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Fault tolerant topology and controls for a three-level hybrid neutral point clamped-flying capacitor converter

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Abstract: This paper details a three level hybrid fault-tolerant converter. The definition of an original decoupling solution between the fourth flying capacitor (FC) leg and the three neutral point clamped (NPC) based phases overcomes topology hybridisation issues. Under normal conditions, a control strategy of the FC-based leg leads to a converter neutral point voltage balance, and decreases the DC side capacitors' volume and cost. Under fault conditions, the presented fault isolation and converter reconfiguration strategies generate a post-fault converter, which is able to operate safely with the added FC-based leg. The proposed topology is an interesting trade-off between converter fault-tolerant capability and its complexity and offers the ability to be simply reconfigured and controlled in the case of switch fault occurrence. Post-fault operation mode is presented and discussed through the simulation results and first experimental tests.

Keywords – Multilevel converter, NPC topology, FC topology, Fault tolerant Control, Reconfiguration.

1. Introduction

Multilevel converters are attractive for medium-voltage applications and quality management for grid connected systems. Nowadays, they are widely used in many industrial fields such as transportation, alternative motor drives, uninterrupted power supply (UPS), and more recently renewable energy. They offer advantages such as handling high voltage and current ratings, low dv/dt, improved output voltage and current spectrum quality and reduced common mode voltages for standard electrical motors [1]. Many multilevel topologies have been addressed in the literature aiming to reduce the stored energy density and the global converter cost and volume [2]. This is achieved by connecting multiple semiconductor devices and some isolated DC sources, which are generally capacitors. The most relevant are the neutral point clamped (NPC) converter [3], the flying capacitor

(FC) converter [4], the stacked multicell converter (SMC) [5], the active neutral point clamped (ANPC) converter [6] and the multilevel modular converter (MMC) [7,8].

The 3-level neutral point clamped (3L-NPC) converter is one of the most prevalent topologies over a large power operation range from some MW [7–9] to some kW [10–15]. A major concern with this topology is the neutral point (NP) voltage regulation. To deal with this issue, passive balance has to be ensured through a low-frequency sizing of the clamping capacitor. This is performed by increasing their values (some mF) in order to avoid fast charging and discharging. Also, active balance by an integration of the neutral point voltage regulation in the converter control algorithm is needed. This can be performed through appropriate modulation techniques applied for conventional three-phase NPC converter [16,17] or by adding a fourth leg whose control aims to balance the neutral point voltage and enables the use of all degrees of freedom of the NPC converter to improve its output performance [18,19]. [20,21] have proposed to add a fourth 3-Level FC-based topology, at 50% duty ratio and quasi-zero voltage-ripple, which is controlled, under normal conditions, in order to guarantee a balanced NP voltage without low-frequency oscillation, independent of the NP current sign and with easy control of the NPC legs. However, an important issue with this hybrid topology is the mutual interactions between the two topologies [22]: on the one hand, the dead-times introduced into the FC commutation cells affect the 3L-NPC output voltages. On the other hand, the NP current injected by the 3L-NPC into the FC leg leads to a possible imbalance of its flying capacitor voltage.

Furthermore, increasing the number of switches may lead to a reduction of the converter reliability at the first failure occurrence, since one switch fault causes system breakdown and results, depending on the application, in economic or/and severe security issues. In [21], the added fourth leg, initially used for NP voltage balance, is controlled differently when a switch failure occurs in order to increase the multilevel converter reliability and to overcome the system availability concerns. However, to achieve the fault tolerance of the proposed 3L-NPC topology, extra switches and a relatively complicated control are needed. In addition, this solution presents some hard limitations such as the fact that the six inner IGBTs have to guarantee short circuit state if they breakdown. This paper analyses a multilevel hybrid converter topology based on the connection of an FC leg with a 3L-NPC converter, and proposes an additional filter between the two converter parts. Its role is to immunise each part from the effects of the other.

In healthy mode, the fourth FC leg keeps its original role to balance the NP voltage. Moreover, such an additional leg enables even asymmetrical operation such as DC/DC conversion by interleaving the converter

legs through dedicated coupled inductors or 3-phase imbalanced operation [23]. Such operation modes are not possible for a standard NPC topology.

After a fault occurrence, authors propose a new isolation technique by means of dual-fuses components and two possible reconfiguration procedures, all involving the addition of only one thyristor per phase. These isolation and reconfiguration techniques are valid for both OC (open-circuit) and SC (short-circuit) faults and guarantee the converter fault tolerance for all semiconductor technologies (press-pack, etc...). Using the FC fourth leg allows sub-sizing of the capacitance value and minimising the stored energy in the neutral point capacitors. Thus, short-circuit issues are clearly less dangerous than in classical NPC operation with bulk and low life-time electrochemical capacitors. The proposed topology is then an interesting trade-off between converter fault-tolerant capability and its complexity.

Moreover, a post-fault operation mode dedicated to the reconfigured converter is synthesized. The principle of this post-fault mode was first proposed for the 3-leg fault tolerant NPC converter [20]. In this work, authors propose to extend it for the hybrid four leg topology. A 400V/10A experimental test bed is conceived to validate the proposed reconfiguration method and post-fault operation mode with the considered four leg NPC-FC hybrid converter, showing its fault tolerant capabilities.

2. Hybrid NPC-FC topology

The considered topology is based on a 3-phase 3L-NPC inverter with an additional 3-level flying capacitor – based (3L-FC) leg, as shown in Fig. 1. A low-size high-frequency LC filter is added between the two converter parts.

The three 3L-NPC legs are clamped thanks to the FC leg and not to the DC bus middle point. The main role of this additional leg is to provide an active neutral point to the NPC inverter under healthy operation: our solution is to control the 3L-FC with a ratio equal to 50% yielding a constant output voltage equal to half the input voltage. This is an interesting alternative to avoid the problem of low-frequency oscillations on the classical passive neutral point [8] and the introduction of a bulk electrolytic capacitors bank whose lifetime is reduced. Furthermore, an active neutral point allows the compromise between THD and switching losses issue to be handled. Besides, with its small flying capacitor capacitance (some film-cap μF) compared to the classic NPC DC bus one (some electrolytic mF), this fourth leg offers an important benefit for reducing the inverter volume, cost and safety risks.

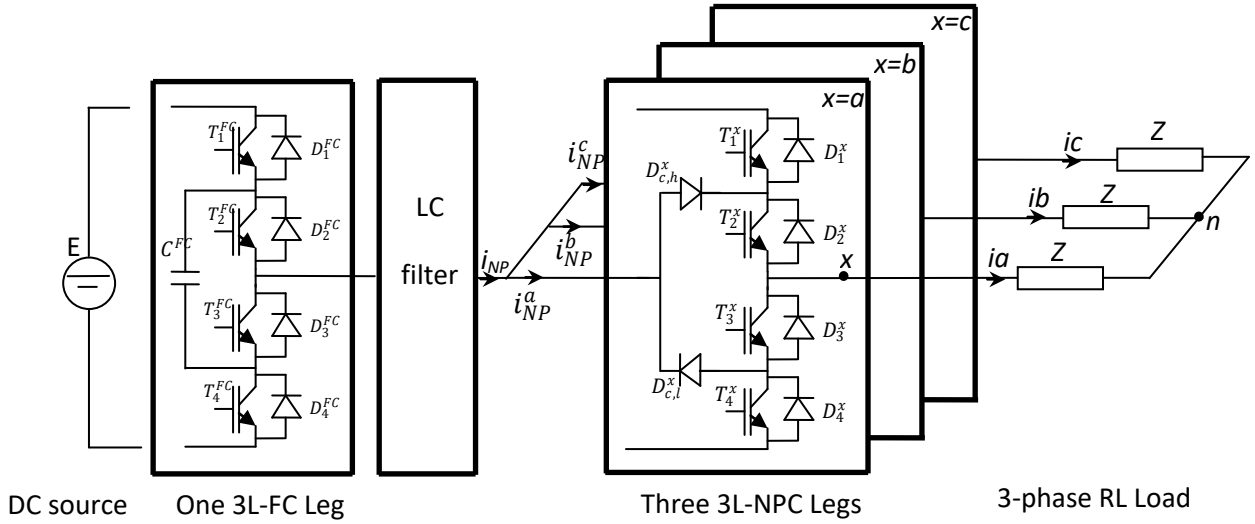


Fig. 1. Considered 3-level fault tolerant hybrid topology

Nevertheless, due to practical implementation constraints (viz. dead-times, two converter switching frequencies), a low-size LC filter must be included [22]. The LC filter capacitor of Fig. 1 is composed of the equivalent decoupling capacitors of the three 3L-NPC legs connected to an additional high-frequency inductor between 3L-FC output and the 3L-NPC's middle point.

In the case of a FC leg IGBTs fault, authors propose a passive redundancy of this leg based on the addition of one FC cell in series with the principal ones as shown in Fig. 2. This solution is derived from the topology of the fault tolerant 5-level flying capacitor DC-DC converter proposed in [24].

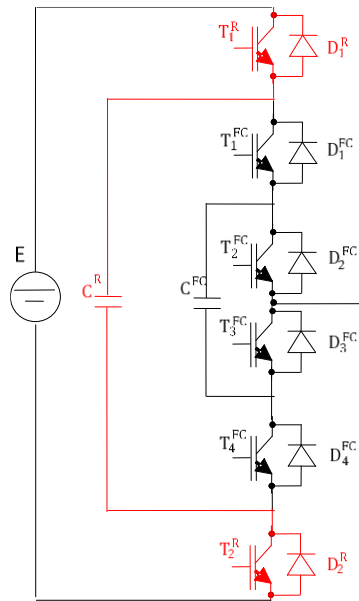


Fig. 2. Fault tolerant 3L-FC leg: In case of an IGBT fault, the redundant cell (in red) replaces the faulty one.

Thanks to the switch redundancy, when an IGBT breakdowns, his complementary IGBT is turned ON. The redundant cell composed of $\{T_1^R, T_2^R, D_1^R, D_2^R, C^R\}$ replaces the faulty one. The FC leg continues to provide the neutral point voltage to the NPC legs. During normal mode, the additional cell is in a permanent on-state. This solution implies the use of DLB modules for the FC because both IGBT failures (open circuit or short circuit) should be in short circuit mode [25].

In the case of one 3L-NPC leg breakdown, the 3L-FC leg is considered as a solution to ensure continuous operation of the converter. In fact, during post-fault operation, the 3L-FC leg can ensure active neutral point voltage balance. The faulty 3L-NPC leg is isolated and the two remaining ones are 3-level modulated.

This paper focuses particularly on the converter fault tolerance after a failure of one IGBT from the three 3L-NPC legs. In the following section, the authors propose an isolation method of the faulty NPC leg and a post-fault reconfiguration technique of the correspondent phase. It is worth mentioning that the proposed fault tolerant converter operation is conditioned on the isolation of the faulty leg and the connection of the corresponding output to the 3L-FC leg added with the LC filter.

3. Improved fault isolation and converter reconfiguration technique

Conventional isolation techniques are based on the blowing up of two symmetrical fuses connected at the upper and lower ends of the leg [20], or by means of passive disconnecter devices embedded in a PCB [26]. The condition these fuses have to fulfil is that their i^2t characteristic must be lower than the IGBT bonding wires to avoid the explosion of the coating. Moreover, classically, the connection of the damaged leg is ensured by two additional IGBT's or one thyristor [21].

In this paper, both isolation and reconfiguration steps are combined through the proposition of a new hardware procedure. It is a simplification of the isolation and reconfiguration technique proposed in [26,27], and applied for a two-level converter. Fig. 3 gives the detailed scheme of the proposed fault-tolerant converter.

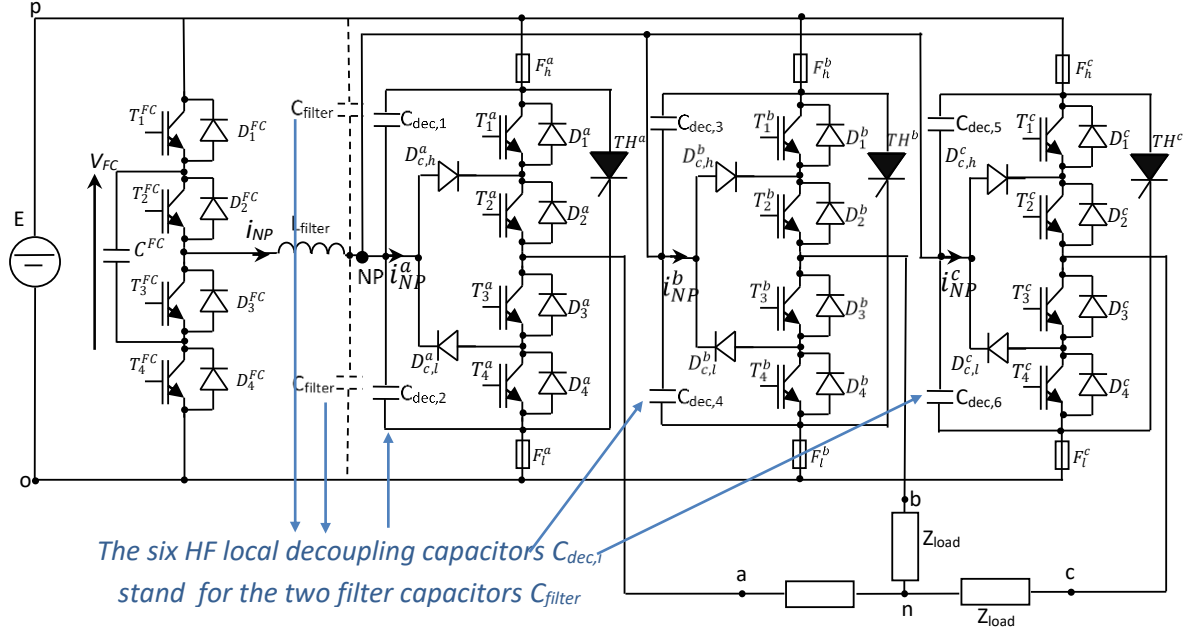


Fig. 3. Detailed scheme of the proposed fault-tolerant converter

Once a fault is detected and its phase x localized ($x = a, b, c$), fuses F_h^x and F_l^x are blown up by a short-circuit created with the corresponding crowbar thyristor TH^x . For example, if IGBT T_2^a is broken, the thyristor TH^a is turned ON in order to have a short circuit through TH^a , F_h^a and F_l^a . These two fuses will be blown and IGBT T_1^a , T_3^a and T_4^a will be separated from the DC bus. Fault detection and localisation are beyond the scope of this paper.

The proposed technique has two essential advantages. First, with forcing the blowing up of the fuses when a switch fault is detected, the three other switches of the failed leg are instantly isolated from the DC supply and the fault spread is avoided. Secondly, there is no need to stipulate which switch among the four is damaged, and which type the fault is (i.e. short circuit or open circuit failure mode).

For the reconfiguration procedure, and when a fault occurs on one of phase x power switches, the thyristor TH^x connects the phase x output and the active neutral point. In fact, with only one thyristor placed between the upper side and lower side fuses and in parallel with each leg, the connection is originally ensured thanks to:

- the anti-parallel diodes of the healthy IGBTs' modules,
- the damaged switch: As described in [26], the i^2t controlled fuses, which ensure the leg isolation, prevent the faulty switch from wire bonding fusion; only the module dies are destroyed. Consequently, the damaged module becomes conductive and bidirectional after the fault occurrence. It can be used to connect the phase x output to the active neutral point.

For instance and as shown in Fig. 4, if a fault occurs on T_1^x/D_1^x switch and when a positive neutral point current (i_{NP}) is flowing, the connection between the load phase and the converter neutral point (NP) takes place through the high side clamping diode ($D_{c,h}^x$), the thyristor (TH^x), the anti-parallel diodes (D_4^x and D_3^x) and the damaged T_1^x/D_1^x switch (which is on conductive mode). In the case of a negative neutral point current, the anti-parallel diodes (D_2^x and D_4^x), the thyristor (TH^x), the damaged T_1^x/D_1^x switch and the negative side clamping diode ($D_{c,l}^x$), ensure the post-fault connection between NP and the load phase x .

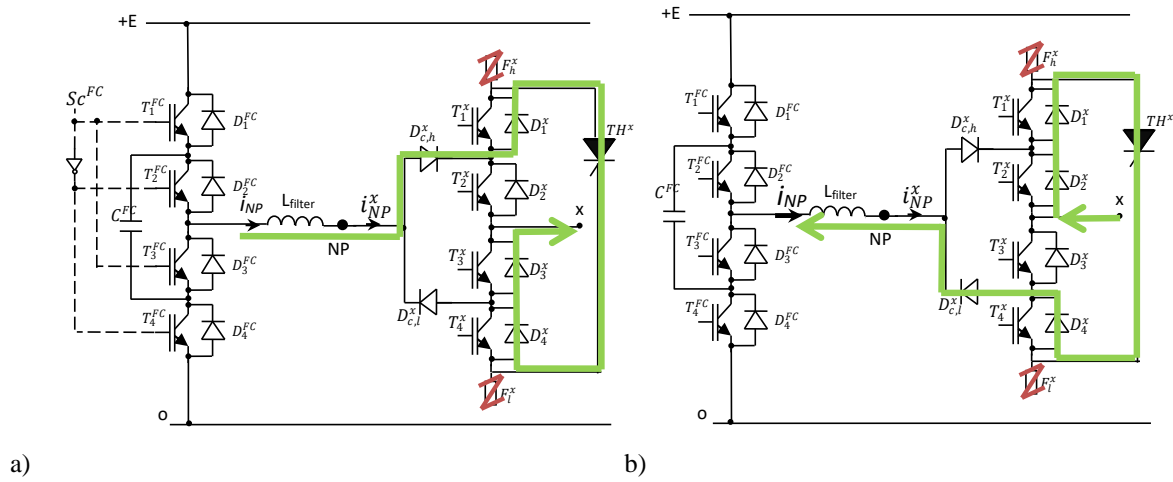


Fig. 4. New fault isolation and post-fault reconfiguration strategy using two fuses and one thyristor per phase. Connection between 'NP' and 'x'. Case of T_1^x/D_1^x switch fault and a) $i_{NP} > 0$, b) $i_{NP} < 0$

Table 1 summarizes the actions to take in case of an IGBT fault. It considers the cases of failure of the FC fourth leg and any of the three NPC legs.

Table 1. Proposed converter reconfiguration after an IGBT fault

Faulty leg	Faulty IGBT	Proposed reconfigurations	Output levels of phase “a” voltage	Output levels of phase “b” voltage	Output levels of phase “c” voltage
FC leg	T_1^{FC}	- T_4^{FC} turned ON - (T_1^R, T_2^R) replaces (T_1^{FC}, T_4^{FC})	3	3	3
	T_2^{FC}	- T_3^{FC} turned ON - (T_1^R, T_2^R) replaces (T_2^{FC}, T_3^{FC})	3	3	3
	T_3^{FC}	- T_2^{FC} turned ON - (T_1^R, T_2^R) replaces (T_2^{FC}, T_3^{FC})	3	3	3
	T_4^{FC}	- T_1^{FC} turned ON - (T_1^R, T_2^R) replaces (T_1^{FC}, T_4^{FC})	3	3	3
NPC leg “a”	T_1^a or T_2^a or T_3^a or T_4^a	- TH^a turned ON - fuses F_h^a and F_1^a blow up - phase “a” connected to FC output	1	3	3
NPC leg “b”	T_1^b or T_2^b or T_3^b or T_4^b	- TH^b turned ON - fuses F_h^b and F_1^b blow up - phase “b” connected to FC output	3	1	3
NPC leg “c”	T_1^c or T_2^c or T_3^c or T_4^c	- TH^c turned ON - fuses F_h^c and F_1^c blow up - phase “c” connected to FC output	3	3	1

With this originally reconfiguration technique, during faulty mode, none of the 12 IGBT modules of the three NPC legs have to support more than $E/2$ voltage. Therefore, an oversizing of these modules is unnecessary. This is an important advantage of the proposed reconfiguration method. Besides, the number of semiconductors necessary for the reconfiguration is reduced compared to reconfiguration methods proposed in [21]. Only one thyristor is needed to ensure both isolation of the leg and connection of the phases to the active midpoint.

One can conclude that with this technique, fault isolation and post-fault reconfiguration are simultaneously achieved with one additional thyristor and regardless of which IGBT is damaged.

4. Normal condition and post-fault operations

4.1. Normal condition operation

During healthy mode, the aim of the 3L-FC leg is to regulate actively the voltage at the neutral point of the 3L-NPC converter neutral point. It consists of maintaining the flying capacitor voltage V_{FC} around $E/2$ where E is the DC bus voltage. This is achieved by two features:

- First, and as introduced by [20], the 3L-FC leg voltage is continuously equal to the intermediate level ($E/2$). The two switching cells are controlled in a complementary way using the unique control signal S_c^{FC} .
 - Secondly, an extra degree of freedom of the FC topology described in [28]: the Flying Capacitor voltage, V_{FC} depends on the i_{NP} sign and the control signal S_c^{FC} . For example, a positive i_{NP} current with a high S_c^{FC} leads to an increase of V_{FC} and with a low S_c^{FC} leads to a V_{FC} decrease.
- Consequently, the active neutral point balance is obtained by charging and discharging the flying capacitor with the i_{NP} using a constant duty cycle $DT=0.5$ and a passive RLC filter, as presented in [29].

4.2. Post-fault operation mode (1L-3L-3L):

The proposed multilevel hybrid converter topology can tolerate any of the 3L-NPC switch faults (Fig. 3). When a short-circuit or an open-circuit fault occurs on one of the 12 switches and after fault isolation for topology reconfiguration described above, the multilevel converter control has to be achieved in order to enable system operation continuity.

As presented in Section 3, the damaged leg is isolated and its output is connected to the active neutral point of the 3L-NPC directly through the failed IGBT module. This is carried out by means of the crowbar thyristor TH^x connected in parallel to each leg (Fig. 4). In order to simplify the proposed faulty mode analysis, phase a is considered as the faulty leg. The same methodology could be applied if a switch fault occurs in phase b or phase c .

The faulty mode is referred to as (1L-3L-3L) because under fault conditions, phase a output would have one level ($V_{ao} = V_{NP} = \frac{E}{2}$) and phases b and c would be both three levels ($0, \frac{E}{2}, E$). The mathematical modelling of the (1L-3L-3L) faulty mode leads to six active voltage vectors (with an amplitude of $E/3$) and one zero voltage vector that can be used to control the reconfigured converter [30].

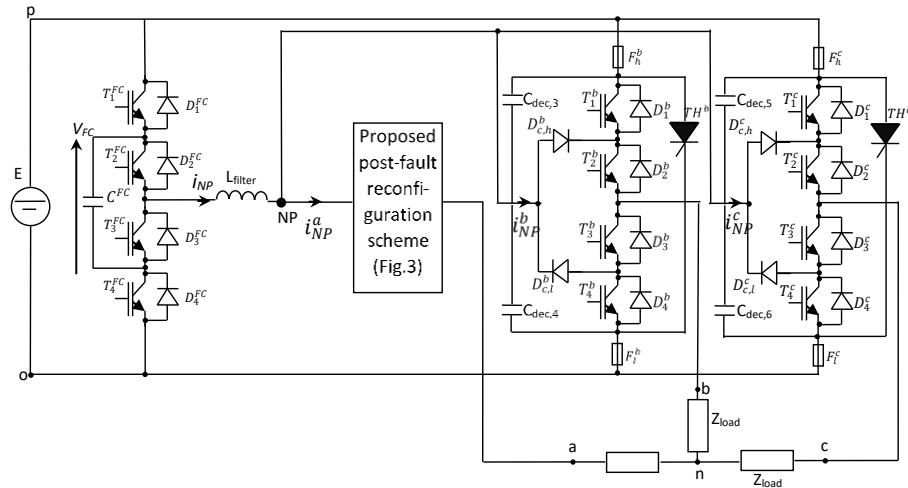


Fig. 5. Proposed (1L-3L-3L) mode after a phase a switch fault (analogue reconfiguration is possible under phase b or phase c switch fault): converter topology

However, the (1L-3L-3L) mode has a large drawback since the maximum modulation depth is reduced by 50%. This 50% reduction leads to a limitation of the power provided by the system. This is not of great concern since operating under fault conditions is considered as a temporarily degraded mode providing converter availability until deep system maintenance and repairs are performed.

It is to mention that in case of a fault of one IGBT from the FC leg, the fault tolerant solution proposed in Fig. 2 allows the output power to be same during normal operation and post-fault operation. Table 2 gives the maximum output voltage module, V_{max} , and maximum modulation depth, M_{max} under linear operation for normal and faulty conditions.

Table 2. Output converter performance under normal and faulty conditions operation

	Normal operation	NPC fault condition operation	FC fault condition operation
maximum output voltage module, V_{max} (V)	$E/\sqrt{3}$	$E/(2.\sqrt{3})$	$E/\sqrt{3}$
maximum modulation depth, M_{max}	1.15	0.57	1.15

The (1L-3L-3L) faulty mode reconfiguration is simulated under a switch fault occurrence at $t=0.02$ s. The simulation parameters are as follows: a 600 V DC bus (L_{filter}), a 50 mH filtering inductance, a 20 μ F filtering capacitor (C_{filter}), a 40 μ F flying capacitor, a 20 kHz switching frequency and 1 μ s dead time.

Under normal conditions (*i.e.* before $t=0.02$ s), the modulation depth is taken equal to its maximum value, $M=M_{max}=1.15$.

In Figs. 6a and 6b, the system availability can be observed with a perfectly balanced operation and quasi-sinusoidal load currents. The 50% decrease of the output current amplitude is due to the reference duty cycle derating which is introduced to take into account the proposed faulty model limitation explained above. This limitation can also be seen on the phase-to-phase voltage V_{ab} given in Fig. 6a. After the switch fault occurrence, V_{ab} has only three levels ($-E/2$, 0 and $+E/2$) and cannot reach the $+E$ and $-E$ levels.

The switch fault occurrence and the proposed faulty mode do not affect the neutral point voltage balance whose ripple remains acceptable (15%) under fault conditions. Figs. 6c and 6d show that the neutral point voltage harmonic amplitude at the switching frequency increases from 1.3% to 4.8% under (1L-3L-3L) faulty mode. This is because the output currents and, consequently, the mean value of charging and discharging FC current have decreased under fault conditions.

In spite of the relative increase of the neutral point voltage ripple and its harmonic distortion, they are acceptable and the system operation performance under fault conditions is verified.

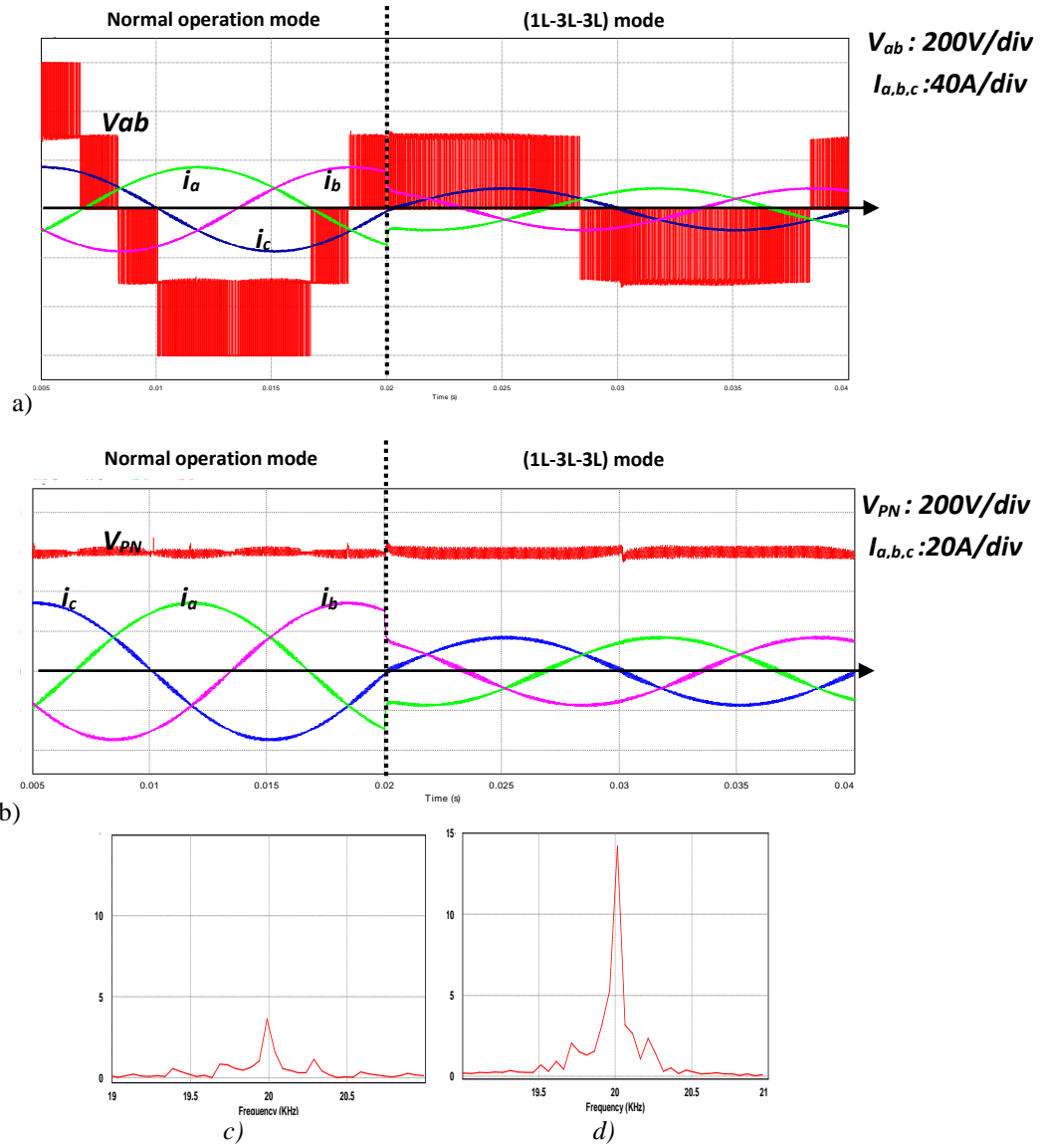


Fig. 6. Transition from normal mode to (1L-3L-3L) faulty mode $E = V$, $f_{sw} = \text{Hz}$, $R = \Omega$, $L = \text{mH}$

- a) Line-to-line voltage, V_{ab} (200 V/div) and load currents, I_a, I_b, I_c (40 A/div)
 b) Neutral point voltage (V_{PN}) before and after fault occurrence (200 V/div) and load currents, I_a, I_b, I_c (20 A/div)
 c) V_{PN} spectrum during normal operating mode (500 Hz/div-5 A/div) b) V_{PN} spectrum under faulty conditions (500 Hz/div-5 A/div)

Table 3 gives a comparison between the features of :

- the conventional 3-level NPC converter
- the proposed fault tolerant converter after a fault of a NPC leg IGBT
- the proposed fault tolerant converter after a fault of a FC leg IGBT

Table 3. Comparison of the proposed fault tolerant solutions

	Number of power switches	Maximum modulation index	Maximum output power after switch fault conditions (p.u)	Active neutral point control under normal conditions	Converter efficiency under switch fault conditions
Conventional 3L-NPC converter	12 IGBT modules	1.15	0	No	N.A. ^(*)
Proposed fault tolerant converter after NPC leg fault	16 IGBT modules + 3 Thyristors +6 rapid fuses	1.15 under N.O. ^(*) 0.57 under F.O. ^(*)	0.5	Yes	++
Fault tolerant converter after FC leg fault	16 IGBT modules +3 Thyristors +6 rapid fuses	1.15 under N.O. ^(*) 1.15 under F.O. ^(*)	1	Yes	++

^(*)N.O.: Normal Operation mode – F.O.: Fault Operation mode –N.A.: Not Applicable

The proposed reconfiguration technique limits the needed power switches: besides the 3L-FC leg, only three thyristors and six rapid fuses have to be added. In terms of cost, and even if it depends on the converter power range, the proposed solutions imply a price increase that is relatively acceptable when one consider the converter reliability enhancement. A dilemma between the required output power and the power loss minimisation has to be considered to point out the most suitable mode for the studied application.

5. Experimental results

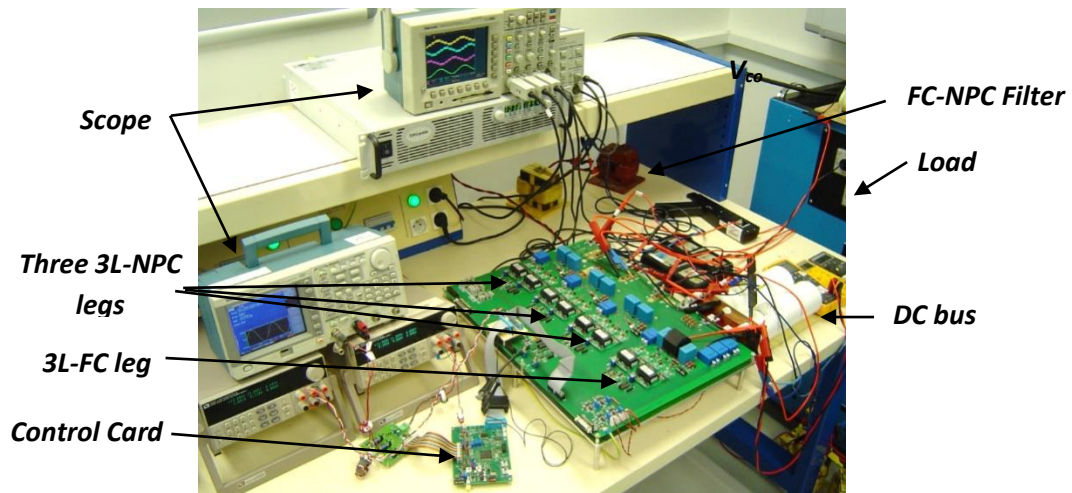
The fault tolerant converter investigated in this paper was experimentally tested with a *15 kW* hybrid topology: one 3L-FC leg and three 3L-NPC legs as presented on Fig. 7a. To point out the fault tolerance capability, a switch fault in phase *a* is considered. Experimental verifications of the reconfiguration from healthy mode to the proposed (1L-3L-3L) mode are carried out using a *400 V* DC bus, a *40 μF* flying capacitor, a *50 mH* filtering inductance, *1 μs* dead-time and a modulation depth taken equal to *0.8*. A *200 μs* ‘dead band’ is introduced between the normal and the (1L-3L-3L) modes in order to avoid overload currents that may be caused by converter operation change.

Fig. 7 and Fig. 8 show some of the obtained results. The fault switch on phase *a* leads to the converter reconfiguration: phase *a* has one level and phases *b* and *c* have three levels. The high and low level ripples of V_{bo} and V_{co} voltages are due to the low neutral point voltage ripple, as shown in Fig. 7c.

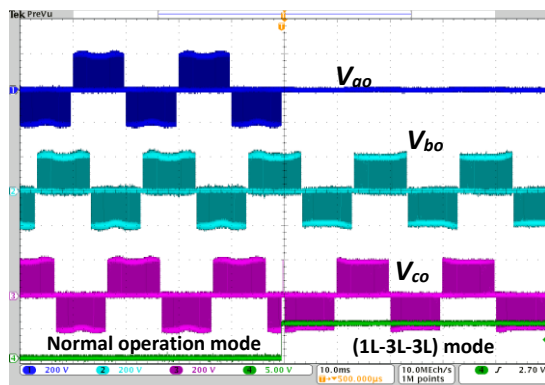
In fact, this figure details the filtering operation between the 3L-FC leg and the 3L-NPC part of the fault tolerant converter. On the one hand, the LC filter removes the residual voltage pulses (caused by the dead-times of the FC leg IGBTs) from the 3L-FC leg output voltage, V_{3L-FC} , and the neutral point voltage is consequently well-balanced (i.e. ripple lower than *10%*) under both normal and faulty conditions.

On the other hand, the HF components of the i_{NP} current are filtered by the L_{filter} inductance improving the V_{FC} balance, since this voltage depends on the i_{NP} current.

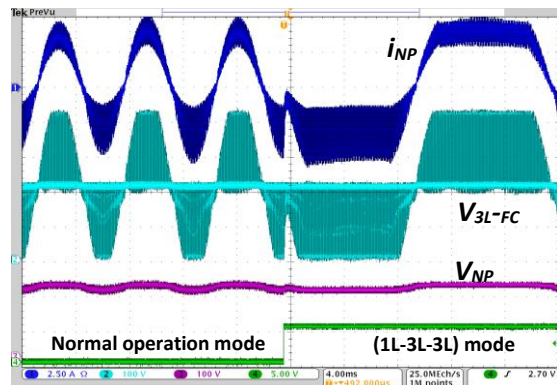
As explained in the previous section, the converter output currents with the proposed (1L-3L-3L) mode are decreased by 50%. Fig. 8.a shows that after the dead band, the output currents are balanced and sinusoidal but with an amplitude 50% lower than under normal conditions.



a)



b)



c)

Fig. 7. Experimental tests on the 3 level fault-tolerant hybrid converter: a) Laboratory setup, b) Transition from normal operation mode to (1L-3L-3L) mode after phase a switch fault occurrence, c) Neutral point current i_{NP} (2.5 A/div), 3L-FC output voltage V_{3L-FC} (100 V/div), neutral point voltage V_{NP} (100 V/div)

In the case of switch fault recovery and if the faulty leg is reconnected to the multilevel converter as before faulty occurrence, transition from faulty mode to normal operation mode was experimentally investigated. The same 200 μ s ‘dead band’ is introduced between the two operation modes. Fig. 8.b shows that the transition is perfectly achieved: a complete power system recovery is obtained with the same performances than before fault occurrence.

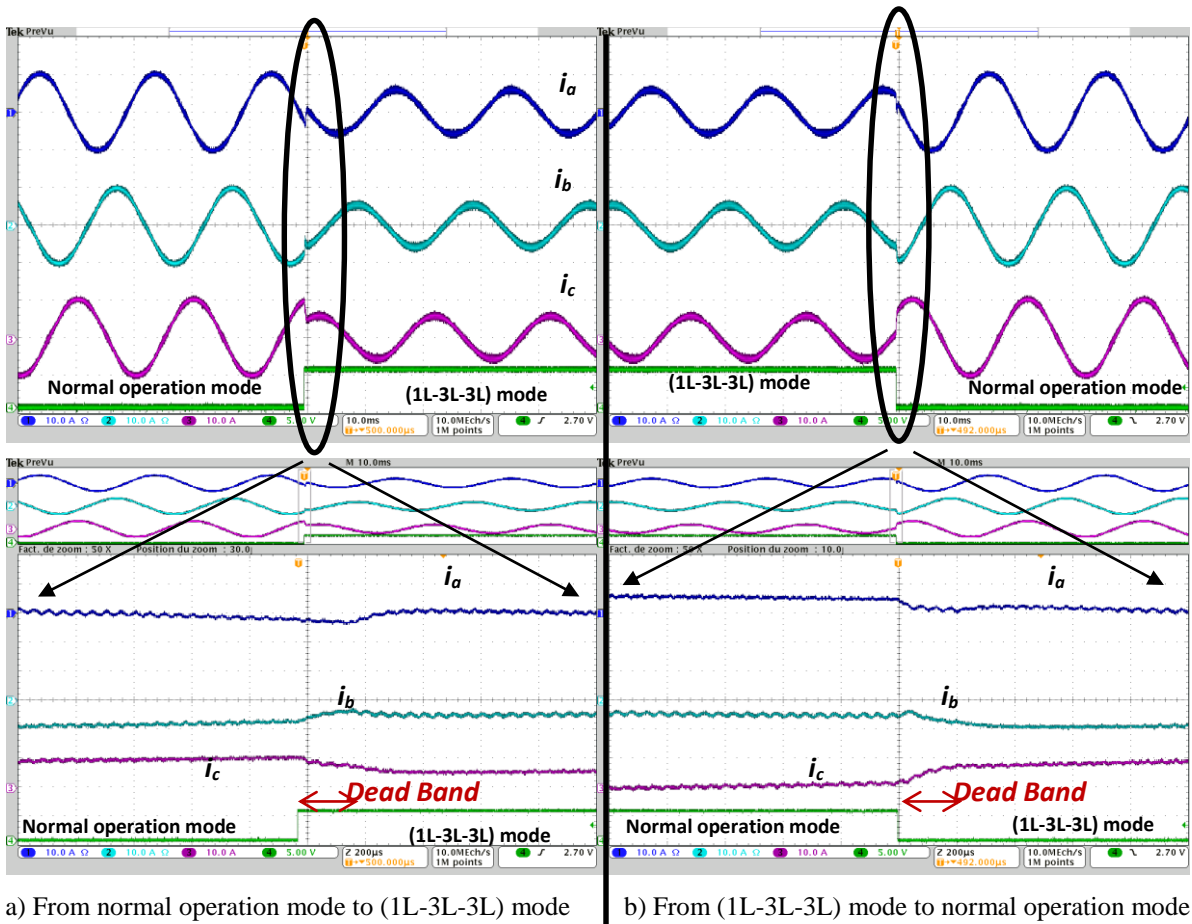


Fig. 8. Transitions between normal operation mode and (1L-3L-3L) mode: case of phase *a* switch fault occurrence. Phases *a*, *b* and *c* output currents i_a, i_b, i_c (10 A/div)

Fig. 9 gives the behaviour of the two fuses during transition from normal mode operation to faulty mode operation.

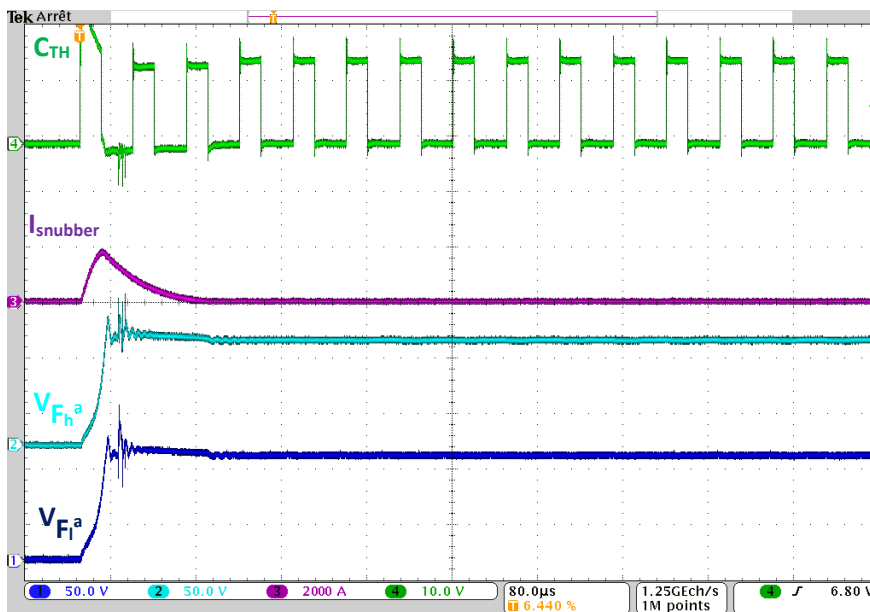


Fig. 9. Fuse behavior during transition from normal mode to faulty mode: Thyristor control signal C_{TH} , Snubber current $I_{snubber}$, F_h fuse voltage V_{Fh} , F_l fuse voltage V_{Fl}

The voltages across the two fuses increase simultaneously until the blowing up. The blowing up of the two fuses is perfectly synchronized, thanks to their few dispersion. In fact, MERSEN fuses (Fig.10) with dispersion less than 5% [31] are used during experimental tests. Post-isolation voltages across fuses are substantially symmetrical. Fuses take 10 μ s to blow up, while snubber current take 40 μ s to reach zero.

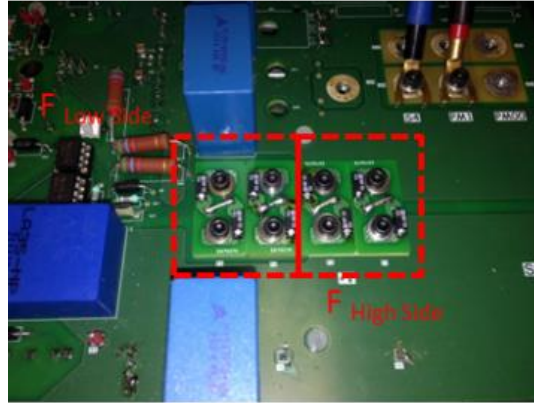


Fig. 10. MERSEN fuses.

6. Conclusion

In this paper, a hybrid fault tolerant multilevel converter topology is analysed. This mainly consists of three 3L-NPC-based legs and a fourth 3L-FC-based leg, connected through an LC filter. The main role of the 3L-FC leg is to provide an active neutral point for the three remaining NPC legs, under both normal and fault condition operation. The proposed topology tolerates failure of any IGBT of the hybrid converter.

Particularly, this study has focused on faulty leg isolation and post-fault phase connection process for the case of a NPC leg IGBT fault. A new fault isolation method and an original hardware reconfiguration technique from normal mode to fault condition operation were proposed. These solutions have interesting advantages:

- reduction of the semiconductors number necessary for the reconfiguration, since just one thyristor is needed to ensure both isolation of the faulty leg and connection of the corresponding phase to the active midpoint,
- ability to simultaneously disconnect the failed leg and connect the load to the fourth leg for any type of IGBT failure mode (open circuit or short circuit mode).
- for each converter leg, there is no need to specify which IGBT among the four is faulty.
- the used IGBT modules do not require any over sizing of their ratings for the post fault operation.

A post fault operation mode named (1L-3L-3L) was investigated and extended to the proposed hybrid converter. This mode provides one voltage level for the faulty leg output and three voltage levels for the healthy ones. The

3L-FC-based leg still actively balances the neutral point voltage. The fault tolerant capability of the proposed power system is ensured with a half output power reduction for the (1L-3L-3L) mode.

The proposed fault tolerant topology was experimentally implemented with a 15 kW power converter on which the (1L-3L-3L) mode is tested with a three-phase 400 V/10 A load.

The original experimental results of the transition from normal operation to faulty operation with concrete isolation of the faulty leg and connection of the phase to the active midpoint with one added thyristor have been discussed. These results confirm the reliability enhancement of the fault tolerant converter and show that it can effectively be introduced, for instance, in renewable energy-based power generation systems.

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