Volume-11, Issue 11, Nov. 2022
JOURNAL OF COMPUTING TECHNOLOGIES (JCT)
International Journal
Page Number: 01-09

A Literature Review on Power System Transient Stability in the Event of Multi-Phase Faults and Circuit Breaker Failures

Abhishek Thakur[1], Manju Gupta[2], Geetam Richhariya[3], Neeti Dugaya[4]
M.Tech Scholar[1], Professor[2], Associate Professor[3], Assistant Professor[4]
[1,2,3,4]Department of Electrical and Electronics Engineering *(EEE)*
[1,2,3,4]Oriental Institute of Science and Technology *(OIST)*, Bhopal INDIA
shineabhishek0126@gmail.com[1], manjugupta@oriental.ac.in[2], geetamrichhariya@gmail.com[3], neetidugaya@oriental.ac.in[4]

***Abstract*— This paper proposes a new event-based logic of the breaker failure protection to improve power system transient stability by shortening the total clearing time of extreme contingencies involving circuit breaker failures. Stability improvement is achieved by using dual-timer protection with shorter safety margin for multi-phase faults close to the power plant and longer safety margin for remote multi-phase faults and single-phase faults. The use of the output signal obtained for a short safety margin depends on how the substation is configured. In the breaker-and-a-half configuration, this output signal is used to speed up the opening of all adjacent circuit breakers. In substations with the dual (or triple) busbar configuration the output signal obtained with a short safety margin is used to speed up the busbar splitting. A case study was performed for a real large-scale power system. Simulation results confirmed the advantages of the proposed logic. Breaker failure protection with the proposed logic has been implemented in a substation of a large power plant.**

***Keywords-* Power System Transient Stability, Breaker Failure Protection, Event-Based Protection, FACTS Controller, Multi-Bus Electrical Power System.**

1. INTRODUCTION

Power systems should be capable of meeting consumer demand while surviving contingencies without violation of established performance standards related to thermal, voltage, frequency and stability limits. A contingency is defined as an event which cannot be predicted in advance, e.g., a short circuit in the network and its clearance followed by a sudden loss of a single or several network elements. Dynamic performance of each power system depends on the severity of the contingency [1], [2]. Therefore, classification of contingencies by severity is key issue for expansion planning and operation of transmission network.

Various planning guidelines published worldwide [3], [4] use different lists of planning contingencies and classifications of contingencies. An event classified in one guideline as a less credible one may be classified in another guideline as a noncredible (extreme) contingency and vice versa.

This paper proposes a method to improve power system transient stability under extreme contingencies with breaker failures. Statistical data described in [14] show that contingencies involving CB failures are very rare. However, the consequences of such events can be very severe, e.g., damage to power system elements, loss of power system transient stability, cascade tripping, non-consequential load loss. In order to avoid such consequences, a breaker failure protection (BFP) is often used [15]–[19] and intensively improved owing to the progress in digital relaying [20]–[23] and communication systems [22].

The main contributions of the paper are the following: (i) A modified logic of the dual-timer BFP is proposed. It uses the distance of the multi-phase fault as an additional criterion to choose between a short or long BF time delay Δt. (ii) The proposed logic of the BFP was verified by a simulation tests conducted for a large-scale real power system and has been implemented in a high-voltage substation of a large power plant.

With the high-speed economic development, because of the increasingly lack of land resources constructions of doublecircuit transmission line on the same tower become an inevitable trend for the main network of power system in China. As the main channel from power plant to system or to load centers in big city, double-circuit lines undertake the task of massive power flow transmission, so the stable operation of them has an important significance for the reliability of power supply. Owing to the key role of double-circuit transmission line, when fault occurs, the impact of short circuit current and the tripping and reclosing of breakers have a great effect on power system stability. The conventional protection and control technology for double-circuit transmission line still use the reclosing scheme of single circuit transmission line, which has the following disadvantages: 1. when cross-line fault occurs, two circuits would be opened and there will be service interruption in large area because of the failing to delivery power flow. 2. Server damage to electric equipment and serious system oscillation are induced by the impact of second fault current when reclosing onto permanent fault. To avoid this disastrous consequence, the tripping and reclosing schemes beneficial to recover stable operation of the circuits and decrease the damage to electric equipment have great theoretical and practical values. The technologies of tripping and reclosing having been studied up to now are summarized and on the basis of these research, the intelligent control technology of tripping and reclosing for double-circuit transmission line on the same tower is present, aiming at improving the system stability after fault occurring, enhancing the connection of the systems on both sides on the line and accelerating the recovery of power supply.

II. LITERATURE REVIEW

Jerzy Andruszkiewicz, *et. al.*, (2022) -In order to improve the fault location process in MV power lines and to reduce the power outage duration times (SAIDI), the circuit-breakers in the vicinity of MV/LV substations with adequately quick protection are used more and more often in order to trip almost instantaneously during short-circuits occurring within a specific line section. The results obtained by such costly investments depend on the effectiveness of the protection relays controlling the circuit-breakers' operation, which can be improved by widening the zones covered by the I≫ short-circuit overcurrent protection. Traditional protection solutions based on phase current measurements are often unsatisfactory due to their relatively narrow protection zones. Poor protection performance applies specifically to the cases of two phase faults, which occur more frequently than three phase faults. The article proposes a simple and easy-to-implement solution in which two phase faults are identified on the basis of the negative sequence current value. The use of the I2 current as a criterion value, supplemented by a filter controlling the Io current level for the cases of double phase-to-earth faults, increases the degree of detection of two phase faults to the level obtained during three phase faults. A significant advantage of the proposed solution is the fact that it does not require changes in the protection method or protection settings' values. The operating conditions of the suggested criteria resulting from negative and zero sequence currents are selected automatically based on the three-phase short-circuit criterion. The results of the simulation analyses prompted the authors to carry out initial study on the implementation of the proposed solution to measurement and control algorithms implemented in controllers cooperating with circuit breakers in MV substation bays and with reclosers protecting particular network sections **[01].**

Umair Shahzad, *et. al.*,(2021) -The paper presented transient stability risk assessment framework incorporating CB failure and severe weather. All associated random variables, such as load demand, fault type, fault location, and FCT were considered using appropriate PDFs. The MC simulation was used to sample these PDFs and consequently, the average risk index,RA, was determined. The procedure was conducted under normal conditions (base case/Case 1), with CB failures (Case 2), and with severe weather (Case 3). Two different test systems (IEEE 14-bus and IEEE 39-bus) were used to validate the effectiveness of the proposed approach. For the IEEE 14-bus system, CB failure is more detrimental as compared to severe weather; however, for the IEEE 39-bus, severe weather is more damaging. The results obtained, signify the need to consider the CB failures and severe weather, in the transient stability risk assessment process. This will be of great aid to the power system planner in the decision-making process in the control centre. Moroever, it is inferred that not all systems exhibit the same behaviour, with respect to transient stability risk, to unsettling events, such as CB failures and severe weather. Thus, extensive simulations, including sensitivity analysis, are required to be incorporated in the transient stability risk assessment procedure. As a future research direction, the proposed approach can be extended to incorporate the impact of converter-interfaced renewable generation, as they are critical in transient stability assessment procedure. State-of-the-art approaches must be developed for CB maintenance procedures, which allows them to operate accurately and timely. Moreover, robust approaches to diminish the impact of disruptive severe weather events on power system is a challenging open research area **[02].**

Alber Filba-Martinez, *et. al.*, (2020) -A novel device has been proposed to improve the fault tolerance and reliability of power converters where switch SCF are especially detrimental. This novel device, designated as iFuse, operates by very quickly transforming an original switch SCF into a switch OCF while at the same time enabling a free-wheeling current path on the failed device. For a converter to present such improved fault tolerance and reliability, an iFuse must be connected in series with each CBVU switch, or at least with those more critical in terms of fault tolerance. Its operating principle is similar to conventional electronic fuses, but it allows selective turn off of only those iFuses whose associated switch has failed in short circuit, all performed in a standalone fashion. Moreover, the iFuse can properly handle the turn off of high short-circuit currents flowing through it, the failed switch, and other healthy devices in the current path. Special care has been taken in the design of the iFuse turn-off procedure so that it is fast enough to avoid the damage of healthy devices due to sustained overcurrent, and so that it does not incur in elevated di/dt that could damage healthy devices due to overvoltage. A signal reporting the health-status of the associated switch has been added. Moreover, the power required for the iFuse operation is provided by recycling the turn-off losses of the associated converter switch. Therefore, there is no need for an additional power supply, allowing its application in all types of converters and simplifying to a great extent the integration of the i Fuse into a compact assembly. The health-status reporting functionality can be easily complemented with the OCF detection, by simply monitoring the associated switch voltage across the power terminals. The iFuse enables the highest improvements in fault tolerance in converters with parallelized power devices, employing NPC multilevel topologies, with redundant legs and/or with multiple phases. If incorporated in multiple power switches, the converter will be able to withstand multiple switch faults. Experimental results demonstrate that the designed circuit allows a fast detection and isolation of a short-circuit-failed switch, while properly stopping currents up to 1 kA without damaging healthy devices **[03]**

Luigi Calcara,*et. al.*, (2019) - During the summer periods of the last years, the number of MV underground cable joints failures greatly increased; - e-distribuzione and University of Roma “La Sapienza” started experimental investigations and technical studies, focused on quantification of the problem, identification of the causes of failures and identification of suitable mitigation actions; - the experimental investigations and findings reported in this paper on failed and not-failed MV cable joints as taken from the service has shown as such failures mainly have been originated by irregularities or defects present in the separation interface of layers of different materials. Inside these interfaces, partial discharge phenomena may take place under the action of the electrical field as locally increased; - quite often, such irregularities or defects have been introduced during the construction phase of the cable joints (handwork). It is possible then to argue that the failure rate of the cable joints may be significantly reduced by studying technological innovations of the same component which should result simplified in terms of elementary materials and be easier to pack on-site also in difficult operational conditions **[04]**.

Uzair Javaid, *et. al.*,(2018)- This paper critically analyses the available and proposed technologies for the ship on-board power supplies and the practices of the state of the art MVAC electrical distribution systems in ships. Different technologies are proposed as supply technologies, in literature, for the future MVDC supplies, e.g., high speed gas turbines, high speed PMSGs, and active rectifiers and MMCs for ac/dc conversion. These technologies have their benefits but they are either not commercially available or are too expensive for marine applications. In commercial drives, multipulse rectifiers are connected to multi-secondary transformers to produce high power quality on the dc-side. As transformers are set to be omitted from the emerging MVDC systems, 3-phase generation can be replaced with N-phase generation, which will provide the benefit of using the multi-pulse rectifiers to have high quality dc supply. As illustration, two designs of multi-phase multi-pulse Fig. 8. Simulation results for dc-side pole to pole fault at 2 s. Considering (i) Rated Xg" with two different points for fault: at 10 m (solid line) and at 200 m (dashed line) from source, (ii) 1.5 Rated Xg" with two different places for fault: at 10 m (solid line) and at 200 m (dashed line) from source and (iii) 1.5 Rated Xg" with ac-side fuses (dotted line). A comparison of fault I2 t with allowed I2 t of two, four and eight parallel devices conductiong. (a) Case 1. (b) Case 2. (a) (b) 75 MVDC supplies, driven by medium speed ICEs (operated in DAC mode) are presented and discussed. These supplies are: i) a 2 x 3-phase generator interfaced with parallel 12-pulse rectifier for a 18 MW, 5 kV dc distribution, and ii) a 3 x 3-phase generator interfaced with series 18-pulse rectifier for a 27 MW, 15 kV dc distribution. To realise these supplies, a 6-pulse DRU sub-module is designed with commercially available diodes, which can withstand thermal load under normal operation. Additionally, these two rectifiers are analysed under different fault scenarios and it is shown that they can handle the high surge currents. However, it is also seen that if the faults are not cleared in a few milliseconds, the rectifiers will fail due to every high fault energy. To protect these rectifiers, special purposes fast fuses could be used, placed on the ac-side, to clear these faults. Additionally, the two notional systems presented here highlight the benefits of multi-phase multi-pulse dc supply. It can be observed that parallel connection of rectifiers improves not only the dc-side supply but also adds redundancy and fault tolerance to the system. Series connection of rectifiers also improves the dc side supply and adds the flexibility in choosing voltage class of generators and motors. The choice of parallel or series rectifiers depends on the system designers, the requirements of the system and the availability of the required equipment**[05]**.

U. Javaid, *et. al.*,(2017) -This paper analyses the available and proposed technologies for ship on-board power supplies and the practices followed in the state of the art MVAC electrical distribution systems in ships. The early adopters of MVDC electrical distribution are expected to consider commercially available technologies. In commercial drives, multi-pulse rectifiers are used to produce high power quality on the dc-side. As transformers are set to be omitted from the up coming MVDC systems, N×3- phase generation can provide the benefit of using the multipulse rectifiers to have high quality dc supply. Two high quality MVDC supplies configurations considering medium speed ICEs, operating in DAC mode, driving i) a 2×3-phase generator interfaced with parallel 12-pulse rectifier for a 5 kV dc distribution, and ii) a 3×3-phase generator interfaced with series 18-pulse rectifier for a 15 kV dc distribution, are proposed and analyzed. Multi-phase multi-pulse MVDC supplies also provide fault tolerance and redundancy, in case of parallel arrangement of rectifiers, and provides flexibility in choosing generator and load voltage class in case of series arrangement of rectifiers**[06]**

John S. Donnal (2017)-Non-contact power monitors can be installed without skilled labor and without any interruption in service. These monitors potentially open exciting new markets in load monitoring and power system diagnostics. This paper introduces new algorithms for gracefully and accurately handling operational environments with diverse physical and electrical configurations and misconfigurations. By explicitly compensating for assumptions implied in [10], non-contact sensors can be adapted to accurately monitor a wide variety of power systems. These sensors and algorithms have been proven over the course a year long study in diverse residential, commercial, and maritime environments used to provided the examples reviewed in this paper**[07]**.

Sebastián Espinoza, *et. al.*, (2016)- Resilience of electric power systems has emerged as a new concept after the recent catastrophic events around the world. It can be expected that resilience will be as important as reliability was in the past. However, the differences between these two concepts have to be considered, particularly that while reliability provides protection against foreseeable low-impact high-probability events, resilience provides protection against high-impact low-probability events, is a time-dependent process and far more complex, as the knowledge of many different fields and thus multidisciplinary work is required. Currently, different research teams are working on defining the concept and developing tools to describe, measure and enhance resilience. As a contribution to the topic, this paper presents a formalization ofthe resilience process and enhancement measures in a multi-phase approach. The proposed resilience framework consists of four phases. These are (i) threat characterization, where the hazard's magnitude, probability of occurrence, spatiotemporal profile and future scenarios are defined; (ii) vulnerability assessment of the system's components, where the identification of the vulnerable components, the application of fragility curves and the assignation of damage states is done; (iii) system's reaction, where the performance of the system through sequential Monte Carlo Simulations and Optimal Power Flows is carried out, and (iv) system's restoration, where the component's recovery is related to the damage caused, human and material resources availability and the accessibility to the affected area. Finally, the whole process is measured in a time-dependent way with the Expected Energy Not Supplied index and the possibility to compare with different systems through the Energy Index of Unreliability. The strategic adaptation cases presented are: normal, which is based on a reduced version of the current national grid; robust, which is a more resistant network; redundant, which is a version with more alternative paths; and responsive, which has faster recovery parameters. These case studies have been illustrated by assessing the impact of floods and windstorms on a reduced version ofthe Great Britain's electric power system. The results show that normal weather events do not represent a threat of major disruption, but when one models a flood event that may happen every 33 years or a windstorm where the normal wind speed is doubled, then the risk of blackouts becomes significantly higher. Regarding the effectiveness of the adaptation cases, for both windstorms and floods the best strategy is to improve the resistance of components, then to count with better restoration procedures and as a third option to invest in redundancy, whereas the last one implicates almost no improvement for floods**[08]**.

Espinoza, Sebastián Andrés, *et.al.*, (2015) -Resilience of electric power systems has emerged as a new concept after the recent catastrophic events around the world. It can be expected that the concept may represent for the future what reliability was in the past, but it has to be taken in consideration that resilience is far more complex, as the knowledge of many different fields and thus a multidisciplinary work is required. Currently, different research teams are working on defining the concept and developing tools to describe, measure and enhance resilience. As a contribution to the topic, this thesis presents a formalization of the resilience process and enhancement measures in a multi-phase approach and applies the framework to windstorms and floods in Great Britain and earthquakes in Chile. Specifically, the following conclusions respond to the specific objectives stated in Chapter 1. Firstly, the proposed resilience framework consists in an assessment and enhancement procedure. The assessment procedure consists of four phases. These are (i) threat characterization, where the hazard's magnitude, probability of occurrence, spatiotemporal profile and future scenarios are defined; (ii) vulnerability assessment of the system's components, where the identification of the vulnerable components, the application of fragility curves and the assignation of damage states is done; (iii) system's reaction, where the performance of the system through sequential Monte Carlo Simulations and Optimal Power Flows is carried out, and (iv) system's restoration, where the component's recovery is related to the damage caused, human and material resources availability and the accessibility to the affected area. Finally, the whole process is measured in a time-dependent way with the Expected Energy Not Supplied index and Energy Index of Unreliability. The enhancement procedure consists of three adaptation strategies, which are based on the normal version of the test systems studied. These are (i) robust strategy, which is a more resistant network; (ii) redundant strategy, which is a version with more alternative paths and (iii) responsive strategy, which has a faster recovery process**[09]**.

Dubey. A, *et. al.*,(2014) -This paper has proposed a novel impedance-based fault location algorithm for an ungrounded distribution system in event of a multi-phase faults. The algorithm makes an efficient use of distribution circuit topology, and a set of one-ended and two-ended fault location algorithms are implemented to handle feeder section with different measuring and topology conditions Both one-ended and two-ended fault location algorithms proposed in this paper are novel in their approach and make no assumption regarding fault impedance. The given test results have proven the effectiveness of proposed method **[10]**.

III. CONSIDERED EXTREME CONTINGENCY

A. General Classification of Contingencies

Typical events that occur often and quite often are referred to as credible and less credible contingencies, respectively. Credible contingencies are usually defined as the loss of a single element. For credible contingencies, all requirements of the performance standard must be met unconditionally. Less credible contingencies are defined as the uncommon loss of particular elements, such as a double line on the same tower or a single busbar, or a common-cause failure with the loss of more than one generating unit. For less credible events, all requirements of the performance standard must be met, but in some cases transmission system adjustments must be made. Credible and less credible events are referred to as planning contingencies. Other events are called non-credible contingencies or extreme contingencies. These are generally events that are very rare, such as a combination of a number of credible contingencies, e.g., an independent and simultaneous loss of at least two lines, the loss of an entire substation with more than one busbar, the loss of an entire power plant with more than two generating units, the loss of a tower with more than two lines etc. Extreme contingencies are not taken into account in planning guidelines due to excessive effort involved in the dimensioning of the transmission network. For such events, violation of some performance standards is accepted [3].

B. More Stringent Requirements for Power System Security

Many planning guidelines used by TSOs are based on a standard [3] published by NERC. This standard classifies planning contingencies into eight categories (P0-P7). Three of these categories, P1, P3 and P6, apply to three-phase faults. The remaining categories P2, P4, P5, P6, P7 relate to single-phase faults. A very simplified description of these categories is provided in Table I. Much more detailed description is provided in standard [3]. Some TSOs apply to their power systems more stringent requirements than those established by NERC. An example is described in [24], which assumes that the performance standard must be met for all NERC categories and, in addition, that the power system must maintain synchronism (transient stability) also in categories P2, P4, P7 extended to the three-phase faults without ground (3Ph) and with ground (3PhE). Such additional categories may be defined in the following way

TABLE I Simplified Description Of The NERC Planning Contingency Categories [3]

	Contingencies
P0	Contingency
P1	Three- phase fault in normal pre-fault state and the post-fault loss of one element of the system
P2	Single- phase fault in normal pre-fault state and loss of a busbar section
P3	Three- phase fault in pre- fault state with loss of generating unit followed by system adjustments
P4	Single -phase fault and loss of multiple network elements caused by stuck breaker attempting to clear a fault
P5	Single- phase fault in normal pre-fault state cleared with delay by back-up protection
P6	Two overlapping single contingencies
P7	Single- phase fault in normal pre-fault state and loss of two any adjacent circuits on a common structure

P2-3Ph (three-phase fault in normal pre-fault state and loss of bus section),
P4-3PhE (three-phase-to-ground fault and loss of multiple elements caused by failure of the single pole of the breaker attempting to clear the fault),
P7-3Ph (three-phase fault in normal pre-fault state and loss of any two adjacent circuits on common structure).

Obviously, from the point of view of power system transient stability, the above-mentioned contingencies are much stricter for the power system than those described in the NERC standard [3]. The standard described in [24] assumes that, for the above-mentioned additional contingencies: P2-3Ph, P4-3PhE, P7-3Ph, the power system must be secured by event-based control and event-based protections.

In contemporary transmission networks independent pole operated CBs with dual trip coils are usually used. For such breakers, an assumption that more than one pole of the breaker get stuck in the closed position is rather non-credible. Therefore, the P4-3PhE contingency assumes that only one pole of the breaker gets stuck when attempting to clear a three-phase fault with or without ground. In such a case a three-phase-to-ground fault after the normal clearing time is reduced to a single-phase fault, which must be cleared by the BFP.

C. P4-3PhE Contingency in the Breaker-and-a-Half Configuration

For substations with the breaker-and-a-half configuration the P4-3PhE contingency should be considered for the failure of the bus breaker and the tie breaker. The bus breaker failure case is illustrated in Fig. 1. A three- phase-to-ground fault (3PhE) lasts on the line D for the normal clearing time (Fig. 1a) and thereafter the tie breaker 6 and two poles of the bus breaker 4 are open (Fig. 1b). As a result, the three-phase-to-ground fault (3PhE) is reduced to a single-phase fault (1PhE). Finally, the short-circuited line D is disconnected by the local breaker back-up protection by opening the bus breaker 1 (Fig. 1(c)). It is important to emphasize here that, for substations with the breaker-and-a-half configuration, failure of the bus breaker does not disconnect any other circuit (lines A, B, C). For this reason, unwanted operation of the BFP does not switch off any additional network element.

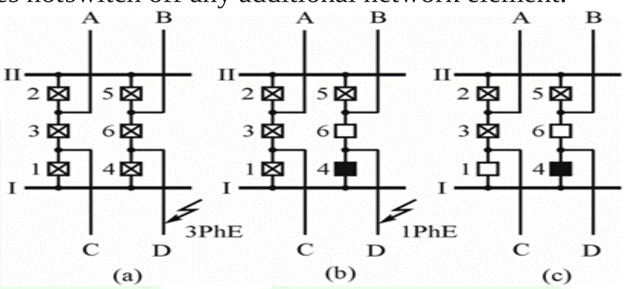

Fig. 1. Three-phase-to-ground fault and the failure of one pole of the bus-side breaker for the breaker-and-a-half configuration (where 1, 2, 4, 5 are bus breakers and 5 is the bus coupler).

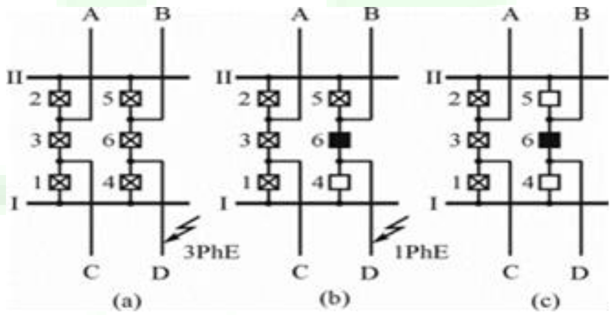

Fig. 2. Three-phase-to-ground fault and the failure of one pole of the tie breaker for the breaker-and-a-half configuration (where 1, 2, 4, 5 are bus and 3, 6 are tie breakers).

If a tie breaker fails (Fig. 2), the short-circuited line D is disconnected in the final stage (Fig. 2(c)) by the local breaker back-up protection by opening the bus breaker 5. As a result, the adjacent line B is also switched off. In this case, an unwanted operation of the BFP switches off additional network elements and can be dangerous for the power system. For this reason the risk of unwanted operation of the BFP following the multi-phase faults must be reduced to the minimum.

A. P4-3PhE Contingency in the Dual Busbars-SingleBreaker Configuration

The case of the P4-3PhE contingency in the dual busbars-single breaker configuration is illustrated in Fig. 3.

A three-phase-to-ground fault (3PhE) lasts on the line D for the normal clearing time (Fig. 3(a)) and thereafter two poles

 ISSN(ONLINE):2278 – 3814

of the bus breaker 4 are opened up (Fig. 3b). As a result, the three- phase-to-ground fault (3PhE) is reduced to a single-phase fault (1PhE). Finally, the short-circuited line D is disconnected by the local breaker back-up protection by opening the bus breaker 3 and the bus coupler 5 (Fig. 3(c)). In this case, the busbar section I and all associated circuits are switched off and disconnected.

IV. IFUSE CONFIGURATION AND OPERATING PRINCIPLE

Fig. 3 presents a diagram of the series connection of an iFuse with a CBVU active switch (Sm). This series connection can be regarded as a new compound device featuring power terminals pt1 and pt2, input binary signal S for the control of Sm, and output binary signal st to report the health status of Sm. The iFuse is composed of a normally-ON active switch (SiF) together with its driving circuitry, the circuitry to quickly diagnose Sm faults, and the iFuse power supply. SiF is a CBVU switch. This allows maintaining the freewheeling path after Sm SCF, which in pre-fault condition is offered by Sm antiparallel diode. The diode shown in the iFuse symbol of Fig. 3(a) denotes the availability of the abovementioned free-wheeling path. The self-power-supply circuit conceived in [22] can be used to power the isolated gate driver of Sm (GDPS) and the iFuse circuitry (iFPS) by recycling Sm turn-off switching losses. Isolated drivers are required to transfer digital signals across the isolation barrier between the converter control and the converter power circuit. Fig. 4 and Fig. 5 show in full detail the circuit of the four main functional blocks making up the proposed iFuse. An nchannel metal-oxide-semiconductor field-effect transistor (MOSFET) is here selected to implement SiF switch. The Smfault automatic-detection circuitry is composed of the forwardcurrent detection circuit (FCDC) and the fault detection logic (FDL). Fig. 5 shows the circuit of the iFPS, following the design of [22] but modified to deliver two voltage supplies(Vfuse and VCC), one of them stabilized with linear voltage regulator U5. Fig. 5 shows the evolution of the main iFuse analog and digital signals described in this section. The compound device shown in Fig. 3(a) will be integrated in a power converter. A SCF of Sm, will be typically followed by a switching state where Sm control signal is low (S = 0) and a positive current iS flows through Sm, with reference to Fig. 3(b). The proposed iFuse solution will stand-alone detect this situation to diagnose the SCF of Sm, to then immediately isolate it from the rest of the circuit by blocking its forward current path. In normal operation, SiF is kept permanently ON thanks to voltage Vfuse feeding SiF's gate through fuse Flatch (see Fig. 4). During this condition and since MOSFET SiF acts as shunt when ON, the FCDC senses the current iS by amplifying the voltage across SiF with the circuit formed by OP operational amplifier and resistors Rf-Rg. The sensed current is then compared through comparator COMP and resistors RIS1-RIS2 to the threshold value IS, th, in order to determine if a positive current is flowing through Sm. This is indicated by Boolean variable IS, such that

$$IS = 0 \text{ when } i_S < I_{S,\text{th}}$$
$$IS = 1 \text{ when } i_S \geq I_{S,\text{th}}. \qquad (1)$$

S S,th S S,th 0 when 1 when . IS i I IS i I = < = ≥ (1) It seems straightforward that then the FDL just needs to look for a concurrent S = 0 and IS = 1 to determine the SCF of Sm. However, it must be taken into account that the described conditions can also be met during Sm turn-off transition in normal operation. Therefore, to avoid a false Sm-failure detection, the fault detection must be disabled during this time interval. To do so, a disable signal

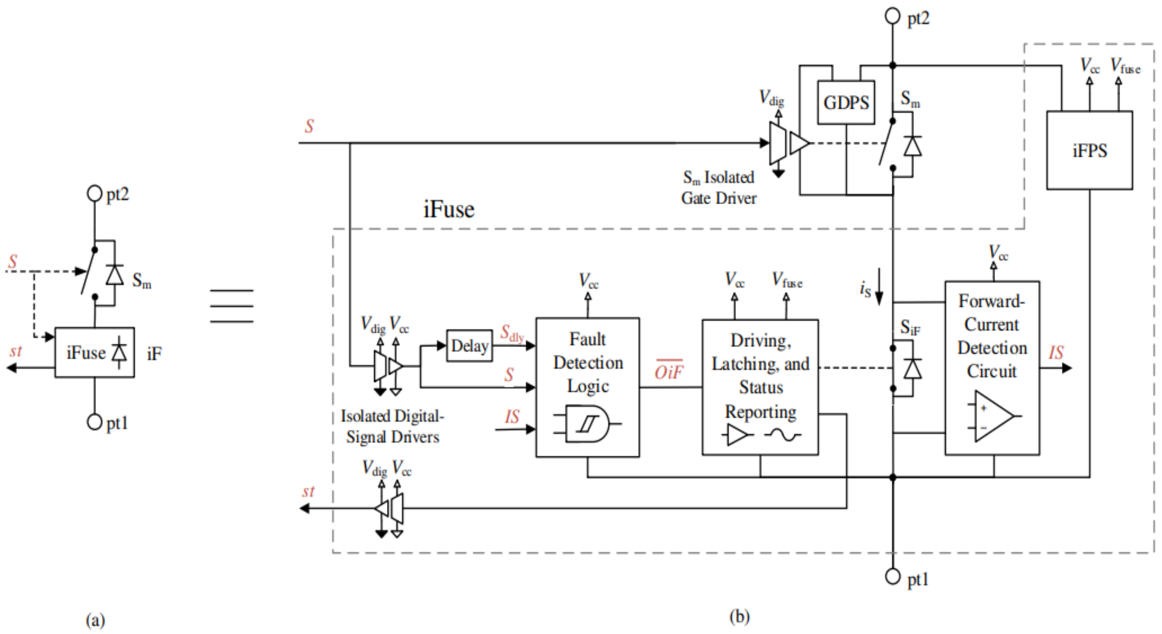

Fig. 3. Diagram of the compound device constituted by switch Sm and the proposed iFuse. (a) Compact representation of the compound device, showing the iFuse symbol. (b) Expanded view of the iFuse device, showing its internal functional blocks. Relevant digital signals appear in red.

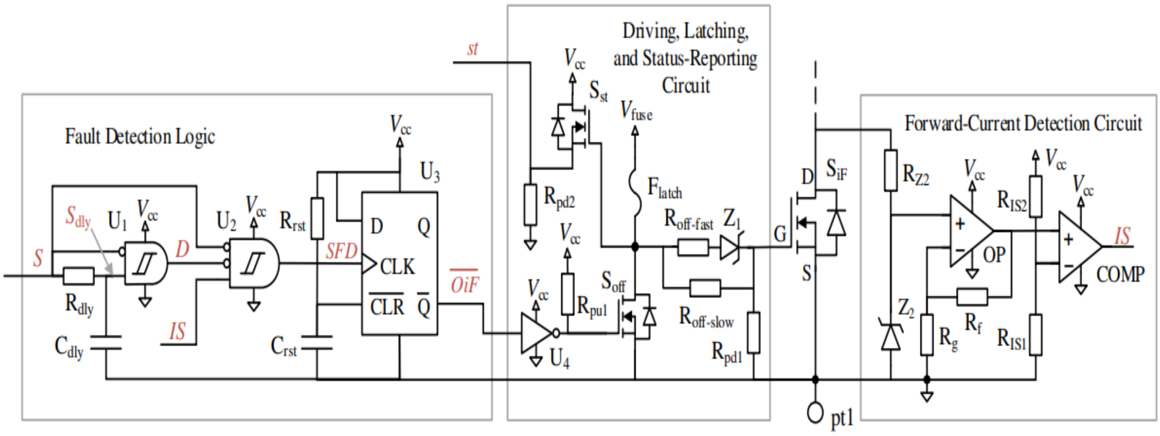

Fig. 4. Schematic of the fault detection logic, the driving, latching, and status-reporting circuit, and the forward-current detection circuit. Relevant digital signals appear in red

$$D = \overline{S} \cdot S_{dly} \quad (2)$$

is defined, where S_{dly} is a replica of S delayed T_{dis} seconds and generated with R_{dly} and C_{dly} RC network.

Finally, the switch fault detection signal

$$SFD = \overline{D} \cdot \overline{S} \cdot IS \quad (3)$$

is generated, where SFD = 1 indicates the detection of Sm SCF. When signal SFD transitions from 0 to 1, it latches signal to zero with the D bistable U3. Therefore, when a fault is detected = 0 permanently, causing MOSFET Soff to turn on, which performs two actions: turning SiF off by discharging its gate and fusing Flatch. Moreover, pull-up resistance Rpu1 ensures that, in case of failure of the FDL block, the iFuse is engaged, turning SiF off. The D bistable is reset to = 1 during the iFuse device power up with Rrst and Crst RC network. Since Sm SCF may result in a short-circuit current flowing through the failed switch as well as other switches, the failure detection procedure must occur before the triggering of the gate-driver overcurrent protection of the healthy switches in the short-circuit current path, such that the short-circuit current is sustained the necessary time for OiF to engage. Moreover, the short-circuit current scenario also imposes that SiF turn off must be performed taking into account two considerations. First, SiF turn off must be quick enough to avoid damage of SiF and other healthy switches located in the short-circuit current path. The maximum energy absorption capability of MOSFET and IGBT chips is around 4 to 5 J per

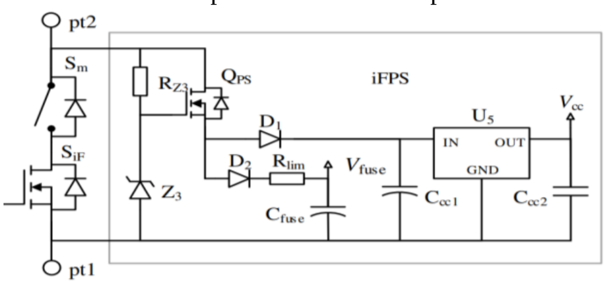

Fig. 5. Schematic of the iFPS circuit

cm2 of die surface, resulting in a maximum permissible short circuit event duration around 10 µs [6], [23]. However, on a second consideration, SiF turn off must be slow enough to avoid high diS/dt values that could cause voltage spikes in the parasitic inductances present in the short-circuit current path, damaging SiF and other healthy devices due to overvoltage. For this reason, the turn off of SiF is performed in two stages. In the first stage, SiF gate is discharged until its gate-to-source voltage vGS,SiF reaches the threshold value VGS,th. In this interval, SiF remains ON since vGS,SiF > VGS,th and SiF's gate discharge is performed quickly to account for the first consideration. In the second stage, vGS,SiF is discharged from VGS,th to zero volts. This is the interval where the true turn off takes place. To account for the second consideration, the gate discharge is performed slower than in the first stage. The abovementioned discharge process is accomplished through.

V. CONCLUSION

A novel device has been proposed to improve the fault tolerance and reliability of power converters where switch SCF are especially detrimental. This novel device, designated. as iFuse, operates by very quickly transforming an original switch SCF into a switch OCF while at the same time enabling a free-wheeling current path on the failed device. For a converter to present such improved fault tolerance and reliability, an iFuse must be connected in series with each CBVU switch, or at least with those more critical in terms of fault tolerance. Its operating principle is similar to conventional electronic fuses, but it allows selective turn off of only those iFuses whose associated switch has failed in short circuit, all performed in a standalone fashion. Moreover, the iFuse can properly handle the turn off of high short-circuit currents flowing through it, the failed switch, and other healthy devices in the current path. Special care has been taken in the design of the iFuse turn-off procedure so that it is fast enough to avoid the damage of healthy devices due to sustained overcurrent, and so that it does not incur in elevated di/dt that could damage healthy devices due to overvoltage. A signal reporting the health-status of the associated switch has been added. Moreover, the power required for the iFuse operation is provided by recycling the turn-off losses of the associated converter switch. Therefore, there is no need for an additional power supply, allowing its application in all types of converters and simplifying to a great extent the integration of the iFuse into a compact assembly. The health-status reporting functionality can be easily complemented with the OCF detection, by simply monitoring the associated switch voltage across the power terminals. The iFuse enables the highest improvements in fault tolerance in converters with parallelized power devices, employing NPC multilevel topologies, with redundant legs and/or with multiple phases. If incorporated in multiple power switches, the converter will be able to withstand multiple switch faults. Experimental results demonstrate that the designed circuit allows a fast detection and isolation of a short-circuit-failed switch, while properly stopping currents up to 1 kA without damaging healthy devices.

REFERENCE

1. Andruszkiewicz, Jerzy, Józef Lorenc, Bogdan Staszak, Agnieszka Weychan, and Beata Zięba. "Overcurrent protection against multi-phase faults in MV networks based on negative and zero sequence criteria." *International Journal of Electrical Power & Energy Systems* 134 (2022): 107449.
2. Shahzad, Umair. "Transient stability risk assessment framework incorporating circuit breaker failure and severe weather." *Australian Journal of Electrical and Electronics Engineering* 19, no. 2 (2022): 137-148.
3. Filba-Martinez, Alber, Salvador Alepuz, Sergio Busquets-Monge, Adria Luque, and Josep Bordonau. "An intelligent electronic fuse (iFuse) to enable short-circuit fault-tolerant operation of power electronic converters." (2020).
4. Calcara, Luigi, Luigi D'Orazio, Maurizio Della Corte, Guglielmo Di Filippo, Alessio Pastore, Davide Ricci, and Massimo Pompili. "Faults evaluation of MV underground cable joints." In *2019 AEIT International Annual Conference (AEIT)*, pp. 1-6. IEEE, 2019.
5. Javaid, Uzair, Francisco D. Freijedo, Drazen Dujic, and Wim van der Merwe. "MVDC supply technologies for marine electrical distribution systems." *CPSS Transactions on Power Electronics and Applications* 3, no. 1 (2018): 65-76.
6. Javaid, Uzair, Francisco D. Freijedo, Drazen Dujic, and Wim van der Merwe. "Marine MVDC multi-phase multi-pulse supply." In *IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 6807-6812. IEEE, 2017.
7. Donnal, John S., Peter Lindahl, David Lawrence, Ryan Zachar, and Steven Leeb. "Untangling non-contact power monitoring puzzles." *IEEE Sensors Journal* 17, no. 11 (2017): 3542-3550.
8. Espinoza, Sebastián, Mathaios Panteli, Pierluigi Mancarella, and Hugh Rudnick. "Multi-phase assessment and adaptation of power systems resilience to natural hazards." *Electric Power Systems Research* 136 (2016): 352-361.
9. Espinoza, Sebastián Andrés. "Multi-phase resilience assessment and adaptation of electric power systems throughout the impact of natural disasters." PhD diss., Pontificia Universidad Catolica de Chile (Chile), 2015.
10. Dubey, Anamika, Hongbo Sun, Daniel Nikovski, Jinyun Zhang, Tomihiro Takano, Yasuhiro Kojima, and Tetsufumi Ohno. "Locating of multi-phase faults of ungrounded distribution system." In *2014 International Conference on Power System Technology*, pp. 1657-1664. IEEE, 2014.
11. H. Wang, M. Liserre, and F. Blaabjerg, "Toward Reliable Power Electronics: Challenges, Design Tools, and Opportunities," IEEE Ind. Electron. Mag., vol. 7, no. 2, pp. 17–26, Jun. 2013.
12. W. Zhang, D. Xu, P. N. Enjeti, H. Li, J. T. Hawke, and H. S. Krishnamoorthy, "Survey on Fault-Tolerant Techniques for Power Electronic Converters," IEEE Trans. Power Electron., vol. 29, no. 12, pp. 6319–6331, Dec. 2014.
13. Y. Song and B. Wang, "Survey on Reliability of Power Electronic Systems," IEEE Trans. Power Electron., vol. 28, no. 1, pp. 591–604, Jan. 2013.
14. A. Matallana, E. Ibarra, I. López, J. Andreu, J. I. Garate, X. Jordà, and J. Rebollo, "Power module electronics in HEV/EV applications: New trends in wide-bandgap semiconductor technologies and design aspects," Renewable and Sustain. Energy Revs., vol. 113, p. 109264, Oct. 2019.
15. Cecati, A. O. Di Tommaso, F. Genduso, R. Miceli, and G. Ricco Galluzzo, "Comprehensive Modelling and Experimental Testing of Fault Detection and Management of a Non-Redundant Fault-Tolerant VSI," IEEE Trans. Ind. Electron., pp. 3945–3954, Jun. 2015.
16. Lu and S. K. Sharma, "A Literature Review of IGBT Fault Diagnostic and Protection Methods for Power Inverters," IEEE Trans.on Ind. Applicat., vol. 45, no. 5, pp. 1770–1777, Jul. 2009.
17. P. Lezana, J. Pou, T. A. Meynard, J. Rodriguez, S. Ceballos, and F. Richardeau, "Survey on Fault Operation on Multilevel Inverters," IEEE Trans. Ind. Electron., vol. 57, no. 7, pp. 2207–2218, Jul. 2010.
18. Y. Neyshabouri and H. Iman-Eini, "A New Fault-Tolerant Strategy for a Cascaded H-Bridge Based STATCOM," IEEE Trans. Ind. Electron., vol. 65, no. 8, pp. 6436–6445, Aug. 2018.
19. M. Farhadi, M. T. Fard, M. Abapour, and M. T. Hagh, "DC–AC Converter-Fed Induction Motor Drive with Fault-Tolerant Capability Under Open- and Short-Circuit Switch Failures," IEEE Trans. Power Electron., vol. 33, no. 2, pp. 1609–1621, Feb. 2018.
20. M. Yaghoubi, J. S. Moghani, N. Noroozi, and M. R. Zolghadri, "IGBTOpen-Circuit Fault Diagnosis in a Quasi-Z-Source Inverter," IEEE Trans. Ind. Electron., vol. 66, no. 4, pp. 2847–2856, Apr. 2019.
21. Z. Wang, X. Wang, M. Cheng, and Y. Hu, "Comprehensive Investigation on Remedial Operation of Switch Faults for Dual Three Phase PMSM Drives Fed by T-3L Inverters," IEEE Trans. Ind. Electron., vol. 65, no. 6, pp. 4574–4587, Jun. 2018.
22. K. Wang, Y. Tang, and C.-J. Zhang, "Open-Circuit Fault

Diagnosis and Tolerance Strategy Applied to Four-Wire T-Type Converter Systems," IEEE Trans. Power Electron., vol. 34, no. 6, pp. 5764–5778, Jun. 2019.
23. J. Amini and M. Moallem, "A Fault-Diagnosis and Fault-Tolerant Control Scheme for Flying Capacitor Multilevel Inverters," IEEE Trans. Ind. Electron., vol. 64, no. 3, pp. 1818–1826, Mar. 2017.
24. J. Nicolas-Apruzzese, S. Busquets-Monge, J. Bordonau, S. Alepuz, and Calle-Prado, "Analysis of the Fault-Tolerance Capacity of the Multilevel Active-Clamped Converter," IEEE Trans. Ind. Electron., vol. 60, no. 11, pp. 4773–4783, Nov. 2013.
25. S. Bolognani, M. Zordan, and M. Zigliotto, "Experimental fault-tolerant control of a PMSM drive," IEEE Trans. Ind. Electron., vol. 47, no. 5, pp. 1134–1141, Oct. 2000.
26. A.L. Julian and G. Oriti, "A Comparison of Redundant Inverter Topologies to Improve Voltage Source Inverter Reliability," IEEE Trans. on Ind. Applicat., vol. 43, no. 5, pp. 1371–1378, Sep. 2007.
27. S. Ceballos, J. Pou, E. Robles, J. Zaragoza, and J. L. Martín, "Performance Evaluation of Fault-Tolerant Neutral-Point-Clamped Converters," IEEE Trans. Ind. Electron., vol. 57, no. 8, pp. 2709–2718, Aug. 2010.
28. X. Kou, K. A. Corzine, and Y. L. Familiant, "A Unique Fault-Tolerant Design for Flying Capacitor Multilevel Inverter," IEEE Trans. Power Electron., vol. 19, no. 4, pp. 979–987, Jul. 2004.
29. M. Gleissner and M.-M. Bakran, "A real-life fuse design for a fault□ tolerant motor inverter," in Proc. Eur. Conf. Power Electron. Appl., pp. 1–11, Sep. 2016.
30. H. Li, R. Yu, Y. Zhong, R. Yao, X. Liao, and X. Chen, "Design of 400 V Miniature DC Solid State Circuit Breaker with SiC MOSFET," Micromachines, vol. 10, no. 5, p. 314, May 2019.

