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Abstract In this paper theoretical and experimental analysis of an AC–DC–AC inverter under DC link capacitor failure is presented. The failure study conducted for this paper is the open circuit of the DC link capacitor. The presented analysis incorporates the results for both single and three phase AC input. It has been observed that the higher ripple frequency provides better ride through capability for this fault. Furthermore, the effects of this fault on electrical characteristics of AC–DC–AC inverter and mechanical properties of the induction motor are also presented. Moreover, the effect of pulsating torque as a result of an open circuited DC link capacitor is also taken into consideration. Theoretical analysis is supported by computer aided simulation as well as with a real time experimental prototype.

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1. Introduction

Modern industrial automation is very much dependent on the control of induction motors. The control mechanism of these motors is straightforward, economical and comparatively less complex with superior performance as compared to the DC motors. However, the extensive utilization of induction motors in automation process has also raised questions about their performance under faulty situations. Unlike other motors, induction machines do not inherit constant speed characteristics, therefore, the speed control mechanism using power electronic switching is deployed for its efficient use. Using power electronics based switching saves precious energy while attaining the desired mechanical attributes. The smooth operation of the industry, however, demands a motor driven with good fault tolerant system.

The list of fault points that are likely to occur in an AC–DC–AC system is given below:

- Power switch failure
- DC link capacitor fault (open circuit or short circuit)
- Gate drive pulse failure

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The performance of the induction motor under semiconductor based faults is well documented in the literature (Mendes and Marques Cardoso, 2003; Lahyani et al., 1998). The likelihood of the above mentioned faults depends on several factors and is already calculated by Mendes et al. and Lahyani et al. (Lahyani et al., 1998; Fuchs, 2003). According to their findings the advent of the modern sophisticated PWM chips has reduced the chances of semiconductor failure. The study of Lahyani et al., about the capacitor failure in SMPS implies well with the scenario of AC–DC–AC system. Their study deduced that the probability of capacitor failure is as high as 60% in switching circuits (Lahyani et al., 1998). It should also be noted that in capacitors, the equivalent series resistance (ESR) increases with the passage of time and in switching circuits this ESR can cause self-heating and eventually cause capacitor failure. The fault on capacitor can be a short circuit as well as an open circuit. Those researchers who have conducted fault studies of AC–DC–AC based induction motor systems have mentioned this fault (Kastha and Bose, 1994; Ebrahim and Hammad, 2003; Biswas et al., 2009; Peugeot et al., 1997; Ribeiro et al., 2000). But there still exists a gray area because, for some researchers the most commercial devices are well protected for capacitor faults (Kastha and Bose, 1994; Ribeiro et al., 2000). The inverter switches and the line to ground faults are discussed by Lu and Sharma (Dhanya et al., 2012). Ebrahim and Hammad (2003) argued about the voltage drop in DC link, but only for a transient instant of time. Similarly, the work of Biswas et al., also deals with the failures of semiconductors and additionally provides the harmonic analysis, leaving aside the fault on the DC link capacitor (Biswas et al., 2009). Another research work on semiconductor based faults is presented by Lu and Sharma (2009). Likewise, the work presented by Lezana et al., Yang et al. and Peugeot et al. also studied the failure of semiconductor components (Peugeot et al., 1997; Lezana et al., 2010; Yang et al., 2012). The fault study dealing with the failure on inductor motor is addressed in Kathir et al. (2011). The authors of this paper have studied the findings on the short circuit capacitor failure earlier in Sher et al. (2014) and the effect of open circuit DC link capacitor in Sher et al. (2012).

In this paper, an extended theoretical analysis is presented about this fault, which is followed by the simulation analysis and the experimental work. The combination of the theoretical, simulation and the experimentation analysis makes this paper a nice information package for the researchers. The investigation presented here will enrich the research community about the performance of AC–DC–AC system under a rippled DC link voltage. This study will also aid the design procedure for a fault tolerant AC–DC–AC system as well as the optimal protection system design.

2. Problem description

In AC–DC–AC system a stiff DC link voltage is required in order to reduce low order harmonics. For this purpose electrolytic capacitors are deployed. The capacitor iron out the ripple in the voltage that occurs due to the rectification of input AC voltage. It also enhances the ride through capability of the system against input voltage variations. In case of any fault in this capacitor, the performance of inverter is degraded that eventually affects the motor performance. In case of capacitor open circuit the ripple appears in the DC link the frequency of which is a function of number of input phases. Thus, for a single phase supply the characteristic frequency (ripple frequency) will have twice the frequency of the AC supply (100 Hz for 50 Hz and 120 Hz for a 60 Hz system) and for three phase it is six times the fundamental frequency (300 Hz for 50 Hz and 360 Hz for 60 Hz system). The impact of input frequency on the DC voltage ripple frequency requires to have analysis of single as well as three phase input supply. Therefore, in this paper the analysis of capacitor open circuit fault is presented for both single as well as a three phase AC input.

3. Analysis of the problem

The electrolytic capacitor connected with the DC link defines the composition of the DC current. Moreover, the presence of low order harmonics has an effect on the torque of the motor. The problem is also linked to the direction of power flow and line impedance. These three aspects are discussed below in detail.

The DC current in an AC–DC–AC inverter depends on the type of load connected and the applied switching algorithm for power electronic switches. It is always complex because it has both AC and DC components where, the AC components can further be classified as low frequency and high frequency AC components. The DC link capacitor lets pass the AC components, thus following the basic property of capacitive reactance ($X_C = 1/2\pi fC$). However, for the line inductance the AC component realizes that the series impedance is a load in shunt with the capacitor. So the AC current splits up in two branches where the high frequency part gets a passage through a capacitor. Considering that the system operation is normal and the power flow direction is from the source to load then it can be concluded that the current is positive. However, if the capacitor is removed then there will be no compensation element for the line inductance. This means that the dominant line inductance will oppose any change in the current and hence it will change the overall behavior of the circuit. In this paper following assumptions are made prior to the mathematical analysis:

- The equations are well approximated using discrete time Fourier series.
- There is no aliasing such that the sampling frequency fulfills Nyquist criteria.
- All the coefficients that are shown in order to verify/express the results are approximated using graphical re-plots on MATLAB and may incur errors which, otherwise are not there once we directly input data to MATLAB using excel sheets.

![Figure 1](image.png) Approximated equivalent circuit of one phase of three phase induction motor.
Analysis of inverter fed induction motor system

- \( C_a \) is the trigonometric components of the approximated Fourier series.
- \( \omega T \) is the ripple frequency of the waveform.
- \( V_p \) is the peak value of input voltage.
- The noise and glitches due to an open circuited DC link capacitor are not taken into consideration.

3.1. Single phase input

For single phase input (220 \( V_{\text{rms}} \)) the rectifier output voltage without a capacitor touches the zero level and has a frequency of twice the input voltage. The mathematical equation of the DC link voltage is given by Eq. (1):

\[
f(t) = 2 \times \left( \frac{325}{\pi} \right) - 4 \times \left( \frac{325}{\pi} \right) \sum_{n=1}^{\infty} \left( \cos \left( \frac{2000\pi n t}{4\pi^2} \right) \right)
\]

(1)

It is obvious from equation (1) that the waveform has even symmetry (2, 4, 6, . . .). Eq. (1) is derived using the idea of discrete time Fourier series, and it has two parts, the first part is DC component and its trigonometric components (which are real all the time) since \( C_n = A_n + iB_n \). It can be noticed that \( B 1, 2, . . ., 8 \) are roughly zero since the waveform depicts even symmetry.

Since the output voltage is a function of DC ripple voltage and the PWM switching scheme, therefore, with ripples the output voltage will be irregular. So the equation is given by:

\[
f(t) = \sum_{n=1}^{\infty} (C_n e^{i\omega t}) - \sum_{n=1}^{\infty} (C_n e^{-i\omega t})
\]

where

\[
C_n = 50 \left( \frac{1}{\sqrt{2}} \right) \left( \frac{150}{2\pi} \right) \left( \frac{0.003}{0.003} \right) \left( \frac{\sin (0.007)\omega t}{\sin (0.007)\omega t} \right)
\]

\[
+ \left( \frac{325}{2\pi} \right) \left( \frac{0.007}{0.007} \right) \left( \frac{\sin (0.007)\omega t}{\sin (0.007)\omega t} \right)
\]

(2)

\[
f(t) = \sum_{n=1}^{\infty} (C_n e^{i\omega t})
\]

(3)

3.2. Three phase input

Three phase input (380 \( V_{\text{rms}} \) line–line) has an advantage over single phase input when it comes to the ripple frequency. Inverter operation with a three phase supply is steadier than the single phase input. The equation for the output waveform of a full wave uncontrolled bridge rectifier is given below:

\[
f(t) = \sum_{n=6.12}^{\infty} \left( \frac{4653}{\pi n (n-1)} \right) \cos (200\pi t + \pi)
\]

(4)

The output equation of the inverter phase-to-phase output can be written as:

\[
f(t) = \sum_{n=1}^{\infty} (C_n e^{i\omega t})
\]

where

\[
C_n = (50 \times 325) \left[ \left( \int_{\frac{\pi}{4}}^{\frac{\pi}{4}+\frac{\pi}{4}} \sin ot e^{-i\omega t} dt \right) \right]
\]

(5)

\[
+ \left( \int_{\frac{\pi}{4}+\frac{\pi}{4}}^{\frac{\pi}{4}+\frac{\pi}{4}} \sin (\omega t + \frac{2\pi}{3}) e^{-i\omega t} dt \right)
\]

(6)

The output voltage of the inverter includes harmonics in it and for single phase AC input the even harmonics will result in pulsating torque. So in order to find the slip for a particular harmonic component, let us assume that \( V_p \) is the frequency of \( V \)th harmonic then slip is given by Murphy and Fred (1988):

\[
S_v = \frac{vN_s \pm N}{vN_s}
\]

(7)

where \( \pm \) sign indicates that a mmf generated by a harmonic can either be in the same direction of rotor or in the opposite direction. From the general theory of induction motor, it is well known that the speed of the motor is given by:

\[
N = (1 - s)N_s
\]

(8)

where

\[
S_v = \frac{v \pm (1 - s)}{v}
\]

(9)

Fig. 1 shows the approximated equivalent circuit for one phase of a three phase induction motor with balanced load. Considering this equivalent circuit the ratio of torque due to fundamental and harmonic component is expressed by [10] and is given below:

\[
T_r / T_s = \pm \left( \frac{\phi_2}{vX_{pu}} \right)^2 \times \left( \frac{r_{2y}}{r_2} \right) \times \left( \frac{S_1}{k + 1} \right)
\]

(10)

where \( T_r \) is the torque due to fundamental component, the second harmonic torque can be calculated by (10). Suppose \( r_{2y}/r_2 = 3 \) and fundamental load slip is 0.03 then \( T_r/T_s \) is 5.62 \times 10^{-3}/X_{su} pu.

If the limit the leakage reactance is supposed to be 0.2 pu then the torque due to second harmonic will be \(-1.405\) or \(-140\%\) of the torque due to fundamental frequency. The minus sign implies that the effect of the second harmonic is not in the direction of fundamental torque. This second harmonic torque will produce a space fundamental mmf with frequency twice the fundamental frequency. This means that the machine will experience a pulsating torque. The behavior of harmonics is different for other harmonic order, e.g., the fourth harmonic is a positive sequence and eighth harmonic is a zero sequence. The Fourier analysis of a three phase rectified waveform reveals
that the dominated harmonics in it are sixth multiple of fundamental component (6th, 12th, 18th, …). According to Eq. (10), the zero sequence component has no impact on the fundamental torque. This is exactly what is reflected in the simulation and experimental work i.e. the motor performance with three phase input was far much better as compared to the single phase input. The use of a DC link capacitor is to dampen the low order harmonics and thus reducing the pulsating torque. Therefore, the presence of voltage ripple will shape the output voltage of an inverter like an envelope of the rectified sine wave.

Figure 2  Simulation Setup.

Figure 3  Inverter voltages and stator currents without fault.

Figure 4  DC link voltages with single phase supply.
The last issue of impedance is also important because the DC voltage is obtained by rectifying the AC voltage therefore, the line inductance of AC supply will also reflect on the DC bus. This effect is compensated through a capacitor, which, if not connected, will result in high voltage spikes. The voltage spikes result in poor power quality and hence can damage the inverter switches. Therefore, a DC link capacitor is required to cope with this issue.

4. Simulation setup

The simulation arrangement based on Matlab/Simulink is depicted in Fig. 2. Although, it shows a three phase input, it can also be used for a single phase AC source. An ideal switch S1 with zero resistance is connected in series with the capacitor that is turned OFF to simulate the capacitor open circuit. This
turn OFF is accomplished by a unit step change applied to switch S1 at time $t = 2.5$ s. A standard model of induction motor available in Simulink is considered for the simulation and its salient features are given below:

- Rated power = 1 HP.
- Rated voltage = 380 V.
- Rated frequency = 50 Hz.
- Rated RPM = 1380 RPM.

The inverter switches are based on MOSFET and their switching control is achieved through conventional Sinusoidal Pulse Width Modulation (SPWM) scheme. The constraints of SPWM are as follows:

- Carrier frequency = 2050 Hz.
- Control frequency = 50 Hz.
- Amplitude modulation ratio = 0.8.
- Frequency modulation ratio = 41.

5. Simulation results

In order to validate the simulation model (Fig. 2), the system is first tested for a healthy condition. In a healthy condition the fault is not simulated. The AC–DC–AC inverter is given single and three phase supply where the input line voltage is 381 V$_{p}$ (for 220 V$_{rms}$) with 50 Hz frequency. The generated ripple frequency is 100 and 300 Hz respectively for single and three phase input.

As seen in Fig. 3 the system shows adequate performance in terms of mechanical and electrical constraints of the load, thus validating our model.

5.1. Single phase input

Some low power applications desire to have a single phase supply for AC–DC–AC system. The use of single phase AC supply reduces the DC link voltage compared with the nominal voltage for three phase input. It also reduces the ripple frequency of the DC link and, therefore, it requires a larger value capacitor. In time $t = 2.5$ sec the fault is created that resulted in the severe degradation of the motor parameters. Fig. 4 shows the effect of capacitor fault on DC link voltages where, the DC link voltage touches the zero level. In Fig. 5 high spikes can be seen in stator current and voltage waveform. As a result the electromagnetic torque is also not normal as discussed in the last section. Fig. 6 shows the zoomed image of inverter phase to phase voltage and three phase stator current after the fault.

5.2. Three phase input

A three phase input is used in an AC–DC–AC inverter for high power applications. The input voltage is rectified through a three phase full wave uncontrolled bridge rectifier. In the simulation arrangement the supply voltage has a frequency of 50 Hz for which the ripple frequency is 300 Hz i.e. 6 times the input frequency. The other benefit using a three phase supply is the average voltage which is calculated as:

$$ V_{dc} = \frac{1}{\sqrt{2}} \times V_{p} \times \frac{1}{11} $$

The advantage of using three phase supply in the context of the problem under investigation, is the ripple frequency which is higher than the single phase supply. Fig. 7 depicts the DC link voltage that shows ripple but the amplitude does not touch to zero. This makes the difference in the performance of motor as argued in Section 3.2 and shown in Fig. 8. The current and voltage of the inverter are shown in Fig. 9. As seen the stator current has minor disturbance as compared with the single phase AC supply, so is the electromagnetic torque that shows the change right after the load and the fault is simulated.

6. Experimental setup

A laboratory setup was built for experimental verification of simulation results as shown in Fig. 10. The experiments were carried out with a 1 HP motor and a three phase inverter built indigenously for the analysis. The capacitor (450 μF at 1000 V) was disconnected for experimenting the scenario of the open circuit. The single phase AC input was supplied directly,
however, for the three phase input a step down transformer was utilized. The motor was connected in delta configuration. The motor stator current was recorded by using a current to voltage converter with a 1Ω resistance while all the measurements are taken with an oscilloscope probe set at 10×.

7. Experimental results

Experimental results follow the pattern seen in the simulation and as discussed in the mathematical analysis of the problem. It shows that the motor current and voltage become distorted.
after the fault. The experimental results show the terminal phase to phase voltage of the AC–DC–AC inverter and the current for one phase of the motor. The fault with single phase input supply and three phase input supply is shown below.

7.1. Single phase input

Fig. 11 shows the inverter output voltage after the fault and Fig. 12 shows the stator current of phase A of the motor. As per the analysis of the problem, the absence of DC link capacitor not only affected the waveform of the output voltage but voltage spikes are also visible. The motor, however, at no load did not stop and continued to run.

7.2. Three phase input

Fig. 13 shows the inverter output voltage after the fault and Fig. 14 shows the stator current of phase A of the motor. Here, as discussed in simulation, the voltage in DC link does not go to zero rather flip flops around an average value. Therefore, the voltage waveform is quite close to the normal inverter output. However, due to the lack of compensation of line impedance, high spikes are visible in the waveform. The stator current waveform is also much close to the sine wave, as an obvious advantage of the high ripple frequency.

8. Conclusion

In this paper an analysis is performed to investigate the performance of the induction motor under the fault of open circuited DC link capacitor. The analysis is performed to enrich the knowledge about the fault studies of AC–DC–AC systems. To investigate the fault two different power supplies were used for the reason that the ripple frequency depends on the total number of phases. The experimental results closely resemble the simulated results which validate our analysis. It is concluded that the fault on the DC link capacitor is much more serious if the AC–DC–AC inverter is given a single phase supply. However, with the three phase supply the system shows better ride through capability under the faulty conditions. This implies that higher ripple frequency will strengthen the
behavior of the system under this kind of fault. This ultimately
leads to a more reliable motor control system. This study has
helped us in establishing the information about the behavior of
induction motor after the fault as well as the stresses on power
electronics switches. The detailed analysis also enriches the theo-
retical study of using a DC link capacitor in AC–DC–AC
inverters and will certainly help in designing a good fault ride
through system.

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