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***Abstract*—This paper presents strategies for maintaining operation of a double-output AC machine drive in the presence of various component failures. With a short/open-switch fault, the drive is capable of operating the AC machine at a reduced power capability by creating an artificial neutral. The procedures of mode transition are shown to depend on the system configuration. This operating method can be applied to both induction and permanent magnet synchronous machines as long as they can sustain a few cycles of increased current. Robust operation of the drive in case of short-circuit fault in the phase winding is also presented. It is also demonstrated in this paper the operating method when one of the two isolated DC sources is interrupted. This work further discusses the two-phase operation mode in which one faulted phase is isolated from the remaining portion of the circuit. Simulink simulation results are presented.**

***Index Terms*—Double-output, fault tolerance, open-winding machine, open circuit fault, short circuit fault**

I. Introduction

THE double-output AC machine drive has attractive features in applications where high power and/or high power quality is desired from an open-winding machine while the DC link voltage is limited, e.g. the electric and hybrid vehicle power conversion system [1]. The typical drive topology for an open winding machine is shown in Fig. 1 [2].

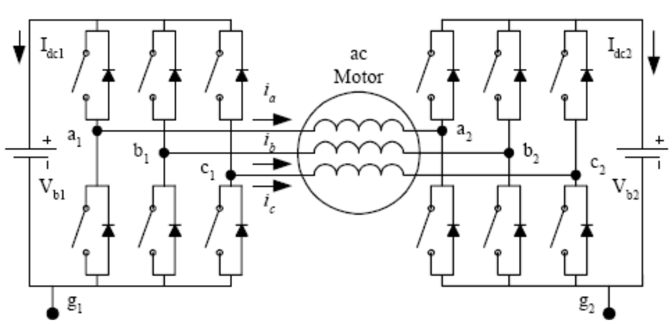

Fig. 1. Double-output AC machine drive

The two grounds in Fig. 1 may or may not be tied together. This provides the flexibility of using either single common DC source feeding both of the inverters, or two isolated DC sources feeding two inverters independently. The major difference between these two configurations is the presence of a zero-sequence path in the former case; therefore they should be operated with different modulation techniques.

In this inverter configuration, since the voltage is directly applied across one phase winding instead of two windings as in a standard drive, the available phase voltage is increased by a factor of $\sqrt{3}$. This result is true even when compared to a standard drive implemented with triplen harmonic voltage components, because the same can be done to both sides of the two inverters. However, in this case the triplen-harmonics injected by the two sides of the inverter must cancel out each other if the inverter has single common DC source, so that no significant circulating current will be induced in the zero-sequence path.

It has been reported in [1] that there is a price to pay because the switching utilization ratio is decreased from 0.159 to 0.138 compared to a standard drive. The double-output arrangement is, however, capable of increasing the high speed power density by 73% for a machine with a specified number of turns because of its increased phase voltage capability. The field weakening operation of this type of inverter has been studied in [3], in which two independent DC sources are adopted. Here, the authors claim a 15% increase in the developed torque with the same current limitations compared to the standard Y-connected machine fed by single inverter. In an investigation concerned with improved power quality, M. Janssen et al. introduced in [4] a control technique for double-output inverter to minimize the torque ripple.

Besides the well known benefits of achieving high power, the double-output inverter also has considerable advantages in fault tolerance and its capability of robust operation in case of device and/or machine failures. Welchko et al. give a brief introduction to a variety of fault tolerant AC machine drive topologies in [5], in which the double-output inverter is covered. The same authors also present detailed work in short-circuit fault mitigation methods for IPM machine using this type of drive topology [6].

In general, the vast majority of faults consist of one of the following: 1) short circuit of a motor phase, 2) open circuit of a motor phase, 3) short circuit of a transistor inverter leg, 4) open circuit of a transistor inverter leg. This paper demonstrates the possibility of robust operation of double-output AC machine drive for these four specific cases as well as the possibility of an interrupted DC source. Both transient and steady state behavior are investigated using Simulink simulation.

II. Operating Principle and System Modeling

A. Modeling of Open-Winding AC Machine

The D-Q-0 model of an open-winding induction machine is not different from the standard Y-connected induction machine. The differential equations in the D-Q-0 frame are given as (1) ~ (7).

$$\underline{v}_{dqs} = \underline{i}_{dqs}R_s + \frac{d}{dt}\underline{\lambda}_{dqs} + j\omega\underline{\lambda}_{dqs} \tag{1}$$

$$\underline{v}_{dqr} = \underline{i}_{dqr}R_r + \frac{d}{dt}\underline{\lambda}_{dqr} + j\omega\underline{\lambda}_{dqr} \tag{2}$$

$$v_{0s} = i_{0s}R_s + L_{ls}\frac{di_{s0}}{dt} \tag{3}$$

$$v_{0r} = i_{0r}R_r + L_{lr}\frac{di_{r0}}{dt} \tag{4}$$

$$\underline{\lambda}_{dqs} = L_{ls}\underline{i}_{dqs} + L_m(\underline{i}_{dqs} + \underline{i}_{dqr}) \tag{5}$$

$$\underline{\lambda}_{dqr} = L_{lr}\underline{i}_{dqr} + L_m(\underline{i}_{dqs} + \underline{i}_{dqr}) \tag{6}$$

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}) \tag{7}$$

Similarly, the D-Q-0 model of an open-winding permanent magnet synchronous machine (PMSM) is identical to that of a standard Y-connected PMSM. The D-Q-0 voltages in this case are simply a sum of the voltages applied by the two inverters, i.e.

$$\underline{v}_{dqs} = \underline{v}_{dq1} - \underline{v}_{dq2} \tag{8}$$

$$v_0 = \frac{1}{3}(v_a + v_b + v_c) \tag{9}$$

$$v_a = v_{a1g1} - v_{a2g2} + v_{g1g2} \tag{10}$$

$$v_b = v_{b1g1} - v_{b2g2} + v_{g1g2} \tag{11}$$

$$v_c = v_{c1g1} - v_{c2g2} + v_{g1g2} \tag{12}$$

A complete over-laid voltage vector hexagon can be found in [2], in which the two DC sources are isolated and different combinations of voltage states are investigated. Special care must be taken when dealing with the zero-sequence component. To be specific, if the two inverters are fed by a common DC source, then there exists a zero-sequence path, which requires consideration of zero-sequence components in (3) and (4).

B. Modulation Method

Three major modulation techniques for the double-output AC drive are presented in [2], i.e. unity power factor control, voltage quadrant control, and optimum inverter utilization control. In the work presented in this paper, a field-oriented controller (FOC) is used.

III. Robust Operation with Shorted Switch

Consider now a short-circuit fault in the upper switch of phase leg *a2* during normal operation as shown in Fig. 2. In this case one end of phase-*a* winding is fixed to the positive DC link. If the AC machine is an induction motor, then depending on the inverter configuration two different methods exist to handle such a fault and continue operation without ceasing operation of the motor.

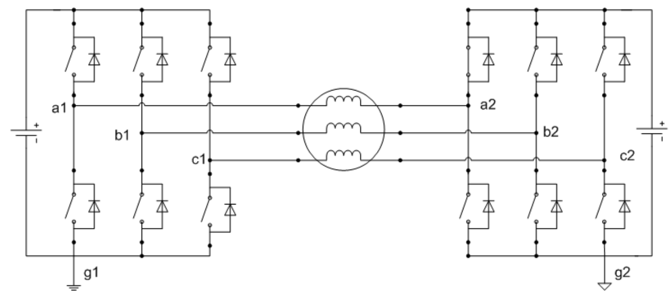

Fig. 2. Short-circuit fault in *a2* upper switch

First, if the inverter has two independent DC sources, then by shorting all three phase legs of inverter-2 to the positive DC link an artificial neutral is created, as shown in Fig. 3, which enables the motor to continue operating as a Y-connected machine at a reduced power rating. Since there is no zero-sequence path in this case, the artificial neutral is isolated from inverter-1.

If the AC drive has one common DC source, then the previous method fails due to the fact that only one polarity of voltage can be applied across the three phase windings. To solve the problem, inexpensive contactors or back-to-back SCRs can be added to the inverter as shown in Fig. 4, and certain procedures need to be followed to create an artificial neutral.

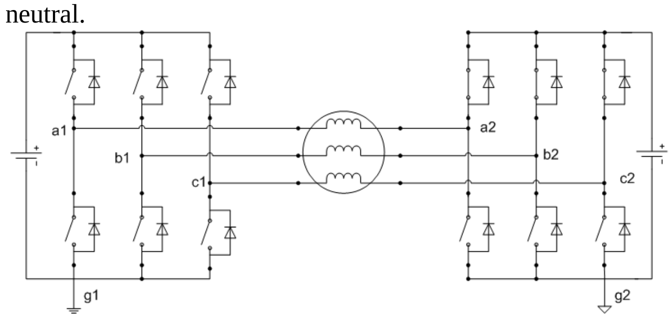

Fig. 3. Artificial neutral in case of shorted-switch fault

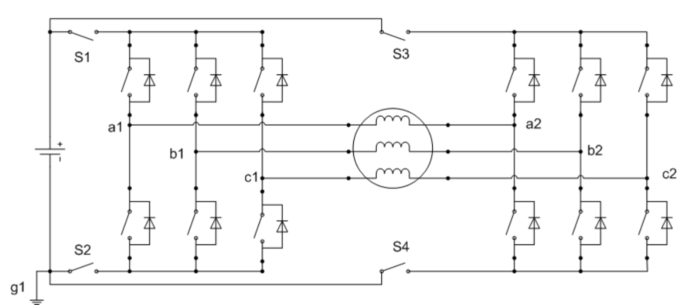

Fig. 4. Double-output inverter with contactors on the DC link

When the short-circuit fault is detected, for example, in the upper switch of *a2*, all six upper switches should be turned on, shorting all the phase terminals to the positive DC bus. Without excitation, the current and flux in the induction machine will die out quickly. Since the machine windings are all shorted together during this period, it is termed the *shorted-winding period*.

After the DC currents diminish, contactors S3 and S4 can be opened to isolate inverter 2 from the DC source. Then inverter-1 is restored to normal operation while inverter 2 has all three upper switches turned on to form an artificial neutral.

Although there will be significant transient short-circuit current present in the phase windings during the *shorted-winding period*, it is necessary to cut off the zero-sequence path so as to prevent large DC current component followed by large induced voltage spikes when the contactors are opened.

A simulation has been implemented in Simulink to demonstrate the transient and steady state responses of the proposed system shown in Fig. 4. The machine parameters used can be found in the Appendix, and a fan load is assumed. The short-circuit fault in the upper switch of *a2* occurs at t = 0.755 sec. The *shorted-winding period* starts at t = 0.756 sec and ends at t = 0.8 sec. Contactors S3 and S4 are then opened, normal operation is restored in the healthy inverter-1, and an artificial neutral is created in the isolated inverter-2. The speed command after fault is adjusted to 60% of the rated.

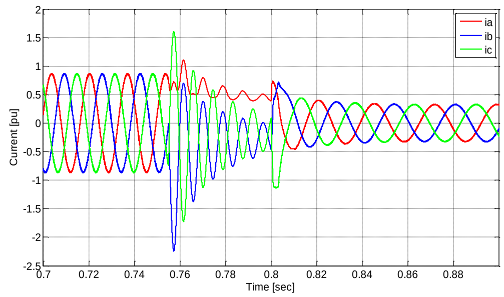

Fig. 5. Three phase currents

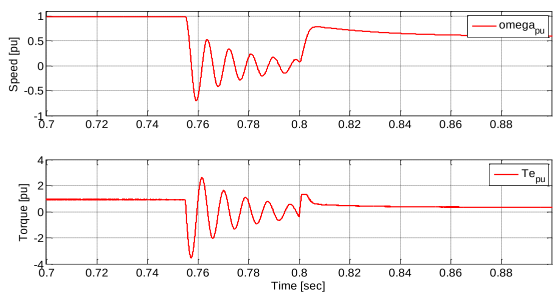

Fig. 6. Rotor speed and developed torque

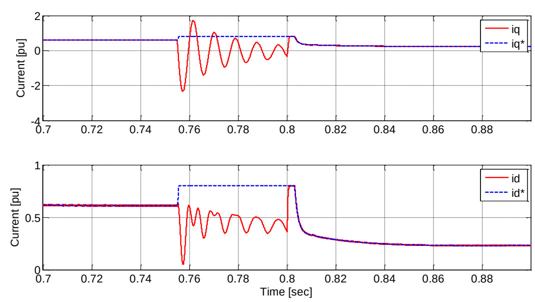

Fig. 7. D-Q currents

As observed from Fig. 5, the current peak during the transient is about 2.2 pu and lasts only for one cycle. The transient peak current depends on the machine parameters as well as the load characteristics. It should be noted that the procedures introduced above may also be applied to a permanent magnet motor drive, as long as the system can sustain characteristic current during the *shorted-winding period*.

IV. Robust Operation with A Shorted Motor Phase

A shorted motor phase presents a difficult challenge to remedy. One approach is to wind the motor to allow the MMFs of the phases to partially cancel. For example, Fig. 8 shows the winding layout of a three phase stator with fully pitched windings where phase-*a* is assumed to be short-circuited. With the proper control of the remaining *b* and *c* phases, the current in phase *a* can be driven towards zero. The amount of reduction required is a matter of the application. Fig. 8 shows the four locations of the magnet flux density as it rotates with respect to the thee-phase windings shown in the top trace. The currents *b* and *c* needed to cancel the magnet flux linking the shorted phase-*a* winding is shown in the bottom trace.

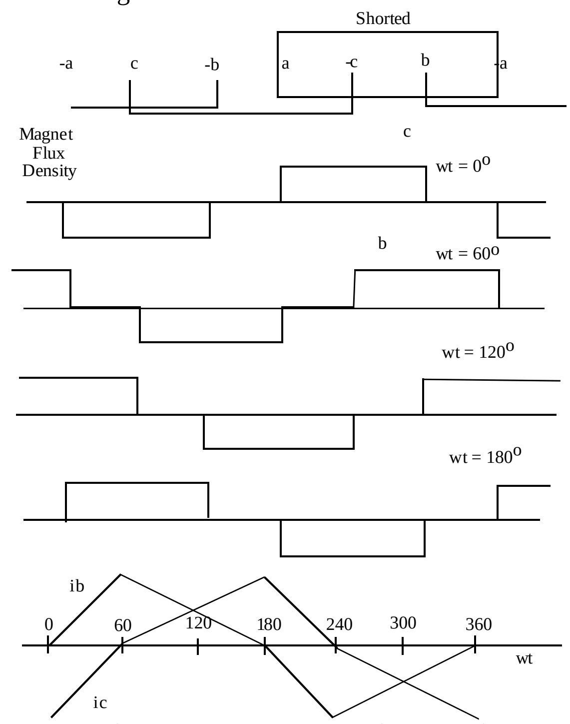

Fig. 8. Top trace: full pitch winding layout; next four traces: four positions of the magnet flux with respect to the stator windings; bottom trace: phase *b* and *c* current needed to reduce the magnet flux linking phase *a*

Since the currents in the two healthy phases do not add up to zero as shown in Fig. 8, the single-DC-source configuration is required in this case to provide a path for the necessary zero-sequence current component. After subtracting the zero-sequence component, the currents in phases *b* and *c* required to reduce the short-circuit current in phase-*a* are shown in Fig. 9.

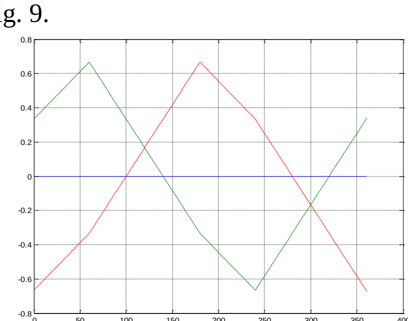

Fig. 9. Phase currents i_b and i_c after subtracting the zero component

V. Robust Operation with An Opened Motor Phase

In the case of an open-circuit fault in one of the stator phase windings, the remaining two healthy phases are capable of producing the same air-gap flux using the following formula:

$$i_{b\_new} = \frac{-3}{2} i_a + \frac{1}{2}(i_b - i_c) \quad (13)$$

$$i_{c\_new} = \frac{-3}{2} i_a - \frac{1}{2}(i_b - i_c) \quad (14)$$

Again, this can only be achieved in the single-DC-source configuration (inverters having the same ground point). Suppose that phase-*a* winding has an open-circuit fault, the following figure shows the phase currents before and after fault which result in same air-gap flux. Currents in phase *b* and *c* have larger amplitude with shifted phase as shown in Fig. 10. Compared with the before-fault case, the zero-sequence current is non-zero after fault, as shown in Fig. 11, which explains why the configuration with two isolated DC sources does not work in this case.

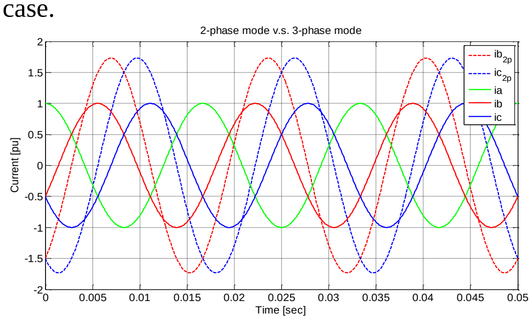

Fig. 10. Phase currents in 2-phase and 3-phase mode

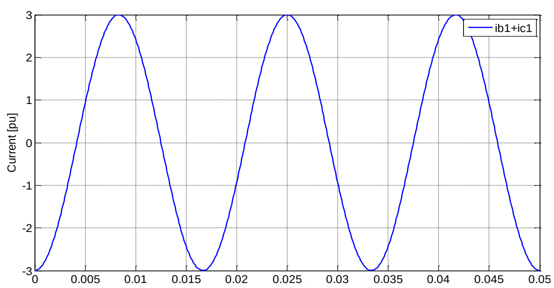

Fig. 11. Zero-sequence current in 2-phase mode

The two-phase operation comes at a price of higher current, which increases the losses. Assuming constant stator resistance, the I^2R loss before and after fault is plotted below. The average loss is essentially doubled as shown in Fig. 12.

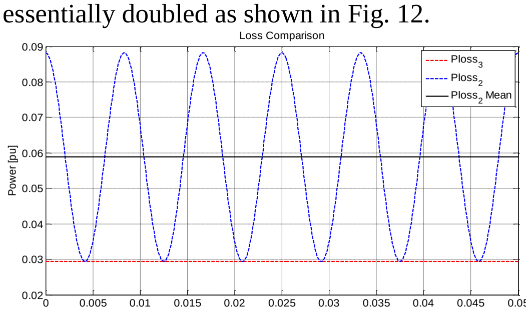

Fig. 12. Stator loss comparison, 2-phase mode v.s. 3-phase mode

The two-phase operation mode provides an alternative in tackling with not only the open-winding fault, but also open/short-switch faults, as long as one has a means to completely cut off the electrical path of the faulted phase. One possible solution is to place anti-parallel SCRs in series with each of the phase windings [5]. However, this not only adds component cost and reduces reliability, but also introduces additional losses during normal operation.

VI. Robust Operation with Opened Switch

The open-switch fault is generally more benign compared to a shorted-switch fault. Without losing generality, assume the upper switch of *a2* is opened due to electrical or mechanical failures, as shown in Fig. 13. One possible solution for continued operation is the same as used in the treatment for the shorted-switch fault, i.e. create an artificial neutral in the faulted inverter-2 by shorting *a2*, *b2*, and *c2* to the negative DC bus, and disconnect from the DC source if a zero-sequence path exists.

Note that with an open-switch fault, it is possible to implement two-phase operation without adding additional components. Again, assume the upper switch of *a2* is open-faulted. If one disables the gate signal as soon as the fault is detected, then the only possible current path is as highlighted in Fig. 13. As long as the induced open-circuit voltage at the phase-*a* terminal does not exceed the DC bus voltage, which is usually true, phase-*a* winding is electrically isolated from the rest of the circuit, and does not carry any current. Therefore, two-phase operation may be achieved without involving any additional circuit components.

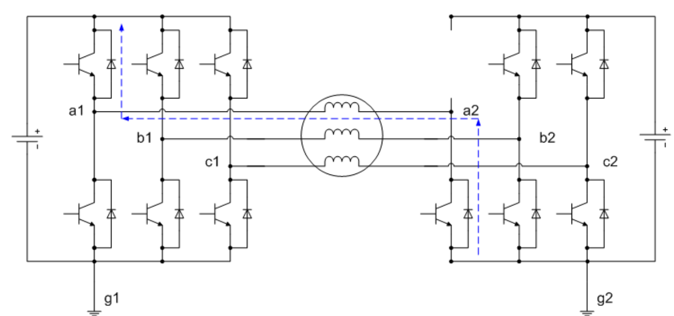

Fig. 13. Illustration of an open-switch fault

VII. Robust Operation with Interrupted DC Source

In cases where continued operation of a motor drive is critical, the double-output AC drive can be intentionally fed by two isolated power sources. For example, the two DC sources can be obtained from separate AC feeders entering the facility from two different distribution lines. Compared with the topology with single common DC source, this configuration requires more system components but provides a certain degree of redundancy. When one source is interrupted, the other source is able to support the drive to ride through the fault and continue operating the machine at reduced power rating.

Suppose that at t = 0.85 sec DC source-2 is interrupted and stops feeding DC link-2, then Vdc2 will start to drop. To continue operating the drive, one can again create an artificial neutral in inverter-2 to form a Y-connected machine. Suppose, for example, at t = 0.86 sec the controller detects the drop-out of the DC source and it immediately turns on the three upper switches of inverter-2 which creates an artificial neutral. At t = 1.06 sec, the controller detects that the voltage on DC-link-2 is restored, which indicates the recovery of DC source-2, so it restores the normal operation in inverter-2 at t = 1.07 sec. Note that there is discharge resistor connected across the DC capacitor and it causes the capacitor voltage to fall when it is not feeding or being fed by an external circuit. Simulation is done in Simulink to demonstrate the behavior of the drive in this scenario as shown in Fig. 14 ~ Fig. 17.

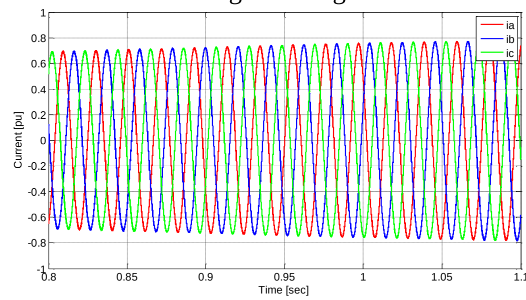

Fig. 14. Three phase currents

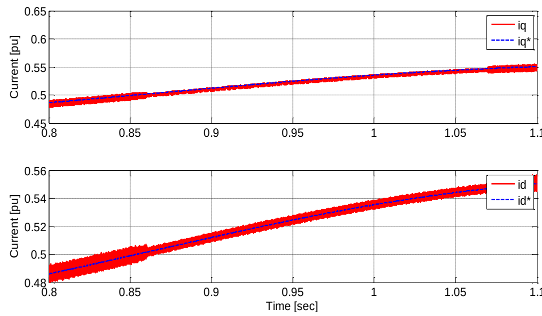

Fig. 15. D-Q currents and commands

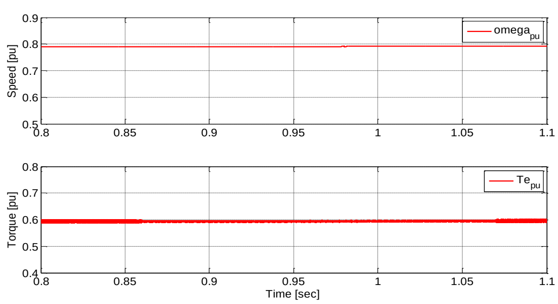

Fig. 16. Rotor peed and developed torque

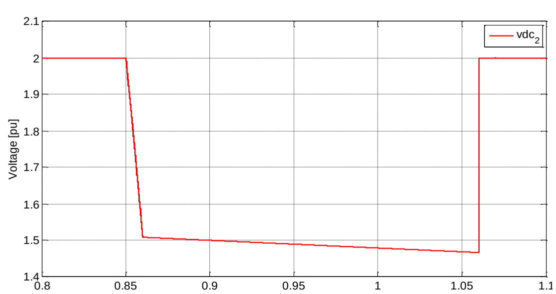

Fig. 17. Voltage of DC-link-2

It is seen that the current disturbance due to the fault condition and robust operation is negligible. These results indicate that the double-output AC drive is capable of handling a failure in one DC source without causing significant disturbance to the machine.

VIII. CONCLUSION

The double-output AC machine drive has been shown to be advantageous for robust operation in case of a variety of inverter drive component failures. Transition procedures are introduced in this paper, which allow the drive to dynamically switch operation modes when there is a short/open-circuit fault in a switch, or if one of the two DC sources has failed. The mitigation technique for short-circuit fault in a phase winding is introduced. The two-phase operation mode is also presented as an alternative in dealing with open/short-circuit faults, and its limitations have been discussed.

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APPENDIX

INDUCTION MACHINE PARAMETERS

Symbol	Quantity	Value and Unit
Pb	Base power	6 kW
Vb	Base voltage	280 V
Ib	Base current	14.3 A
Zb	Base impedance	19.6 Ω
Fb	Base frequency	60 Hz
Tb	Base torque	31.8 Nm
Rs	Stator resistance	0.015 pu
Rr	Rotor resistance	0.02 pu
Xls	Stator leakage reactance	0.15 pu
Xlr	Rotor leakage reactance	0.15 pu
Xm	Magnetizing reactance	2 pu
J	Inertia	0.001 kg m^2
P	Pole number	4

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