60**, (9), pp. 4136–4146

[21] Sheng, H., Wang, F., Tipton, C.W.: 'A fault detection and protection scheme for three-level DC–DC converters based on monitoring flying capacitor voltage', *IEEE Trans. Power Electron.*, 2012, **27**, (2), pp. 685–697

[22] Kim, S.Y., Nam, K., Song, H.S., *et al.*: 'Fault diagnosis of a ZVS DC–DC converter based on DC-link current pulse shapes', *IEEE Trans. Power Electron.*, 2008, **55**, (3), pp. 1491–1494

[23] Wang, Z., Shi, X., Tolbert, L., *et al.*: 'A d*i*/d*t* feedback based active gate driver for smart switching and fast overcurrent protection of IGBT modules', *IEEE Trans. Power Electron.*, 2014, **29**, (7), pp. 3720–3732

[24] Chen, L., Peng, F., Cao, D.: 'A smart gate drive with self-diagnosis for power MOSFETs and IGBTs'. 2008 Twenty-Third Annual IEEE Applied Power Electronics Conf. and Exposition, Austin, TX, USA, February 2008, pp. 1602–1607

[25] Ribeiro, R.L.A., Jacobina, C.B., Silva, E.R.C., *et al.*: 'Fault detection of open-switch damage in voltage-fed PWM motor drive systems', *IEEE Trans. Power Electron.*, 2003, **18**, (2), pp. 587–593

[26] Park, B.G., Lee, K.J., Kim, R., *et al.*: 'Simple fault diagnosis based on operating characteristic of brushless direct current motor drives', *IEEE Trans. Ind. Appl.*, 2011, **58**, (5), pp. 1586–1593

[27] Jung, S.M., Park, J.S., Kim, H.W., *et al.*: 'An MRAS based diagnosis of open-circuit fault in PWM voltage-source inverters for PM synchronous motor drive systems', *IEEE Trans. Power Electron.*, 2013, **28**, (5), pp. 2514–2526

[28] Karimi, S., Gaillard, A., Poure, P., *et al.*: 'FPGA-based real-time power converter failure diagnosis for wind energy conversion systems', *IEEE Trans. Ind. Electron.*, 2008, **55**, (12), pp. 4299–4308

[29] Lezana, P., Aguilera, R., Rodriguez, J.: 'Fault detection on multicell converter based on output voltage frequency analysis', *IEEE Trans. Ind. Electron.*, 2009, **56**, (6), pp. 2275–2283

[30] Awadallah, M., Morcos, M.: 'Automatic diagnosis and location of open switch fault in brushless DC motor drives using wavelets and neuro-fuzzy systems', *IEEE Trans. Energy Convers.*, 2006, **21**, (1), pp. 104–111

[31] Meinguet, F., Sandulescu, P., Kestelyn, X., *et al.*: 'A method for fault detection and isolation based on the processing of multiple diagnostic indices: application to inverter faults in AC drives', *IEEE Trans. Veh. Technol.*, 2013, **62**, (3), pp. 995–1009

[32] Peuget, R., Courtine, S., Rognon, J.P.: 'Fault detection and isolation on a PWM inverter by knowledge-based model', *IEEE Trans. Ind. Appl.*, 1998, **34**, (6), pp. 1318–1326

[33] Bento, F., Cardoso, A.J.M.: 'A comprehensive survey on fault diagnosis and fault tolerance of DC–DC converters', *Chin. J. Electr. Eng.*, 2018, **4**, (3), pp. 1–12

[34] Abul Masrur, M., Chen, Z., Murphey, Y.: 'Intelligent diagnosis of open and short circuit faults in electric drive inverters for real-time applications', *IET Power Electron.*, 2010, **3**, (2), pp. 279–291

[35] Zhang, W., Xu, D., Enjeti, P., *et al.*: 'Survey on fault-tolerant techniques for power electronic converters', *IEEE Trans. Power Electron.*, 2014, **29**, (12), pp. 6319–6331

[36] Song, Y., Wang, B.: 'Analysis and experimental verification of a fault tolerant HEV power train', *IEEE Trans. Power Electron.*, 2013, **28**, (12), pp. 5854–5864

[37] Jayabalan, R., Fahimi, B.: 'Monitoring and fault diagnosis of multi converter systems in hybrid electric vehicles', *IEEE Trans. Veh. Technol.*, 2006, **55**, (5), pp. 1475–1484

[38] Ribeiro, E., Cardoso, A.J.M., Boccaletti, C.: 'Fault analysis of dual active bridge converter'. IECON 2012-38th Annual Conf. on IEEE Industrial Electronics Society, Montreal, WI, USA, 2012, pp. 398–403

[39] Pei, X., Nie, S., Chen, Y., *et al.*: 'Open-circuit fault diagnosis and fault-tolerant strategies for full-bridge DC–DC converters', *IEEE Trans. Power Electron.*, 2012, **27**, (5), pp. 2550–2565

[40] Jamshidpour, E., Poure, P., Gholipour, E., *et al.*: 'Single-switch DC–DC converter with fault-tolerant capability under open- and short-circuit switch failures', *IEEE Trans. Power Electron.*, 2015, **30**, (5), pp. 2703–2712

[41] Jamshidpour, E., Poure, P., Saadate, S.: 'Switch failure diagnosis based on inductor current observation for boost converters', *Int. J. Electron.*, 2016, **103**, (9), pp. 1498–1509

[42] Jamshidpour, E., Shahbazi, M., Saadate, S., *et al.*: 'FPGA based fault detection and fault tolerance operation in DC–DC converters'. 2014 Int. Symp. on Power Electronics, Electrical Drives, Automation and Motion, Amalfi, Italy, 2014, pp. 37–42

[43] Jamshidpour, E., Poure, P., Saadate, S.: 'Photovoltaic systems reliability improvement by real-time FPGA-based switch failure diagnosis and fault-tolerant DC–DC converter', *IEEE Trans. Ind. Electron.*, 2015, **62**, (11), pp. 7247–7255

[44] Ribeiro, E., Cardoso, A.J.M., Boccaletti, C.: 'Fault-tolerant strategy for a photovoltaic DC–DC converter', *IEEE Trans. Power Electron.*, 2013, **28**, (6), pp. 3008–3018

[45] Park, T., Kim, T.: 'Novel fault tolerant power conversion system for hybrid electric vehicles'. 2011 IEEE Vehicle Power and Propulsion Conf., Chicago, IL, USA, 2011, pp. 1–6

[46] Ribeiro, E., Cardoso, A.J.M., Boccaletti, C.: 'Fault diagnosis in non-isolated bidirectional half-bridge DC–DC converters'. IECON 2014 – 40th Annual Conf. of the IEEE Industrial Electronics Society, Dallas, TX, USA, October 2014, pp. 4458–4463

[47] Ribeiro, E., Cardoso, A.J.M., Boccaletti, C.: 'Fault diagnosis in a multi-input power interface for a photovoltaic wind supply system for telecommunications'. Intelec 2013; 35th Int. Telecommunications Energy Conf., SMART POWER AND EFFICIENCY.VDE, Hamburg, Germany, October 2013, pp. 1–6

[48] Bento, F., Cardoso, A.J.M.: 'Open-circuit fault diagnosis in interleaved DC–DC boost converters and reconfiguration strategy'. 2017 IEEE 11th Int. Symp. Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Tinos, Greece, August 2017, pp. 394–400

[49] Ribeiro, E., Cardoso, A.J.M., Boccaletti, C.: 'Fault diagnosis in unidirectional non-isolated DC–DC converters'. 2014 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, WI, USA, August 2014, pp. 1140–1145

[50] Park, K., Chen, Z.: 'Open-circuit fault detection and tolerant operation for a parallel-connected SAB DC–DC converter'. 2014 IEEE Applied Power Electronics Conf. and Exposition-APEC 2014, Fort Worth, TX, USA, August 2014, pp. 1966–1972

[51] Ribeiro, E., Cardoso, A.J.M., Boccaletti, C.: 'Open-circuit fault diagnosis in interleaved DC–DC converters', *IEEE Trans. Power Electron.*, 2014, **29**, (6), pp. 3091–3102

[52] Nie, S., Pei, X., Chen, Y., *et al.*: 'Fault diagnosis of PWM DC–DC converters based on magnetic component voltages equation', *IEEE Trans. Power Electron.*, 2014, **29**, (9), pp. 4978–4998

[53] Cho, H.K., Kwak, S.S., Lee, S.H.: 'Fault diagnosis algorithm based on switching function for boost converters', *Int. J. Electron.*, 2015, **102**, (7), pp. 1229–1243

[54] Pei, X., Nie, S., Kang, Y.: 'Switch short-circuit fault diagnosis and remedial strategy for full-bridge DC–DC converters', *IEEE Trans. Power Electron.*, 2015, **30**, (2), pp. 996–1004

[55] Givi, H., Farjah, E., Ghanbari, T.: 'Switch and diode fault diagnosis in nonisolated DC–DC converters using diode voltage signature', *IEEE Trans. Ind. Electron.*, 2018, **65**, (2), pp. 1606–1615

[56] Bi, K., An, Q., Duan, J., *et al.*: 'Fast diagnostic method of open circuit fault for modular multilevel DC/DC converter applied in energy storage system', *IEEE Trans. Power Electron.*, 2017, **32**, (5), pp. 3292–3296

[57] Farjah, E., Givi, H., Ghanbari, T.: 'Application of an efficient Rogowski coil sensor for switch fault diagnosis and capacitor ESR monitoring in nonisolated single-switch DC–DC converters', *IEEE Trans. Power Electron.*, 2017, **32**, (2), pp. 1442–1456

[58] Hemmati, E., Shahrtash, S.M.: 'Systematic approaches for designing Rogowski coils', *IET Sci. Meas. Technol.*, 2014, **9**, (3), pp. 259–267

[59] Metwally, I.A.: 'Novel designs of wideband Rogowski coils for high pulsed current measurement', *IET Sci. Meas. Technol.*, 2014, **8**, (1), pp. 9–16

[60] Amaral, A., Cardoso, A.: 'Simple method for measuring the equivalent series inductance and resistance of electrolytic capacitors', *IET Power Electron.*, 2010, **3**, (4), pp. 465–471

[61] Bento, F., Cardoso, A.J.M.: 'Fault tolerant DC–DC converters in DC microgrids'. 2017 IEEE Second Int. Conf. on DC Microgrids (ICDCM), Nuremberg, Germany, 2017, pp. 484–490

[62] Bento, F., Cardoso, A.J.M.: 'Fault diagnosis in DC–DC converters using a time-domain analysis of the reference current error'. IECON 2017-43rd Annual Conf. of the IEEE Industrial Electronics Society, Beijing, People's Republic of China, 2017, pp. 5060–5065

[63] Chen, Y., Nie, S., Pei, X., *et al.*: 'State monitoring and fault diagnosis of the PWM converter using the magnetic field near the inductor components'. 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 2010, pp. 1901–1907

[64] Nie, S., Chen, Y., Pei, X., *et al.*: 'A DSP-based diagnostic system for DC–DC converter using the shape of voltage across the magnetic components'. 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 2010, pp. 1908–1915

[65] Aouine, Q., Labarre, C., Costa, F.: 'Measurement and modeling of the magnetic near field radiated by a buck chopper', *IEEE Trans. Electromagn. Compat.*, 2008, **50**, (2), pp. 445–449

[66] Langer eMV-Technik Company: 'LF1 user guidelines'. 2012 Available at: http://www.langer-emv.de

[67] Hernando, M.M., Fernandez, A., Arias, M., *et al.*: 'EMI radiated noise measurement system using the source reconstruction technique', *IEEE Trans. Ind. Electron.*, 2008, **55**, (9), pp. 3258–3265

[68] Reck, J.N., Hu, K., Li, S., *et al.*: 'Fabrication of two-layer thin-film magnetic-field microprobes on freestanding SU-8 photoepoxy', *IEEE Trans. Device Mater. Reliab.*, 2010, **10**, (1), pp. 26–32

[69] Qing, X., Chen, A.N.: 'Proximity effects of metallic environments on high frequency RFID reader antenna: study and applications', *IEEE Trans. Antennas Propag.*, 2007, **55**, (11), pp. 3105–3111

[70] Chen, Y., Pei, X., Nie, S., *et al.*: 'Monitoring and diagnosis for the DC–DC converter using the magnetic near field waveform', *IEEE Trans. Ind. Electron.*, 2011, **58**, (5), pp. 1634–1647

[71] Ding, X., Poon, J., Celanovic, I., *et al.*: 'Fault detection and isolation filters for three-phase AC–DC power electronics systems', *IEEE Trans. Circuits Syst. I, Regul.Pap.*, 2013, **60**, (4), pp. 1038–1051

[72] Smith, K., Ran, L., Penman, J.: 'Real-time detection of intermittent misfiring in a voltage-fed PWM inverter induction-motor drive', *IEEE Trans. Ind. Electron.*, 1997, **44**, (4), pp. 468–476

[73] Fang, J., Li, W., Li, H., *et al.*: 'Online inverter fault diagnosis of buck-converter BLDC motor combinations', *IEEE Trans. Power Electron.*, 2015, **30**, (5), pp. 2674–2688

[74] Freire, N., Estima, J., Cardoso, A.: 'A voltage-based approach without extra hardware for open-circuit fault diagnosis in closed-loop PWM AC regenerative drives', *IEEE Trans. Ind. Electron.*, 2014, **61**, (9), pp. 4960–4970

[75] Shao, S., Wheeler, P., Clare, J., *et al.*: 'Fault detection for modular multilevel converters based on sliding mode observer', *IEEE Trans. Power Electron.*, 2013, **28**, (11), pp. 4867–4872

[76] Yazdani, A., Sepahvand, H., Crow, M., *et al.*: 'Fault detection and mitigation in multilevel converter STATCOMs', *IEEE Trans. Ind. Electron.*, 2011, **58**, (4), pp. 1307–1315

[77] Diallo, D., Benbouzid, M., Hamad, D., *et al.*: 'Fault detection and diagnosis in an induction machine drive: a pattern recognition approach based on concordia stator mean current vector', *IEEE Trans. Energy Convers.*, 2005, **20**, (3), pp. 512–519

[78] Zidani, F., Diallo, D., Benbouzid, M., *et al.*: 'A fuzzy-based approach for the diagnosis of fault modes in a voltage-fed PWM inverter induction motor drive', *IEEE Trans. Ind. Electron.*, 2008, **55**, (2), pp. 586–593

[79] Chowdhury, F., Aravena, J.: 'A modular methodology for fast fault detection and classification in power systems', *IEEE Trans. Control Syst. Technol.*, 1998, **6**, (5), pp. 623–634

[80] Khomfoi, S., Tolbert, L.: 'Fault diagnostic system for a multilevel inverter using a neural network', *IEEE Trans. Power Electron.*, 2007, **22**, (3), pp. 1062–1069

[81] Khomfoi, S., Tolber, L.: 'Fault diagnosis and reconfiguration for multilevel inverter drive using AI-based techniques', *IEEE Trans. Ind. Electron.*, 2007, **54**, (6), pp. 2954–2968

[82] Murphey, Y., Masrur, M., Chen, Z., *et al.*: 'Model-based fault diagnosis in electric drives using machine learning', *IEEE/ASME Trans. Mechatronics*, 2006, **11**, (3), pp. 290–303

[83] Lin, F.-J., Hung, Y.-C., Hwang, J.-C., *et al.*: 'Fault-tolerant control of a six-phase motor drive system using a Takagi–Sugeno–Kang type fuzzy neural network with asymmetric membership function', *IEEE Trans. Power Electron.*, 2013, **28**, (7), pp. 3557–3572

[84] Shao, S., Watson, A., Clare, J., *et al.*: 'Robustness analysis and experimental validation of a fault detection and isolation method for the modular multilevel converter', *IEEE Trans. Power Electron.*, 2016, **31**, (5), pp. 3794–3805

[85] Pazouki, E., Sozer, Y., De Abreu-Garcia, J.A.: 'Fault diagnosis and fault-tolerant control operation of nonisolated DC–DC converters', *IEEE Trans. Ind. Electron.*, 2018, **54**, (1), pp. 310–320

[86] Pazouki, E., De Abreu-Garcia, J.A., Sozer, Y.: 'Short circuit fault diagnosis for interleaved DC–DC converter using DC-link current emulator'. 2017 IEEE Applied Power Electronics Conf. and Exposition (APEC), Tampa, FL, USA, 2017, pp. 230–236

[87] Zhuo, S., Xu, L., Gaillard, A., *et al.*: 'Robust open-circuit fault diagnosis of multi-phase floating interleaved DC–DC boost converter based on sliding mode observer', *IEEE Trans. Transp. Electrification*, 2019, **5**, pp. 638–649

[88] Zhuo, S., Gaillard, A., Guo, L., *et al.*: 'Active disturbance rejection voltage control of floating interleaved DC–DC boost converter with switch fault consideration', *IEEE Trans. Power Electron.*, 2019, **34**, pp. 12396–12406

[89] Poon, J., Jain, P., Konstantakopoulos, I.C., *et al.*: 'Model-based fault detection and identification for switching power converters', *IEEE Trans. Power Electron.*, 2017, **32**, (2), pp. 1419–1430

[90] Izadian, A., Khayyer, P.: 'Application of kalman filters in model-based fault diagnosis of a DC–DC boost converter'. IECON 2010-36th Annual Conf. on IEEE Industrial Electronics Society, Glendale, AZ, USA, 2010, pp. 369–372

[91] Ahmeid, M., Armstrong, M., Gadoue, S., *et al.*: 'Real-time parameter estimation of DC–DC converters using a self-tuned kalman filter', *IEEE Trans. Power Electron.*, 2017, **32**, (7), pp. 5666–5674

[92] Poon, J., Jain, P., Spanos, C., *et al.*: 'Fault prognosis for power electronics systems using adaptive parameter identification', *IEEE Trans. Ind. Appl.*, 2017, **53**, (3), pp. 2862–2870

[93] Cen, Z., Stewart, P.: 'Condition parameter estimation for photovoltaic buck converters based on adaptive model observers', *IEEE Trans. Reliab.*, 2017, **66**, (1), pp. 148–160

[94] Li, T., Parsa, L.: 'Design, control, and analysis of a fault-tolerant soft-switching DC–DC converter for high-power high-voltage applications', *IEEE Trans. Power Appl.*, 2018, **33**, (2), pp. 1094–1104

[95] Lukic, Z., Blake, C., Huerta, S.C., *et al.*: 'Universal and fault-tolerant multiphase digital PWM controller IC for high frequency DC–DC converters'. APEC 07-Twenty-Second Annual IEEE Applied Power Electronics Conf. and Exposition, Anaheim, CA, USA, 2007, pp. 42–47

[96] Tezak, N., MacAn, M.: 'Adaptive PWM control scheme of interleaved boost converter for AC traction application'. Proc. 14th Int. Power Electronics and Motion Control Conf. EPE-PEMC 2010, Ohrid, Macedonia, 2010, pp. T9–72

[97] Ribeiro, E., Monteiro, A., Cardoso, A.J.M., *et al.*: 'Fault tolerant small wind power system for telecommunications with maximum power extraction'. 2014 IEEE 36th Int. Telecommunications Energy Conf. (INTELEC), Vancouver, DC, USA, 2014, pp. 1–6

[98] Gleissner, M., Bakran, M.M.: 'Design and control of fault-tolerant nonisolated multiphase multilevel DC–DC converters for automotive power systems', *IEEE Trans. Ind. Appl.*, 2016, **52**, (2), pp. 1785–1795

[99] Tolbert, L.M., Khan, F.H.: 'Bi-directional power management and fault tolerant feature in a 5 kW multilevel DC–DC converter with modular architecture', *IET Power Electron.*, 2009, **2**, (5), pp. 595–604

[100] Khan, F.H., Tolbert, L.M.: 'Multiple-load-source integration in a multilevel modular capacitor-clamped DC–DC converter featuring fault tolerant capability', *IEEE Trans. Power Appl.*, 2009, **24**, (1), pp. 14–24

[101] Cui, S., Hu, J., De Doncker, R.W.: 'Fault-tolerant operation of a TLC-MMC hybrid DC–DC converter for interconnection of MVDC and HVDC grids', *IEEE Trans. Power Appl.*, 2019, p. 1

[102] Choudhary, V., Ledezma, E., Ayyanar, R., *et al.*: 'Fault tolerant circuit topology and control method for input series and output-parallel modular DC–DC converters', *IEEE Trans. Power Appl.*, 2008, **23**, (1), pp. 402–411

[103] Hayashi, Y., Matsugaki, Y., Ninomiya, T., *et al.*: 'Active gate controlled sic transfer switch for fault tolerant operation of ISOP multicellular DC–DC converter'. 2016 IEEE Int. Conf. on Power Electronics, Drives and Energy Systems (PEDES), Trivandrum, India, 2016, pp. 1–6

[104] Haji-Esmaeili, M.M., Naseri, M., Khoun-Jahan, H., *et al.*: 'Fault-tolerant and reliable structure for a cascaded quasi-*Z*-source DC–DC converter', *IEEE Trans. Power Appl.*, 2017, **32**, (8), pp. 6455–6467

[105] Yao, C., Ruan, X., Wang, X., *et al.*: 'Isolated buck–boost DC/DC converters suitable for wide input-voltage range', *IEEE Trans. Power Appl.*, 2011, **26**, (9), pp. 2599–2613

[106] Lee, J., Jeong, Y., Han, B.: 'An isolated DC/DC converter using high-frequency unregulated LLC resonant converter for fuel cell applications', *IEEE Trans. Ind. Appl.*, 2011, **58**, (7), pp. 2926–2934

[107] Costa, L., Buticchi, G., Liserre, M.: 'A fault-tolerant series resonant DC–DC converter', *IEEE Trans. Power Electron.*, 2017, **32**, (2), pp. 900–905

[108] Costa, L.F., Buticchi, G., Liserre, M.: 'A family of series resonant DC–DC converter with fault-tolerance capability', *IEEE Trans. Ind. Appl.*, 2018, **54**, (1), pp. 335–344

[109] Lu, D.D.C., Soon, J.L., Verstraete, D.: 'Derivation of dual-switch step-down DC/DC converters with fault-tolerant capability', *IEEE Trans. Power Appl.*, 2016, **31**, (9), pp. 6064–6068