Finite Element Analysis on Multiple IGBT Switch Open-Circuit Fault in PWM Inverter Fed Induction Motor

Kripanidhi Pyasi¹ and N Praveen Kumar²

¹Department of Electronics and Communication Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India -641112
²Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India-641112

¹kripanidhipyasi1993@gmail.com, ²n_praveenkumar@cb.amrita.edu

Abstract. This study analyzes the single and multiple IGBT switch open circuit fault in an inverter fed induction motor (IM) using Finite Element Method. The finite element simulation is carried out in ANSYS Maxwell and Simplorer for various fault conditions such as single IGBT switch open in an inverter leg, two IGBT switch open in the inverter same leg and in different leg. A three-phase 7.5kW IM is modelled in ANSYS Maxwell which is fed through a three-phase voltage source inverter modelled in ANSYS Simplorer. Inverter switches are controlled using sinusoidal pulse width modulation technique. Several electromagnetic parameters such as torque, speed, line voltage, phase current, flux line & flux density distribution over the machine and radial air gap flux density are analysed.

1. Introduction

The voltage source inverter (VSI) is commonly used circuit for induction motor (IM) speed control. A fixed dc voltage is applied as input to the VSI that produces the required ac output voltage using controlled switching of the IGBT switches. The three-phase inverter acts as a three-phase voltage source in which the amplitude, phase and frequency are controllable. Mostly sinusoidal pulse width modulation (SPWM) technique is used to control the on and off periods of inverter IGBT switches. The three-phase SPWM controlled VSI is used in many applications like electric drives, UPS, home appliances etc. Any faults in inverter will affect the smooth operation of the entire system and therefore to avoid the detrimental effects and to increase the credibility and operational availability of the system, the detection, analysis and tolerance of faults are necessary. Three-phase IM are largely used in many industrial applications because of its properties like low cost, robust, easy construction, less sensitive to operating surroundings and self-starting capability. The induction motor is fed from a voltage source inverter for speed control applications. The various faults that occur in IM are stator winding short circuit, broken rotor bar, bearing and eccentricity faults. Also when IM is fed from an inverter, faults can occur in power converters like open circuit and short circuit of power electronic switches. Majority of these inverter use IGBT as electrical switch because of its high voltage, high current rating and the capability to support short circuit currents longer than 10μs. Though IGBTs are rugged, failures often occur due to high electrical and thermal stresses which are experienced from various applications [1].
About 38% and 53% of failures in variable frequency drives (VFD) are caused by power electronic components and control circuits, respectively [1],[2]. The importance of condition monitoring in IM drives are becoming popular by protecting it from undesirable and catastrophic failure. This improves the efficiency and reduces investment cost of replacing and repairing the converter and machine. In [3] fault-endurable drivessystems are used to assure uninterrupted operations and to run the systems after repairing or dissociating the faulty parts. Inverter switch open circuit faults occur for a number of reasons such as device driver failure, contacts breakdown because of over-heat or bond-wire rupturing. In [4] current control deviation in stator reference frame is observed using an expletive voltage test. Additional voltage testing depends on adequate voltage reserves in the faulty direction. The voltage reserves are highest in the working regions, in which the voltage disturbances because of single-switch fault is minimized and an added validation is advantageous. This algorithm detects fault in switching intervals even during transients and indicate the faulty switches

Electric machines [5] are correlated with multi-discipline(electric, electromagnetic and mechanical) domain which makes the electric drive systems coupled with nonlinear components. If the system becomes subject to a dynamic state, these inequalities will intensify. Therefore accounting for non-linearity effects in modelling would enhance the reliable analysis of the system. The finite element method (FEM) incorporates the non-linear effects and analyse the electromagnetic fields of IM. It is better than analytical method because of accurate modelling of IM. The FEM is a well-established tool used for electrical and electromagnetic fields problems, it makes a model more accurate by including winding type, material, magnetic saturation and effects of air gap spatial harmonics etc., [6]. Finite element analysis (FEA) allows considerable flexibility when designing IM to include precise geometric shapes, material properties, slots, shapes, and winding types. Using FEM, the distribution of flux over the motor and in the air gap can be analyzed for healthy and various abnormal conditions. In [7], FEM is used to analyze stator winding inter-turn fault for various percentages of inter-turn short and winding phase-phase short in [8]. The fragmented rotor bar fault is analysed using FEM in [9], [10] and bearing fault of IM in [11]. An IGBT short circuit faults in a PWM inverter fed induction motor is analysed using FEM in [12] and single IGBT switch open circuit fault in [13].

This paper presents the FEA of three-phase voltage source inverter fed IM under the various fault conditions such as single IGBT switch open circuit, two IGBT switches open circuit in same leg and two IGBT switch open circuit in different inverter leg. Various machine parameters such as phase currents, speed, and flux density distribution over IM and air gap flux are analyzed for all the fault conditions in comparison with healthy motor.

2. Modelling of VSI fed IM using ANSYS Maxwell and ANSYS Simulator

A simulation study is accomplished on 3-phase, 380V, 1440rpm, 50Hz, 7.5kW IM model in ANSYS Maxwell as shown in Figure 1. ANSYS Simploer is used to design a SPWM controlled voltage source inverter and to model switch open circuit fault and for applying load torque. The IM model in ANSYS Maxwell is co-simulated with the PWM inverter modelled in ANSYS Simploer which is shown in Figure 2. A switching frequency of 2 kHz is used to control the inverter. The inverter switch open circuit fault is incorporated using step function. The design detail of induction motor used for the analysis is given in Appendix. The IM fed from the PWM inverter operates in an open-loop controlled manner. SPWM control strategy is used to provide pulses for IGBT switches. In Figure 2 the step switches 2, 3 and 4 are used to create open circuit faults for different conditions. The switch step 2 is controlled to emulate single switch open circuit fault. The switches step 2 and 3 is opened to emulate two IGBT switch open fault in same leg and finally switches step 2 and 4 are controlled to emulate two IGBT open circuit fault in different leg.
3. Results

The induction motor is started no load and rated load of 49Nm is applied at \( t = 0.4s \) and the model is simulated for a total time of 1.2s for all cases. Single IGBT open-circuit fault is implemented at \( t=0.7s \) in inverter leg c by opening Step 2 switch and the bottom switch in the same leg is opened at \( t=0.9s \) by opening Step 3 for two IGBT switch implementation. Another simulation set-up is used to implement two IGBT open-circuit fault in different legs by opening Step switch 3 in leg c at \( t=0.7s \) and Step switch 4 in leg b at \( t=0.9s \).

Figure 3 shows the inverter line voltage between two healthy legs a and b, \( V_{ab} \), and between healthy and faulty leg b and c, \( V_{bc} \), for single switch open condition in inverter leg c at \( t=0.7s \). The inverter line voltage between two healthy legs a & b, \( V_{ab} \), shows a clear pulse width modulated waveform whereas the negative half magnitude of line voltage \( V_{bc} \) reaches an unprecedented level with severe distortion due to opening of switch in leg c.

(a). Line voltage between healthy legs (\( V_{ab} \)).

(b). Line voltage between healthy and faulty leg (\( V_{bc} \)).

Figure 1. IM model in ANSYS Maxwell.

Figure 2. Co-simulation between ANSYS Simplorer and IM in ANSYS Maxwell.

Figure 3. Inverter line voltage under single IGBT switch open circuit fault in leg c.
(a). Line voltage between two healthy legs (\(V_{ab}\)).  

(b). Line voltage between healthy and faulty leg (\(V_{ca}\)).

**Figure 4.** Inverter line voltage under two IGBT switch open circuit fault in leg c.

Figure 4 depicts the inverter line voltage between healthy legs a and b, \(V_{ab}\), and between healthy and faulty leg c and a, \(V_{ca}\), for two switch open circuit fault in inverter leg c. When both the switch gets open circuited in leg c at \(t=0.9s\), line voltage \(V_{ca}\) is highly distorted in both the half cycles with huge voltage ripples. Figure 5 illustrates inverter line voltage \(V_{bc}\) when top switch from leg c is opened at \(t=0.7s\) and bottom switch from leg b is opened at \(t=0.9s\). When both switches are opened huge imbalance is noticed in line voltage \(V_{bc}\).

**Figure 5.** Inverter line voltage under two IGBT switch open circuit fault in legs b and c (\(V_{bc}\)).

(a). Healthy phase current (Phase A).  

(b). Faulty phase current (Phase C).

**Figure 6.** Winding currents of IM under single IGBT switch open circuit in inverter leg c.

Figure 6 describes the phase currents of induction motor in phase A and C under one switch open circuit fault condition. The peak value of phase current in healthy phase A is 22A under rated load.
is increased to a value of nearly 50A at t=0.7s when the fault happens. In the faulty phase C, distortions are noticed in the negative half cycle at t=0.7s due to opening of switch in leg c.

Figure 7. Winding currents of the IM under two IGBT switch open circuit in inverter legs b and c.

Figure 7 illustrates the 3 phase currents of induction motor when two IGBT switches are open circuited at t=0.9s in inverter leg b & c. Top switch of inverter leg c is getting opened at t = 0.7s and bottom switch of inverter leg b is opened at t = 0.9s. When the switches are open at t=0.9s, huge imbalance is noticed in all the 3 phase currents with their magnitude reaching a very high value thereby damaging the motor.

Figure 8(a). Speed of IM when top switch in leg c opened at t=0.7s and bottom switch in leg c are opened at t=0.9s.

Figure 8(b). Speed of IM when switch in each leg b & c are open-circuited at t=0.7s and t=0.9s.

Figure 8(a) depicts the speed of IM when top switch in leg c is open circuited at t=0.7s and bottom IGBT switch in inverter leg c is opened at t=0.9s. The IM continues to run with a drop in speed from
1440 rpm to 1400 rpm with increase in speed oscillations. Figure 8(b) shows the speed when a switch in each leg b & c are opened at t=0.7s and at t=0.9s. At t=0.9s when switches in inverter leg b and c are open-circuited, the IM speed drops and comes to stand still.

Figure 9(a) shows the symmetric distribution of flux lines over IM in all the pole pitches. The flux distribution becomes asymmetrical when both the switches in inverter leg c is opened which is indicated in Figure 9(b). The asymmetry in flux gets increased when a switch in each inverter leg b and c are opened as seen from Figure 9(c). The unbalance in the phase currents during switch open-circuit causes these distortions in flux distribution over IM.
Figure 10. Distribution of flux density in IM.

Figure 10 illustrates the distribution of flux density over IM under healthy and faulty conditions. The flux density is symmetric over the four pole-pitch of IM whereas saturation in flux density is noticed when the switches in inverter leg b & c are open-circuited. The distribution of flux density is asymmetric when fault occurs and reaches saturation due to high magnitude of fault currents.

Figure 11. Radial air gap flux density of IM.
Figure 11 depicts the radial air gap flux density of the induction motor with respect to radial air gap distance for healthy and various fault conditions. The radial air gap flux density is sinusoidal and properly distributed over the pole-pitches of IM under the healthy condition. The harmonics in the waveform of air gap flux density is due to stator and rotor slot effects, windings and saturation. The asymmetry in the air gap flux increases with various inverter faults of increasing severity. The harmonic content in radial air gap flux density is increased due to switch open-circuit fault for several fault severities such as single switch open-circuit fault, two switches open in same leg and in different inverter leg.

Figure 11. Healthy condition. (b). When single switch in leg c is opened. (c). When two switches in inverter leg c are open-circuited. (d). When a switch each in inverter leg b & c are open-circuited.

Figure 12. Spatial FFT of Radial air gap flux density of IM.

Figure 12 depicts the spatial FFT spectrum of radial air gap flux density of induction motor for different conditions with respect to radial distance. The healthy motor spectrum shows a fundamental component of 0.49Wb/m² and other harmonics due to slot effects, windings and saturation which are having appreciable magnitudes. The fundamental amplitude and the other harmonic amplitudes keep on decreasing as fault severity increases. The amplitude of fundamental component reduces to 0.44 Wb/m² for single switch open, to 0.4 Wb/m² for two switches open in same leg and finally to a value of 0.14 Wb/m² for a switch open-circuit in inverter leg b and c. The other harmonic amplitudes also decreases to a lower value based on fault severity which can be seen from Figure 12(d).

4. Conclusion

In this paper, FEM analysis on analytical and electromagnetic field parameters are carried out on SPWM inverter fed IM under healthy condition, single IGBT inverter switch open-circuit condition, two IGBT switch open in same inverter leg and in different legs. When the inverter IGBT switches are open circuited, the respective faulty leg phase current is getting disturbed from the normal condition and this influences the healthy phase by increasing the phase current and torque ripple of induction.
motor. The vibrations in torque induce speed oscillations, which affects the induction motor average speed. The flux lines and flux density distribution over the IM becomes asymmetrical due to the fault and the asymmetry increases based on severity of fault. The distribution of radial airgap flux density becomes unsymmetrical and from the spatial FFT spectrum it is clear that the fundamental component of radial airgap flux density keeps decreasing based on fault severity. The magnitude of fundamental component from a value of 0.49 Wb/m² for healthy condition decreases to a value of 0.14 Wb/m² for IGBT open-circuit in different legs. The amplitude of other harmonics in the spectrum also reduces due to the fault.

5. Appendix

1. THREE PHASE INVERTER

| Generalized Data |
|------------------|
| DC Voltage: 560V. |
| Inverter Type: Voltage Source |
| Switching Technique: SPWM |
| PWM Carrier Frequency: 2KHz |
| PWM Fundamental Frequency: 50Hz |

2. THREE PHASE INDUCTION MOTOR DESIGN PARAMETERS

| Generalized Data | Stator Data | Rotor Data |
|------------------|-------------|------------|
| Output Power: 7.5 KW. | No. Slots: 48 | No. Slots: 44 |
| Rated Voltage: 380 V | Outer Diameter: 210 mm | Air-gap: 0.35 mm |
| No. of Poles: 4 | Inner Diameter: 148 mm | Inner Diameter: 48 mm |
| Rated Speed: 1440 rpm | Stator Core Length: 250 mm | Rotor Length: 250 mm |
| Frequency: 50Hz | Steel Type: M 19_24G | Steel Type: M 19_24G |
| Rated Torque: 49.3 Nm | No. of Parallel Branches: 2 | Conductors per Slot: 30 |
| Rated Current: 15 A | Winding Type: Double layer |
| Rated Slip: 3% |

References

[1] Lu B and Sharma S K 2009 A literature review of IGBT fault diagnostic and protection methods for power inverters IEEE Transactions on industry applications45(5) 1770-77
[2] Estima J O and Cardoso A J M 2011 A new approach for real-time multiple open-circuit fault diagnosis in voltage-source inverters IEEE transactions on industry applications47(6) 2487-9.
[3] Eickhoff H T, Seebacher R, Muetze A, and Strangas E G 2017 Enhanced and fast detection of open-switch faults in inverters for electric drives IEEE transactions on industry applications53(6) 5415-25
[4] Bianchi N2005 Electrical machine analysis using finite elements CRC press
[5] Bose B K 2010 Power electronics and motor drives: advances and trends Elsevier
[6] Vinothraj C, Praveen Kumar N and Isha T B 2018 Bearing Fault Analysis in Induction Motor Drives Using Finite Element Method International Journal of Engineering & Technology7(3.6) 30-34
[7] Praveen Kumar N and Isha T B 2019 FEM based electromagnetic signature analysis of winding inter-turn short-circuit fault in inverter fed induction motor CES Transactions on Electrical Machines and Systems3(3) 309-315.
[8] Praveen Kumar N, Isha T B and Balakrishnan P 2016 Radial electro-magnetic field analysis of induction motor under faulty condition using FEMBiennial International Conference on Power and Energy Systems: Towards Sustainable Energy1-6
[9] Praveen Kumar Nand Isha T B 2016 Electromagnetic field analysis of 3-Phase induction motor drive under broken rotor bar fault condition using FEM IEEE International Conference on Power Electronics, Drives and Energy Systems 1-6

[10] Praveen Kumar Nand Isha T B 2019 Electromagnetic signature study of a closed loop speed controlled three-phase induction motor under broken rotor bar fault using finite element method Journal of Engineering Science and Technology 14(5) 2731-45.

[11] Praveen Kumar N, Vinothraj C and Isha T B 2018 Effect of wear and tear bearing fault in induction motor drives using FEM IEEE International Conference on Power Electronics, Drives and Energy Systems 1-6

[12] Praveen Kumar N, Ashwini G, Muthukumaran V, Pavithra R, Priyanka D and Balakrishnan P 2018 PWM Inverter Switch Short Circuit Fault Analysis in Three Phase Induction Motor Using FEM Journal of Adv Research in Dynamical Control Systems 10(3) 640-646

[13] Praveen Kumar N, Sreemathi R, Chandar K R, Vaijayanthi V and Kumar S P 2017 PWM inverter switch open-circuit fault analysis in three phase induction motor drive using FEM International Conference on Energy, Communication, Data Analytics and Soft Computing 1244-48