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Investigation of Fault-Mode Behaviors of Matrix Converters

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ABSTRACT

This paper presents a systematic investigation of the fault-mode behaviors of matrix converter systems. Knowledge about converter behaviors after fault occurrence is important from the standpoint of reliable system design, protection and fault-tolerant control. Converter behaviors have been, in detail, examined with both qualitative and quantitative approaches for key fault types, such as switch open-circuited faults and switch short-circuited faults. Investigating the fault-mode behaviors of matrix converters reveals that converter operation with switch short-circuited faults leads to overvoltage stresses as well as overcurrent stresses on other healthy switching components. On the other hand, switch open-circuited faults only result in overvoltage to other switching components. This study can be used to predict fault-mode converter behaviors and determine additional stresses on remaining power circuit components under fault-mode operations.

Keywords: Matrix converter, Fault-mode behaviors, Open-circuited switch fault, Short-circuited switch fault

1. Introduction

Since the modern trends of power electronic converters are bi-directional power flow, compact realization and more system integration, a matrix converter presents a promising structure due to its four quadrant operation, lack of dc-link reactive components, small size, sinusoidal input/output waveforms and high temperature/pressure driving capability [1]. Matrix converters have been starting to penetrate industrial fields in which they can offer a beneficial value, such as military/civil aircraft and electric vehicle applications with more electrically driven actuation systems [2, 3]. This is due to the fact that high temperature operations as well as space and weight savings are essential issues in these areas. In addition, highly reliable system operation even after some parts of a system have failed is extremely important in consideration of the safety-critical requirements in these fields [3]. Common practical methods of improving reliability are likely to design a converter circuit conservatively, or to have parallel redundancy in its components. Obviously, both of these approaches are expensive, which aggravates the high cost problem of matrix converters. As power converters play an important role in safety critical systems, there is a clear need to explore and analyze matrix converter behaviors after key converter faults take place. While fault-mode investigation including fault-tolerant operating techniques and fault diagnosis for inverter systems have been more or less studied up to the present [3-8], systematic studies on converter faults and the fault-mode behaviors of matrix converters have not been presented in the literature.

In this paper, the objective is to clearly address and explain the input and the output behaviors of matrix

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converters under fault conditions. The fault-mode behaviors of matrix converters are investigated for the key converter fault types. Possible fault types in matrix converters have been identified, and then, fault-mode performances are examined with mathematical analysis. The key types of faults in matrix converters have been considered, including switch open-circuited faults and switch short-circuited faults. The study of fault-mode behaviors in matrix converters shows that converter operation with switch short-circuited faults leads to overvoltage stresses as well as overcurrent stresses on other healthy switching components. On the other hand, switch open-circuited faults only result in overvoltage to other switching components. The results are useful for designing optimal protection systems, predicting the fault-mode operations of matrix converters and designing fault-tolerant control systems.

2. Matrix converter faults

The 3×3 matrix converter shown in Fig. 1 consists of an array of 9 bi-directional switches, which can be in the common-emitter configuration or the common-collector configuration of an anti-series connection with two IGBTs (Insulated Gate Bipolar Transistors). In addition, a clamp circuit with two B6 rectifiers using fast-recovery diodes and a dc capacitor is linked between the input and the output terminals of the converter. The clamp circuit provides a current path through any of the input and output terminals, which protects the matrix converter against possible overvoltage from both the supply and the load sides. The clamp circuit only operates for switch commutation moments under normal operating conditions, and the clamp voltage v_{CP} is equal to the line-to-line peak voltage of the supply. On the other hand, it works as a temporary storage device to absorb the reactive energies from the input and the output terminals under fault-mode operating conditions. Since the matrix converter is arranged with no intermediate dc-link capacitor, it is free from faults associated with dc buses, such as dc-link capacitor short-circuit faults and earth faults on dc buses. Accordingly, the matrix converter system, as shown in Fig. 1, can generate the following types of faults: single switch open-circuited faults (F_1), single-switch short-circuited faults (F_2), input supply single line to ground faults (F_3), line to line short-circuits at the motor terminal (F_4) and single line to ground faults at the motor terminal (F_5). This paper limits its scope to faults that occur in the converter itself. Faults inside a motor operated by a matrix converter or failures in the supply power lines are not dealt with in this study. Moreover, the possibility of multiple faults occurring at the same instant is negligible, and thus, effects of multiple faults on converter behaviors are removed from the analysis. The secondary faults as a consequence of primary faults are ruled out from the investigation as well, since effective protection circuits prevent any such subsequent faults.

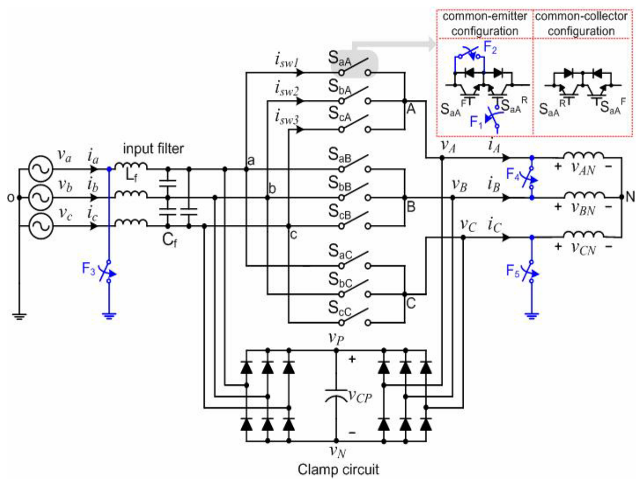


Fig. 1. Matrix converter system with possible failure modes.

3. Analysis of fault mode behaviors with a switch open-circuited fault

The switches of matrix converters are controlled by gate drive amplifiers supplied by isolated dc power supplies. A malfunction in either the gate drive circuits or the isolated power supplies results in open-circuited faults of the switches. A failure in the isolated power supplies yields open-circuited faults in more than one IGBT, depending on the connection types of the bi-directional switches, such as the common-emitter and the common-collector configurations. Open-circuit faults in switches yield deviations in the output phase voltages and the output line currents, which, in turn, affect the input line currents.

Considering the voltage sources at the input terminals and the inductive loads at the output terminals of the converter, the input phases and the output phases must not be shorted and opened, respectively. These fundamental constraints placed on matrix converter operation lead to only one switch in one output phase conducting at any time. This basic operating principle of converters can be expressed as:

$$T_{ak} + T_{bk} + T_{ck} = 1 \quad (k = A, B, C) \tag{1}$$

where, T_{jk} (j = a, b, c and k = A, B, C), corresponding to the switching states of the bi-directional switch S_{jk}, assumes '1' and '0' for the turn-on and the turn-off conditions, respectively. This fundamental operating rule determines converter behavior under open-circuit faults of the switch. Under normal conditions, the output phase voltages are equal to one of the input phase voltages at any instant, depending on which switch is closed. On the other hand, with a single IGBT failure with the open-circuit damage, the corresponding output phase voltage with the faulty switching device is decided by the polarity of the output current and the switching pattern of the open-circuited switch. Furthermore, the configuration types of the bi-directional switches yield different fault-mode behaviors under open-circuited switch faults.

3.1 Common-emitter configuration

With the gate drive circuit for S_{aA}^{R}, for example, inoperative in a matrix converter implemented in the common-emitter configuration, the corresponding switch S_{aA}^{R} is open-circuited, which leaves only the freewheeling diode of S_{aA}^{R} available. Assume that the gate drive control patterns remain the same before and after the fault. In the case that the output current i_A is positive and the bi-directional switch S_{aA} is commanded to turn on, the converter behaves the same as in normal conditions. However, with a negative output current i_A, the open-circuited fault of S_{aA}^{R} disables the current conduction capability through the bi-directional switch S_{aA} when the S_{aA}^{R} is commanded to close. As a result, the reactive energy of the inductive load, fed from the converter, turns on the diodes of the clamp circuit. The output current in the negative direction links the output phase with the faulty switch to the positive dc bus of the clamp circuit after the fault occurrence, instead of the input phase voltage v_a as in normal operation. This operation forces the output line current i_A to go down to zero. This occurs because the output voltage of a matrix converter is always lower than the input peak voltage due to the limited maximum voltage transfer ratio and because the clamp voltage is almost equal to the peak line input voltage. Therefore, the A-phase current with the IGBT S_{aA}^{R} failed in the open-circuit is zero during most of the negative half output cycle. However, even after a fault, the negative current i_A can flow during some parts of the cycle when the duty ratio of the faulty switch S_{aA} is small. Note that the open-circuited faults occurring at S_{aA}^{R}, S_{bA}^{R} or S_{cA}^{R} eliminate most parts of the negative direction in the output current i_A. In addition, the inductive energy transferred to the clamp capacitor from the load increases the dc voltage v_{CP} of the clamp circuit. The voltage rise of the clamp capacitor depends on the energy transferred from the A-output phase to the clamp circuit, ΔQ_A, and the clamp capacitor size, C_{cp}, as in [9].

$$v_{CP} = \sqrt{\frac{\left(\frac{1}{2} v_{Co}^{2} C_{CP}\right) + \Delta Q_A}{\frac{1}{2} C_{CP}}} \tag{2}$$

where, v_{Co} is the initial value of the clamp capacitor.

An open-circuited fault occurred at the IGBT S_{aA}^{F} prevents the positive direction of the output current i_A through the bi-directional switch S_{aA}. During the positive half cycle of the output current i_A, the output phase A is connected to the negative dc-link of the clamp circuit, when the switch S_{aA} is commanded to turn on. This also forces the output phase current i_A to decrease, resulting in distorted current waveforms. Moreover, the clamp voltage v_{CP} rises as well. Note that the open-circuited faults occurred at S_{aA}^{F}, S_{bA}^{F} or S_{cA}^{F} eliminate most parts of the positive direction in the output current i_A. As a consequence, the open-circuited faults of the switches in a matrix converter result in portions of missing current in the faulty output phase during half of the output current period. A matrix converter in a common-emitter configuration requires nine isolated power supplies dedicated to their respective bi-directional switch cells [9]. Accordingly, a failure in any of the isolated power supplies yields an open-circuited fault in the corresponding bi-directional cell. The bi-directional switches with open-circuit faults completely lose their current conduction capability. Thus, the corresponding output line current, with the faulty bi-directional switch, is zero during the entire output cycle. It should be noted that the rising clamp voltage increases the peak voltage stresses of the other healthy switches tied to the faulty device in the same output phase. Therefore, the open-circuited switch fault leads to overstresses on the healthy switches connected to the same output leg as the faulty switch. As a result, the healthy switches tied to the open faulty switch in the same output phase can secondarily fail. Since the open-circuited fault of an IGBT in a matrix converter raises the clamp voltage v_{CP} to a dangerous level, it is necessary to monitor the clamp voltage in practical matrix converters. Moreover, a chopper circuit with a power resistor and a switching device is required to limit the clamp voltage to a safe level to avoid overvoltage failure of the healthy switches. After the fault occurrence of one switch in the output phase *A*, the output phase voltage v'_{Ao} can be written as:

$$v'_{Ao}(t) = \begin{cases} T_{Aa}v_{No} + T_{Ab}v_b + T_{Ac}v_c, & i_A > 0 \\ T_{Aa}v_{Po} + T_{Ab}v_b + T_{Ac}v_c, & i_A < 0 \end{cases} \quad (3)$$

3.2 Common-collector configuration

In a matrix converter constructed with a common-collector configuration, failures in the gate drive circuits result in open-circuited faults in the corresponding IGBTs. Thus, the open-circuited faults in an IGBT lead to the same phenomena as those of the common-emitter configuration. On the other hand, the open-circuited faults resulting from isolated power supply failures yields different behaviors. Due to the arrangement, failures of the isolated power supplies give rise to two distinct consequences on converter behaviors. The failure of a power supply, for example, dedicated to $S_{aA}{}^R$, $S_{aB}{}^R$, and $S_{aC}{}^R$ causes the converter to stop working, because all three output currents are null. In the meantime, the failure of a power supply, for instance, dedicated to $S_{aA}{}^F$, $S_{bA}{}^F$, and $S_{cA}{}^F$ forces the output current i_A to be zero, during most parts of the negative output current i_A. Therefore, failures in the isolated power supplies for a common-collector configuration yield either total power interruption or the elimination of one output current in the negative output cycle. Table 1 shows the results of failures in either the gate drive circuits or the isolated power supplies, depending on the switch configurations.

Table 1. Results of failures in gate drive parts.

	gate drive failure	isolated power supply failure
common-emitter configuration	Elimination of one output current in half cycle	Elimination of one output current
common-collector configuration	Elimination of one output current in half cycle	Total power interruption or elimination of one output current in negative half cycle

4. Switch short-circuited fault

A short-circuited fault in the switch of a matrix converter results in a short-circuit condition between the two input lines through the input *LC* filter, during some time slots, due to the matrix converter operation in (1). The short-circuit condition of the two input lines gives rise to an extremely high current in the switches and the input lines. This is only limited by the internal impedance of the supply system, the inductance of the input filter and the on-state resistances of the switches. As a result, the converter switching devices tied to the short-circuited switch at the same output phase as well as the converter input lines are exposed to extremely high current stress under this fault-mode behavior. In the end, it is expected that fast-acting fuses against switch short-circuit faults, placed in series with either the input inductors or the switching devices, blow to protect the supply side of the converter. However, detailed converter behavior until the fuse blows depends on which switch failed, the fault initiation point and the magnitudes of the input supply voltages. Furthermore, the existence of an input *LC* filter makes this fault-mode behavior more complicated. Converter behavior with open-circuited faults undergoes changes, according to the switch configurations such as the common-emitter or the common-collector structures. However, the switch configurations have no effects on converter behavior after switch short-circuited faults. While the converter output voltage after an open-circuited fault is affected by the polarity of the output currents and the faulty switch patterns in (3), the output phase voltage with a damaged switch is dependent on the polarity of the input supply voltages. This will be explained in the following analysis. Converter behavior after the short-circuited fault of a switching device is first examined, by initially neglecting the input *LC* filter of the converter. This assumption eliminates the need to model the interaction of the short-circuit situations with the input *LC* filter. The short-circuit behavior is then extended by including the effect of the input filters.

Let us consider that the IGBT $S_{aA}{}^{F}$ is permanently short-circuited, at point *F* as shown in Fig. 2. Although the fault occurs at the instant of *F*, the converter exhibits no abnormal behaviors until point *A*. This is due to the fact that, during the period from point *F* to point *A*, the freewheeling diode of $S_{aA}{}^{R}$ becomes reverse-biased whenever switch S_{aB} or S_{aC} turns on. Accordingly, this reverse-biased diode prevents the short-circuit condition of the supply voltages. With this intuition, four regions can be defined, according to the magnitude of the supply voltages in reference to the *a*-phase voltage of the faulty switch, which are shown in Fig. 2.

In region 1, the input *a*-phase voltage is lower than both v_b and v_c. This can be considered a *safe region* for the short-circuited fault of the switch $S_{aA}{}^{F}$, because no short-circuit condition is constructed.

In region 2, the input voltage of the faulty switch, v_a, becomes higher than the voltage of v_b. Thus, in the case that switch S_{aB} turns on, the freewheeling diode of $S_{aA}{}^{R}$ is forward-biased, which produces the short-circuit condition of the supply voltages v_a and v_b through the input *LC* filter. With the assumption of no *LC* filter, the input voltages v_a and v_b are directly short-circuited through the freewheeling diode of $S_{aA}{}^{R}$, the IGBT $S_{aB}{}^{R}$ and the freewheeling diode of $S_{aB}{}^{F}$. Assume that the internal impedance between the input phase *a* and the output phase *A*, denoted R_{eq}, equals the impedance between the input phase *b* and *A*. Due to the restricted output current i_A with the load inductance and the extremely high short-circuit currents through S_{aA} and S_{bA}, the input currents can be written as:

$$i_a = \begin{cases} i_{sw1} = -i_{sw2} = -i_b = \dfrac{v_{ab}}{2R_{eq}} & , \text{ when } S_{bA} \text{ ON} \\ T_{aB} i_B + T_{aC} i_C & , \text{ when } S_{cA} \text{ ON} \\ i_A & , \text{ when } S_{aA} \text{ ON} \end{cases} \tag{4}$$

Note that the input currents i_a and i_b are quite high due to a very small R_{eq}, with S_{bA} turned on. In the meantime, the input current i_a remains quite small, compared to $v_{ab}/(2R_{eq})$, when either S_{cA} or S_{aA} is turned on. The current i_a is sketched in Fig. 2 with a series of rectangular pulses with a height of $v_{ab}/(2R_{eq})$. Likewise, the output phase voltage v_{Ao} is, with no *LC* filter effects, simply given by:

$$v_{Ao} = \begin{cases} \dfrac{1}{2}(v_a + v_b) & , \text{ when } S_{bA} \text{ ON} \\ v_c & , \text{ when } S_{cA} \text{ ON} \\ v_a & , \text{ when } S_{aA} \text{ ON} \end{cases} \tag{5}$$

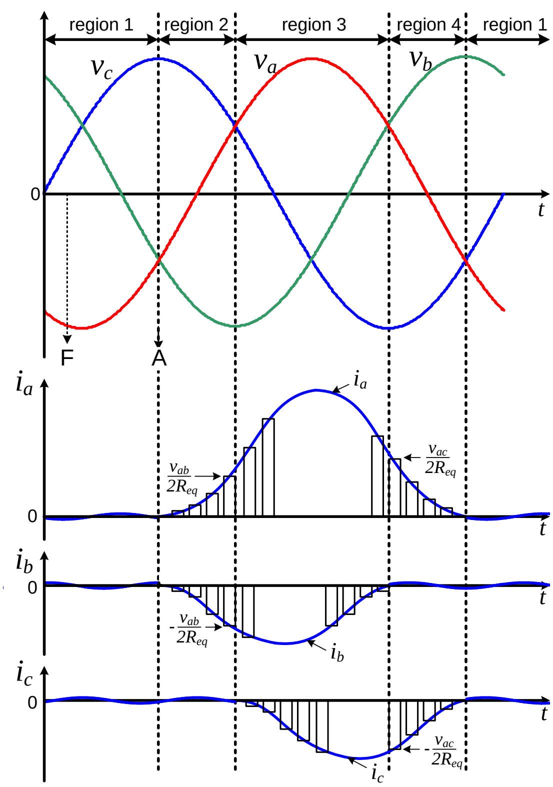


Fig. 2. Input current waveforms under short-circuited fault of $S_{aA}{}^{F}$ at the point *F*.

Including the effects of the input *LC* filter filters out the high-frequency components in the rectangular pulses of the input currents i_a and i_b , as shown in Fig. 2. As a result, the input currents in input lines *a* and *b*, in region 2, significantly build up. These currents are proportional to the input line-to-line voltage v_{ab}. The input phase *a* current is nearly the same as that of phase *b* in region 2. On the other hand, the input current i_c is not involved with the short-circuit condition in region 2, because the freewheeling diode of $S_{aA}{}^{R}$ is still reverse-biased when the switch S_{aC} conducts. As a result, the input phase *c* current remains low in this region.

In region 3, the input voltage of the faulty switch $S_{aA}{}^{F}$, v_a, is higher than both v_b and v_c. In this region, turning on either S_{aB} or S_{aC} yields the short-circuit conditions of the two input supply voltages. Without giving consideration to the input *LC* filter, the input currents in region 3 can be given as:

$$i_a = \begin{cases} i_{sw1} = -i_{sw2} = -i_b = \dfrac{v_{ab}}{2R_{eq}} & , \; when\ S_{bA}\ ON \\ i_{sw1} = -i_{sw3} = -i_c = \dfrac{v_{ac}}{2R_{eq}} & , \; when\ S_{cA}\ ON \\ i_A & , \; when\ S_{aA}\ ON \end{cases} \quad (6)$$

Without the LC filter effects, the output phase voltage with respect to the supply neutral v_{Ao} is also given by:

$$v_{Ao} = \begin{cases} \dfrac{1}{2}(v_a + v_b) = -\dfrac{1}{2}v_c & , \; when\ S_{bA}\ ON \\ \dfrac{1}{2}(v_a + v_c) = -\dfrac{1}{2}v_b & , \; when\ S_{cA}\ ON \\ v_a & , \; when\ S_{aA}\ ON \end{cases} \quad (7)$$

It can be noted that, by adding the input *LC* filter, the input current i_c rises considerably in this mode. This current is proportional to the input line-to-line voltage v_{ac}. In the meantime, the input phase *b* current is proportional to the voltage v_{ab}. The phase *a* current is the sum of the currents in phase *b* and phase *c*.

In region 4, the freewheeling diode of $S_{aA}{}^{R}$ is reverse-biased when the switch S_{aB} conducts. Thus, the input phase *b* current is not concerned with the short-circuit condition.

Table 2 summarizes the short-circuit conditions of the input supply voltages, depending on the closed switches and the supply voltage regions, in the case of short-circuit faults of $S_{aA}{}^{F}$. If fast-acting fuses against short-circuited faults are placed in the three input lines, the corresponding i^2t stresses on the fuses of phase *a* and phase *b* are the same as in region 2. Therefore, the fuses on phase *a* and phase *b* will blow randomly, if they blow in region 2. However, if the fuses survive in region 2, then the phase *a* fuse will definitely blow in region 3. Moreover, the fault current profiles in Fig. 2 indicate that a short-circuited fault at $S_{aA}{}^{F}$ occurring in region 3 will cause only the phase *a* fuse to blow. However, if a fault occurs in either region 2 or 4, a faulty or healthy phase fuse will blow randomly. A short-circuited fault occurring at a switch rather than $S_{aA}{}^{F}$ creates input current profiles similar to the ones shown in Fig. 2, with only a time-shift depending on the supply voltage polarities. From the above investigation, it is clear that the short-circuited fault builds extremely high current waveforms in the input lines.

Now, the behaviors of the input current, the switch current, the output voltage and the clamp voltage, taking into consideration the input of a *LC* filter, are investigated during one switching period in region 3. Fig. 3 illustrates the waveforms of the switch current i_{sw1} and the output phase voltage v_{Ao} in region 3 under a short-circuited fault occurrence at $S_{aA}{}^{F}$. Fig. 4 shows the mode operations under the short-circuit fault-mode condition.

Table 2. Input supply short-circuit conditions with short-circuited fault of $S_{aA}{}^{F}$.

region	S_{aB} ON	S_{aC} ON
1	no short-circuit	no short-circuit
2	short-circuit of v_a and v_b	no short-circuit
3	short-circuit of v_a and v_b	short-circuit of v_a and v_c
4	no short-circuit	short-circuit of v_a and v_c

Mode 1: With the switch $S_{aA}{}^{F}$ having failed in the short-circuited manner, mode 1 is initiated once the switch S_{aB} turns on. When the switch S_{aB} turns on, the freewheeling diode of $S_{aA}{}^{R}$ is forward-biased. Due to the

existence of the input line inductances and the output load inductance, the input currents i_a and i_b as well as the output current i_A do not respond immediately after turning on S_{aB}. Thus, the short-circuit condition with the input capacitor C_a, the forward-biased diode of $S_{aA}{}^R$ and the turned-on switch S_{aB} is built as shown in Fig. 4 (a). The conducting IGBT can be modeled with a threshold voltage V_{CEo} and an equivalent on-resistance R_K. Likewise, the conducting diode is expressed with a threshold voltage V_{Do} and an equivalent on-resistance R_{Dk}. Consequently, the input capacitor voltage v_{Ca} of this mode can be expressed as:

$$v_{Ca}(t) = (2V_{Do} + V_{CEo}) + R_{Dk} i_{sw1}(t) + \left(R_{Dk} + R_k\right) i_{sw2}(t) \quad (8)$$

Because the switch currents i_{sw1} and i_{sw2} are extremely high in the short-circuit condition, the threshold voltages can be neglected. Moreover, the switch currents, i_{sw1} and i_{sw2} are nearly equal in this mode, since the output current i_A is limited to a low value due to the load inductance. As before, the symmetric line impedances, including the on-resistance, are assumed in the switch lines. Suppose that R_{aA} is the resistance between input phase *a* and output phase *A* through switch S_{aA}. In addition, the resistance between input phase *a* and output phase *B* via the switch S_{aB} is denoted as R_{aB}. By assuming $R_{eq} = R_{aA} = R_{aB}$, the switch current i_{sw1}, in this mode, is written by:

$$i_{sw1}(t) \approx -i_{sw2}(t) = \frac{V_{Cao}}{2R_{eq}} e^{-(t-t_0)/\left(2R_{eq}C_a\right)} \quad (9)$$

where, V_{Cao} is the voltage stored in the input capacitor C_a at the instant of $t = t_0$. During normal operating conditions, the input capacitor voltage v_{Ca} is almost equal to the line-to-line input voltage v_{ab}. However, during the short-circuit fault condition, the voltage v_{Ca} is much higher than that obtained from the normal situation, due to the excessively high input currents going into the capacitor, which will be shown in modes 5 and 6. Thus, as shown in Fig. 3, a current spike appears at the switch lines tied in the short-circuit condition with the input capacitor, due to the retarded response of the input and the output lines with the inductances. Due to the small line impedance R_{eq}, the capacitor C_a discharges quickly and the capacitor voltage v_{Ca} decays to zero. A secondary fault takes place when this pulse-like overcurrent exceeds the rating of the pulsed collector current of a healthy IGBT.

Mode 2: At the instant of t_1, the input capacitor C_a completely discharges and its current i_{Ca} become zero. The fast-decaying switch current i_{sw1} becomes equal to the difference between the input current i_a, and the input capacitor current i_{Cc}, as shown in Fig. 4 (b). Since the input inductance is generally smaller than the load inductance, the short-circuit condition between the two input voltages v_a and v_b is constructed with the input inductances (L_a and L_b) and the line impedance ($2R_{eq}$). Since the input capacitor voltage v_{Ca} is zero, the voltages across the input capacitors C_b and C_c are equal, which results in:

$$i_{Cb}(t) = i_{Cc}(t) = \frac{1}{2} i_c(t) \quad (10)$$

From Fig. 4 (b) and (10), the input current i_a is:

$$i_a(t) = i_{sw1}(t) + \frac{1}{2} i_c(t) \quad (11)$$

Since the load current i_A is very small, when compared with the input currents in the short-circuit condition, the two switch currents i_{sw1} and i_{sw2} can be considered to be equal, which can be expressed as:

$$i_{sw1}(t) \approx i_{sw2}(t) = i_b(t) + \frac{1}{2} i_c(t) \quad (12)$$

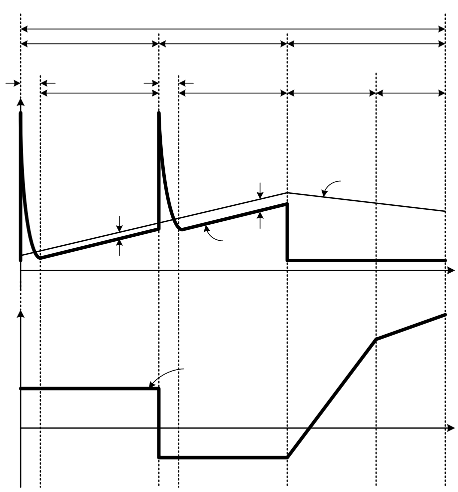
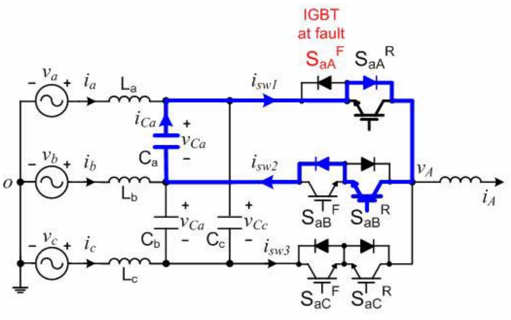
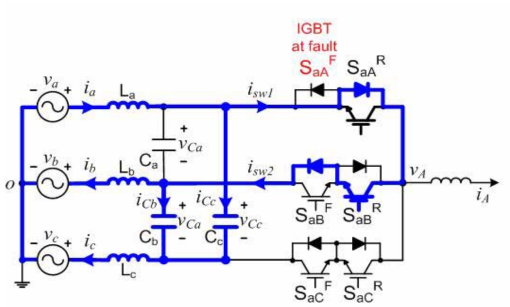


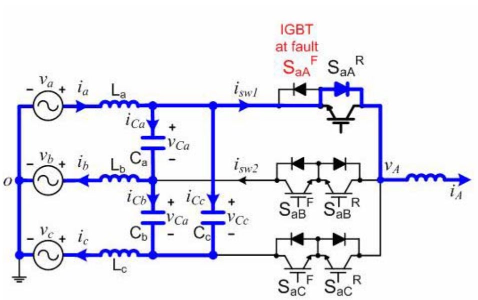
Fig. 3. Waveforms of switch current and output phase voltage under short-circuited fault of $S_{aA}{}^F$ during one switching period in region 3.



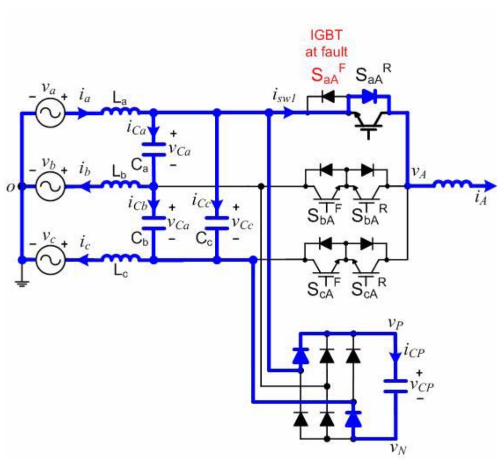
(a) mode 1 ($t_0 \le t \le t_1$)



(b) mode 2 ($t_1 \le t \le t_2$)



(c) mode 5 ($t_4 \le t \le t_5$)



(d) mode 6 ($t_5 \le t \le t_6$)

Fig. 4. Short-circuited behaviors in one switching period.

Applying (12) to (11), the relationship for the input currents are obtained as:

$$i_a(t) = i_b(t) + i_c(t) \tag{13}$$

The output phase voltage can be expressed as:

$$v_{Ao}(t) = v_a(t) - L_a \frac{di_a(t)}{dt} - R_{eq} i_a(t) + \frac{R_{eq}}{2} i_c(t) \tag{14}$$

Due to the voltage across the inductor L_a, the output phase voltage is somewhat diverged from $0.5(v_a + v_b)$, which was obtained without consideration of the *LC* filter.

Mode 3 and 4: With the switch $S_{aA}{}^F$ having failed in the short-circuited manner, mode 3 starts when the switches S_{aB} and S_{aC} turn off and on, respectively. The behaviors during mode 3 and 4 are similar with those of mode 1 and 2, except for the short-circuit situation with the input voltages v_a and v_c.

Mode 5: In this mode, the faulty switch S_{aA} is commanded to close, and the other healthy switches S_{aB} and S_{aC} turn off. As a result, the switch current i_{sw1} is equal to the output current i_A, which is small compared to the input current i_a. Consequently, nearly all the input current i_a flows into the input capacitors C_a and C_c. Thus, the capacitor voltages v_{Ca} and v_{Cc} increase considerably, and the input current i_a reduces. The output phase voltage v_{Ao} is:

$$v_{Ao}(t) = v_a(t) - L_a \frac{di_a(t)}{dt} - R_{eq} i_A(t) \approx v_a(t) - L_a \frac{di_a(t)}{dt} \tag{15}$$

Due the decreasing input current i_a, the output phase voltage v_{Ao} almost linearly increases.

Mode 6: Once the voltage v_{Ao} rises over the positive dc-bus voltage v_P, the diodes of the clamp circuit turn on. Consequently, the input current i_a in this mode is:

$$i_a(t) \approx i_{Ca}(t) + i_{Cc}(t) + i_{CP}(t) \tag{16}$$

In this mode, the amount of energy stored in the input inductor L_a with a drastically high input current i_a is transferred to the clamp capacitor C_{CP}. The reactive energy delivered to the clamp capacitor from the input inductor increases the clamp voltage v_{CP} and decreases the input current i_a. Since the clamp capacitor appears in parallel with the input capacitors, the increasing rate of the output phase voltage v_{Ao} is slower than that of mode 4, as shown in Fig. 3. Moreover, the input capacitor voltage across C_a and C_c rises considerably due to the very high input current, when compared to those of the normal operating conditions. The high input capacitor voltages, in turn, generate high spike-current-waveforms in modes 1 and 3. It can be expected that locating fast-acting fuses in series with the nine bi-directional switch cells provides better protection than placing the fuses at the input lines, considering the pulse-like currents in modes 1 and 3. Similarly with the clearance of the fuses at the input lines, the fuses in series with the faulty switch S_{aA} and the healthy switch S_{aB} will blow randomly, if they blow in region 2. However, if the fuses survive in region 2, then the fuse associated with the faulty switch S_{aA} will definitely blow. After the fuse blows, the fault-mode behavior operates the same as when the bi-directional switch cell S_{aA} is open-circuited.

5. Simulation results

A matrix converter fed by a line-to-line 460 V_{rms} / 60 Hz utility mains has been simulated with an *R-L* load (2.5 Ω and 15 mH). The switching frequency and the output frequency were chosen to be 10 kHz and 55 Hz, respectively.

Fig. 5 illustrates the waveforms of the input currents, the output currents, the clamp circuit voltage and the output phase voltage obtained from a matrix converter, in the case of an open-circuited fault occurring to the switch $S_{Aa}{}^F$ at the instant of t = 60 msec. The input and the output currents of the matrix converter are no longer a balanced sinusoidal set after the fault occurrence. It can be seen that the positive parts of the output current i_A with the faulty switch $S_{Aa}{}^F$ drop to zero after the open-circuited fault and remain at zero during most of the periods. Thus, the output phase *B* current is the same as that of output phase *C*, when the current i_A is equal to zero. However, the negative parts of the output current i_A still flow even after the open-circuited fault. The dc-bus voltage of the clamp circuit increases due to the reactive energy transferred from the faulty phase. It is shown that the increasing clamp circuit voltage leads to an increase in the output phase voltage, which in turn increases the blocking voltage of the remaining healthy switches.

Fig. 6 illustrates the waveforms of the supply voltages, the input currents, the output currents, the clamp circuit voltage and the output phase voltage obtained from a matrix converter, in the case of a short-circuited fault occurring to the switch $S_{Aa}{}^F$ at the instant of t = 58 msec.

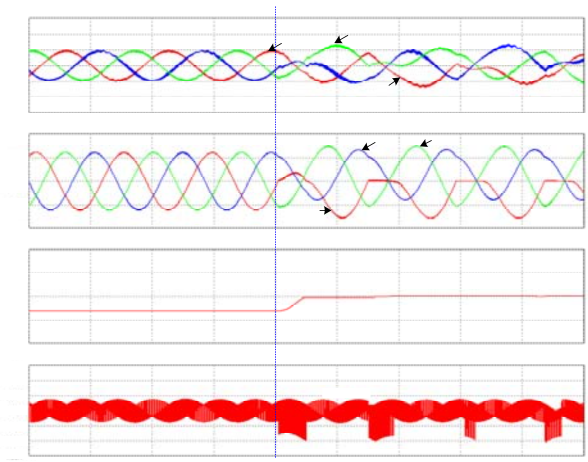


Fig. 5. Matrix converter behaviors under switch open-circuited fault of $S_{Aa}{}^F$ at the instant of t = 60 msec a) input currents b) output currents (c) clamp circuit voltage (d) output phase voltage.

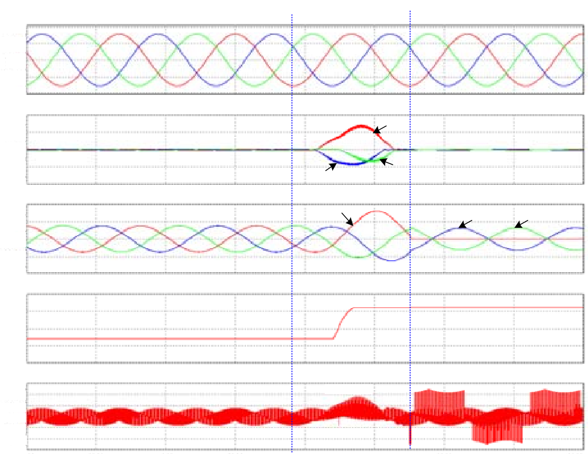


Fig. 6. Matrix converter behaviors under switch short-circuited fault of $S_{Aa}{}^F$ at the instant of t = 58 msec a) input currents b) output currents (c) clamp circuit voltage (d) output phase voltage.

It is shown that the input currents i_a and i_b increase dramatically when the input voltage v_a is higher than v_b. The input current i_c also rises considerably in the case of $v_a > v_c$. The large stored energy in the line inductances creates a voltage rise in the clamp circuit. The fuse in series with the switch S_{aA} is cleared at the instant of t = 75 msec. After clearing the fuse, the converter behaviors are the same as the open-circuited fault of the bi-directional switch cell S_{aA}, where the output current i_A keeps to zero during the entire output cycle.

The clamp circuit voltage increases under both the open-circuited and the short-circuited fault conditions. However, the voltage increases more after a short-circuited fault. This is due to the fact that the more reactive energies stored in the input inductor, with higher input currents, are transferred into the clamp capacitor.

6. Conclusions

This paper systematically describes the effects of different types of switch faults on matrix converter systems. Knowledge about converter behaviors after fault occurrence is important from the standpoint of reliable system design, protection and fault-tolerant control. On the other hand, the study of fault-mode behaviors of matrix converters is extremely complicated, due to their unique ability to directly link time-varying ac supply voltages to a load. The complexity is further aggravated by the presence of input *LC* filters, which affect short-circuit mode behaviors. The converter behaviors have been, in detail, examined with both qualitative and quantitative analysis for switch open-circuited faults and switch short-circuited faults. Investigating the fault-mode behaviors of matrix converters reveals that converter operation with switch short-circuited faults leads to overvoltage stresses as well as overcurrent stresses on other healthy switching components. On the other hand, the switch open-circuited faults only result in the overvoltage of other switching components. This study shows that practical matrix converter systems require a monitoring system for the clamp voltage, a dc chopper circuit across the clamp capacitor and fast-acting fuses in series with each bi-directional switch cell.

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