SRTTU

Journal of Electrical and Computer Engineering Innovations

JECEI, Vol. 1, No. 2, 2013

Regular Paper

# Fuzzy Logic Based Life Estimation of PWM Driven Induction Motors

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**ARTICLE INFO**

**ARTICLE HISTORY:**
Received 23 October 2013
Revised 11 December 2013
Accepted 20 December 2013

**KEYWORDS:**
Insulation aging
Life model
Peak voltage
Thermal stress

**ABSTRACT**

Pulse-width modulated (PWM) adjustable frequency drives (AFDs) are extensively used in industries for control of induction motors. It has led to significant advantages in terms of the performance, size, and efficiency but the output voltage waveform no longer remains sinusoidal. Hence, overshoots, high rate of rise, harmonics and transients are observed in the voltage wave. They increase voltage and thermal stresses; resulting into accelerated insulation aging. This paper presents the application of fuzzy logic to life estimation of PWM driven induction motors. Insulation stress parameters are experimentally computed for wide range of switching frequency and used in fuzzy logic based life estimation algorithms. The results obtained with the fuzzy expert system show a performance approaching attainable for the life model based on the inverse power law.

## 1. Introduction

Standard induction motors that have been designed to operate from fixed frequency sinusoidal power are being used with pulse width modulated (PWM) adjustable frequency drives (AFDs) in an increasing number. The application of PWM inverters has led to significant advantages in terms of the size, performance, efficiency and flexibility of control of the machinery & the process. Insulated Gate Bipolar Transistors (IGBTs) are the preferred power switching device in modern PWM inverters because they are easily turned on and off from simple, low-cost driver circuits and their high switching speed not only reduce switching losses but allow higher frequency PWM patterns to be developed to improve motor current waveforms and overall dynamic performance. The output voltage waveform of today's PWM drive is not a sine wave, but a series of square wave pulses that produces a reasonable approximation of sine wave current.

Recent proliferation of PWM controllers in industries has resulted into the increasing problem of power quality and harmonics on supply side [1] and premature failure of induction motors on the load side. In general the effect of non-sinusoidal voltage and current waveform is associated with insulation degradation due to thermal aging [2, 3], but the effect of voltage peaks, rate of rise of voltage and wave shape can also be predominant [4, 5]. The additional stresses caused by such voltages eventually lead to accelerated aging of the insulation in the motors [6, 7] and to rotor and bearing failure [8, 9]; thus reduce the life of the machine [10]. These waveforms have sharp rise time with the voltage not evenly distributed in the windings [11, 12] as it would under standard sinusoidal conditions. As much as 80% of the full phase-to-phase voltage may appear across the first coil of a phase winding. Various industrial surveys show that problems initiated in the stator winding insulation are one of the leading root causes of 30 %–40 % of ac machine failures. The frequency spectrum of these voltages reveals the presence of high frequency harmonics of non-negligible magnitude [13]. When exposed to the voltage waveforms containing high amount of harmonics, the heat generation as a result of the dielectric and core loss will be larger as compared with the power frequency excitation. This type of complex voltage waveform may increase the dielectric heating in the stress grading tape (SGT) and the conductive armor tape (CAT) in the insulation system. The surface heating may produce localized hot spots in these tapes that can cause the coil ground wall insulation to deteriorate, eventually leading to motor failure [14]. IEC/TS 60034-18-42 recommends a qualification test that uses repetitive impulse voltages for evaluating these two crucial components of PWM fed motor insulation systems. This type of voltages and their parameters have influence on the partial discharge (PD) mechanism and degradation processes in insulation systems [15]. PD processes occurring under PWM voltages are different from the ones under conventional ac power frequency voltage. This is due to the physical mechanism of PD and the injection and extraction of space charge. Hence the PD inception voltage and extinction voltage reduce [16]. Therefore PD activities which may be negligible in 50 Hz sinusoidal conditions accelerate insulation degradation. This may result into decreased life or even failure of insulation due to the increased operating temperature or to thermal runaway [17]. The life test data for different insulation samples with long time electrical and thermal stresses show significant reduction in the endurance capability of the insulation material [18]. The severity of insulation stress increases with the cable length and switching frequency. Motor insulation aging and breakdown can cause a costly, forced outage. This can result into significant loss of revenue as well as repair/replacement costs. Therefore, prevention of such outages is a major concern for both the manufacturer and the end user. Therefore one of the rapidly expanding areas for both research and product development efforts is the monitoring techniques that diagnose the condition of turn-to-turn insulation of low voltage machines [19]. Due to premature failure of many standard motors operated with power electronic control, it becomes obvious that a detailed analysis of the wave shape and their impact on insulation life is necessary.

It is the intent of this paper to describe how fuzzy logic can be applied to the life estimation of the insulation of PWM driven induction motor. Mathematical analysis is carried out to extract the parameters of the PWM voltage waveform responsible for accelerated insulation aging. The main factors, which are causing the excess insulation stress, include voltage peaks ($V_p$), rate of rise of the voltage ($dV/dt$), voltage spikes, frequency of repetition of these voltage spikes, dielectric and core losses, current peaks ($I_p$) and harmonics present in the voltage waveform. They are experimentally computed as a function of switching frequency ($f_s$) and compared with sinusoidal voltage. A fuzzy expert system based on inverse power law is designed for the life estimation. Additional information on fuzzy logic theory and applications may be found in [20].

## 2. Mathematical Analysis

When voltage applied across the insulation is non-sinusoidal, the Fourier decomposition of waveform is as under:

$$V(t) = \sum_{n=1}^{N} V_n \sin(n\omega_1 t + \psi_n) \tag{1}$$

where $n$ = harmonic order, $\omega_1$ = fundamental frequency, $\Psi_n$ = phase shift of the harmonic being considered, $N$ = number of harmonics; $V_1$ = RMS value of the fundamental, $V_n$ = RMS value of the n^th^ harmonic, $V$ = Total RMS value. From equation (1), it can be shown that;

$$\left(\frac{dV(t)}{dt}\right)_{rms} = \frac{\omega_1}{\sqrt{2}}\sqrt{\sum_{n=1}^{N} n^2 V_n^{\ 2}} \tag{2}$$

Hence for the fundamental;

$$\left(\frac{dV}{dt}\right)_{rms} = \frac{\omega_1 V_1}{\sqrt{2}} \tag{3}$$

Equation (2) & (3), show the slopes for non-sinusoidal & sinusoidal waveform respectively. The voltage stress is due to increase in the voltage magnitude. Hence stress factor ($K_{st}$) is defined as;

$$K_{st} = \frac{V_p}{V_{1p}} \tag{4}$$

where; $V_p$ is peak of the distorted voltage and $V_{1p}$ is the peak of the reference sinusoidal voltage wave. The heat generated in the insulation depends on the dielectric loss in the insulation and the losses in the winding conductor. The dielectric loss in the insulation is given by;

$$P_f = \omega E^2 \varepsilon_0 \varepsilon_r \tan\delta \tag{5}$$

where $\omega$ is the angular frequency given by;

$$\omega = 2\pi f \tag{6}$$

$E$ is the electric field given by;

$$E = V/d \tag{7}$$

tanδ is the loss factor given by;

$$\tan\delta = \omega R_s C_s \tag{8}$$

$R_s$ and $C_s$ are the insulation resistance and capacitance respectively. Therefore for a given insulating material it can be shown;

$$P_f = K(Vf)^2 \tag{9}$$

Hence for sinusoidal waveform;

$$P_f = K(V_1 f_1)^2 \tag{10}$$

and for non-sinusoidal waveform;

$$P_f = K\sum_{n=1}^{N}(f_n V_n)^2 \tag{11}$$

$K$ is constant, $f_n$ and $V_n$ for $n$ = 1 to $N$ can be obtained from the Fast Fourier Transform (FFT) of the voltage signal. Hence the more distorted is the voltage waveform the more will be the dielectric power loss. As core loss also depends on the frequency it may be combined with the dielectric loss. Hence dividing (11) by (10), gives the increase in frequency dependent power loss, $\Delta P_f$.

The resistive loss in the conductors is given by;

$$P_w = (I)^2 R_w \tag{12}$$

where $I$ is the RMS value of the current; $R_w$ is the winding resistance. If the current is non-sinusoidal;

$$P_w = \sum_{j=1}^{J} I_j^2 R_w \tag{13}$$

$j$ shows the number of samples of current wave over one cycle. Hence higher the peak value of the current ($I_p$) and higher the harmonic content in the wave, more will be the heat generated in the winding. Dividing (13) by (12), gives the increase in winding loss, $\Delta P_w$. Hence the total increase in thermal loss (T) can be estimated as;

$$T = \Delta P_f + \Delta P_w \tag{14}$$

When in service, an insulation system is subjected to one or more stress that causes irreversible changes of insulating material properties with time, thus reducing progressively the ability of insulation in enduring the stress itself. This process is called aging and ends when the insulation is no more able to withstand the applied stress. The relevant time is called insulation life time. Insulation life time modeling consists of looking for adequate relationships between insulation life time and the magnitude of the stresses applied to it. The stresses which mostly age and cause failure of electrical insulation system are voltage and thermal stresses. The life models based either on inverse power law (IPL) [21];

$$L = C_1 E^{-n} \tag{15}$$

or on the exponential law;

$$L = C_2 \exp(-hE) \tag{16}$$

have been proposed. $C_1$, $C_2$, $n$ and $h$ are constants' depending on temperature and other factors of influence, $E$ is the magnitude of the electrical field and $L$ is the life in hours. Equation (15) and (16) provide straight lines in log-log or semi log coordinate systems, respectively with slopes -1/n (or -1/h). $E$ is the ordinate and log ($L$) the abscissa. Coefficient $n$ (or $h$) is called voltage endurance coefficient (VEC). Larger the VEC better is the insulation endurance. Additional information on insulation aging and life models may be found in [21, 22].

## 3. Experimental Setup

A 3 phase, 440 volts, 50 Hz, 3 hp, 1440 rpm, random wound induction motor (IM) is connected to a PWM adjustable frequency drive with a cable of 10 meter length. The motor is driven at full load at rated speed. The switching frequency is varied from 1 kHz to 15 kHz. The voltage and current applied to the motor no longer remain sinusoidal under this condition. Current and voltage signals are measured at motor terminal by Digital Storage Oscilloscope (DSO) using small shunt (0.2 ohm) and potential divider (1 k: 40 k) respectively. FFT of voltage and current waveforms for different switching frequencies is obtained by the DSO. The waveforms are analyzed using the DSO software in the computer. The complete experimental set up is shown in Figure 1.

## 4. Experimental Results

Experimental results are taken for the entire range of switching frequency but for the same load and speed. The results are shown in table 1. When motor is switched on with PWM drive voltage in the form of series of square wave pulses starts entering the motor winding through the connecting cable. Each cycle consists of number of pulses depending on the switching frequency. These voltages are shown in Figure 2 for switching frequency of 1 kHz and 15 kHz respectively. Figure 3 shows the current waveforms for switching frequency of 1 kHz and 15 kHz respectively. It is obvious from the waveforms that as the switching frequency is increased the current becomes smooth but number of spikes increase. This increases the winding loss.

Figure 4 is the enlarged view of the voltage spikes. Spikes are present in the line voltage as well as in the phase voltage. The spike may be of impulse shape (Figure 4 a) or it may have oscillatory nature (ringing; Figure 4 b). The inductance and capacitance of the cable, the motor and the output circuit of the drive may constitute a resonant circuit that can cause the edges of the voltage pulses to assume this damped ringing waveform. Combined with the voltage reflection phenomena, this ringing can result in voltage peaks that are significantly more than twice the bus voltage of the drive. The rise time and *dV/dt* are computed from this diagram. National Electrical Manufacturers Association (NEMA) and International Electro-technical Commission (IEC) have different definitions for rise time and *dV/dt*.

In this paper *dV/dt* has been computed as per the definition given by IEC 60034-25. It is observed that the rise time is reducing with the switching frequency. Sharp rise in the voltage magnitude results into unequal voltage distribution across the winding. Low voltage motors are random wound hence they are severely affected due to this. Frequency of occurrence of these spikes also affects the insulation. The spikes which appear in the voltage waveform depend on so many parameters like the turn on time of the IGBT; hence on switching frequency, charging and discharging of the winding capacitance, characteristic impedance of the motor, length of the connecting cable, inductance and capacitance of the cable etc. These spikes may initiate the PD process if magnitude exceeds PD inception voltage. Any specific formula does not exist to compute the frequency of occurrence of these spikes. Hence statistical approach is applied to compute number of spikes per second. 50 cycles set is recorded 20 times randomly for each switching frequency. For each set of 50 cycles i.e. for one second number of spikes (*N*) with magnitude more than 1.5 times the applied voltage is counted and average is taken.

Figure 5 shows the FFT of the voltage waveforms for switching frequency of 1 kHz and 15 kHz respectively. It is observed from the waveforms that harmonic voltages of relatively large magnitude are impressed in the winding due to PWM voltage. As the switching frequency is increased the magnitude and order of these harmonic voltages is increasing. This increases the frequency dependent losses.

Stress parameters are plotted as a function of switching frequency ($f_s$). Stress parameter is the ordinate and switching frequency is the abscissa. Voltage peak and thermal losses are computed as per unit (pu) of reference sinusoidal values. "S" represents the sinusoidal input on X-axis.

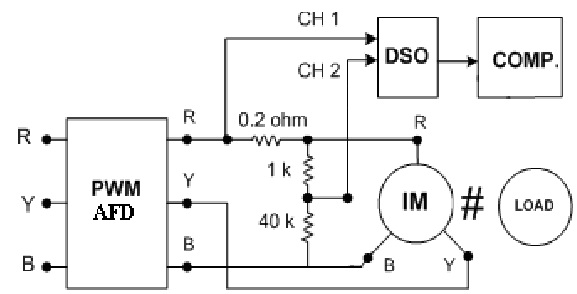


Figure 1: Experimental setup

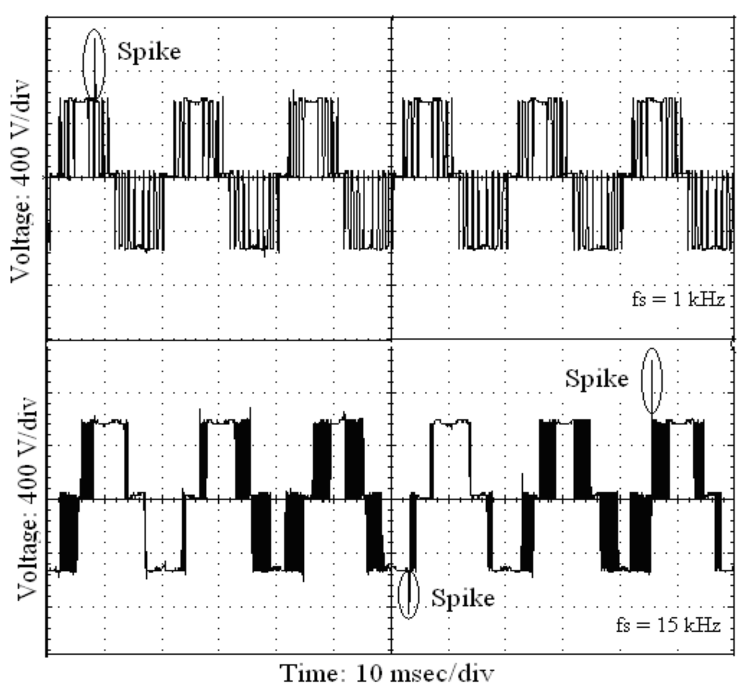


Figure 2: PWM voltage waveform

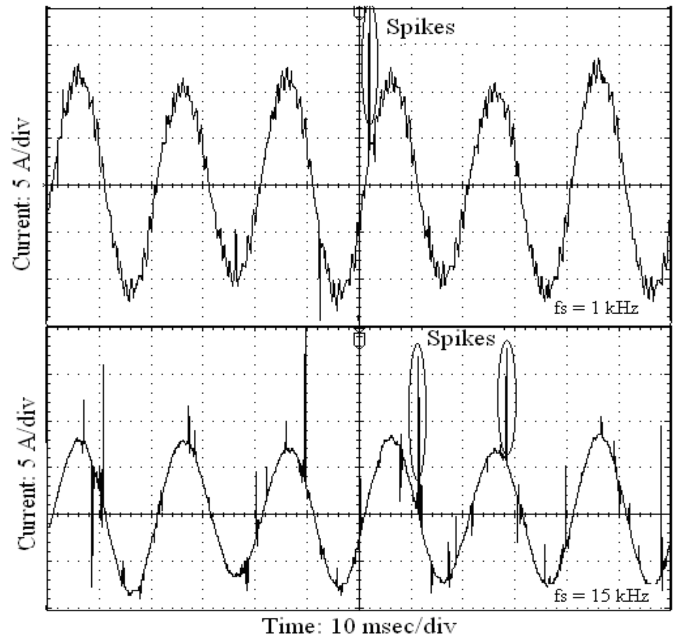


Figure 3: PWM current waveform

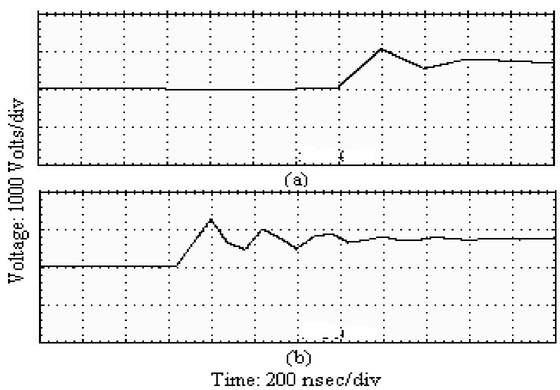


Figure 4: Enlarged view of voltage spikes

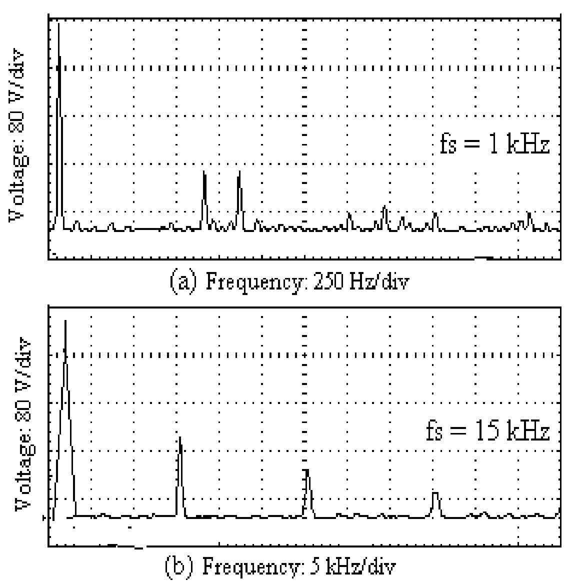


Figure 5: FFT of voltage waveform

TABLE 1

EXPERIMENTAL RESULTS

| $f_s$ (kHz) | V (Volts) | $V_p$ (Volts) | dV/dt (kV/μsec) | I (Amp) | T (watt) |
|---|---|---|---|---|---|
| SIN | 420 | 597 | --- | 4.9 | 351 |
| 1 | 476 | 1037 | 5.2 | 4.9 | 740 |
| 5 | 478 | 1264 | 6.3 | 4.9 | 766 |
| 8 | 485 | 1307 | 6.5 | 4.9 | 778 |
| 11 | 499 | 1350 | 6.7 | 4.9 | 794 |
| 15 | 505 | 1449 | 7.2 | 4.9 | 814 |

Figure 6 shows the variation of voltage peak ($Vp$). It is increasing with the switching frequency indicating increase in the voltage stress. Figure 7 shows the variation of thermal losses ($T$). They are increasing with the switching frequency resulting into more thermal stress. Figure 8 shows the variation of number of voltage spikes per second of magnitude more than 1.5 times the applied voltage ($N$). This is increasing with the switching frequency. This is very important parameter as it indicates the occurrence of partial discharge activity.

## 5. FUZZY LOGIC APPLICATION

Fuzzy logic is a form of multi valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. A fuzzy expert system is an expert system that uses a collection of fuzzy membership functions and rules to reason about data. For fuzzy logic based life estimation three insulation stress parameters viz. voltage peak ($Vp$) and thermal loss ($T$) in multiple of the reference value and number of high voltage spikes per sec ($N$) are taken as inputs.

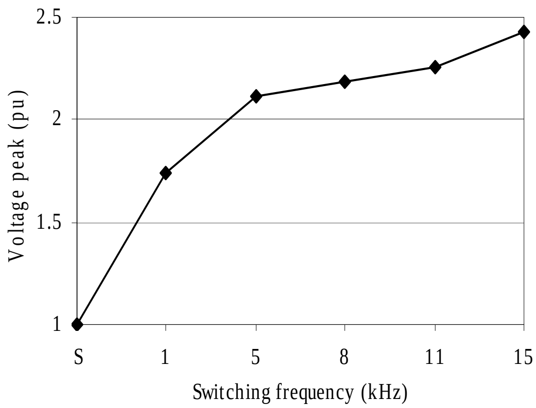


Figure 6: Variation of voltage peak

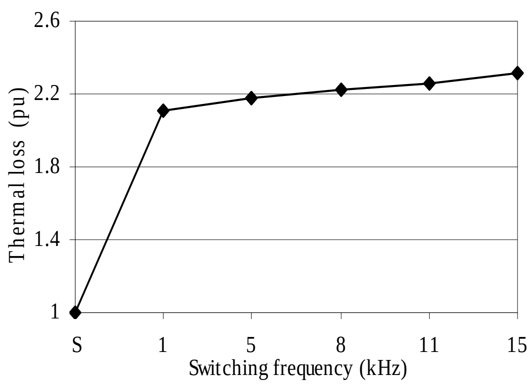


Figure 7: Variation of thermal loss

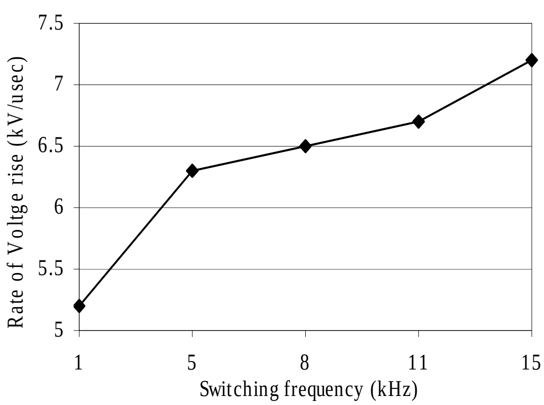


Figure 8: Variation of number of high voltage spikes/sec

The fuzzification process is accompanied by generalizing the crisp number set and sub set of all the input values. In fuzzy logic system crisp inputs are mapped into fuzzy sets by means of a fuzzifier. A fuzzy set is described by a membership function, which assumes values in the interval [0, 1]; it constitutes a measure of the extent of similarity of an element to the fuzzy sub set. The ranges of the inputs are decided from the experimentally obtained results. The highest value of these parameters is taken when the break down of the insulation had occurred. The stress input parameters are classified as low, medium, high and very high according to their magnitudes.

The estimated life is classified as very poor, poor, average and normal. The membership functions for the voltage peak, number of high voltage spikes per sec and thermal loss are given in Figures 9, 10 and 11 respectively. The membership function for the output (life in percentage) is given in Figure 12. For all the membership function graphs the parameter value is taken along x-axis and the degree of the membership function is taken along y-axis. The membership functions and the rules are framed with reference to the life model based on inverse power law (IPL) and considering all the possible combinations of the inputs computed from the experimental results with the entire switching frequency range. Total 26 rules are framed. The test data is not the accelerated life test data; hence the life is not computed in hours it is computed in terms of the percentage of the normal life. For 50 Hz sinusoidal voltage input condition life is assumed 100%. PWM voltage results into over stressing; hence the life is computed as percentage of the life under sinusoidal input condition.

The results of the fuzzy expert system are presented in table 2 for PWM voltage at different switching frequencies. The experimental data of table 1 for the voltage peak ($Vp$) and the thermal loss ($T$) is computed as multiple of the reference sinusoidal value and given as inputs. "$N$" is number of high voltage spikes per sec. These values and the estimated life in percentage (% $L$) of the reference 50 Hz sinusoidal voltage input are presented in table 2. From the results it is obvious that as the stress parameters increase the estimated life reduces. The de-fuzzification of the resultant membership function is performed using center of gravity (COG) algorithm. Schematic diagram for the flow of information is given in Figure 13.

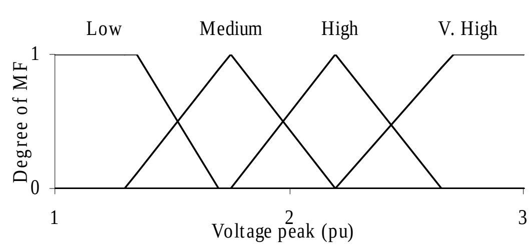


Figure 9: Membership function for voltage peak

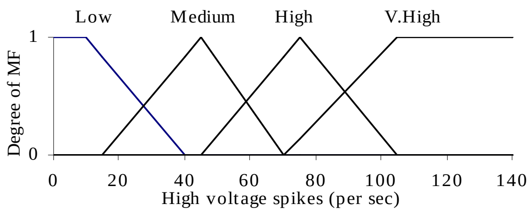


Figure 10: Membership function for high voltage spikes/sec

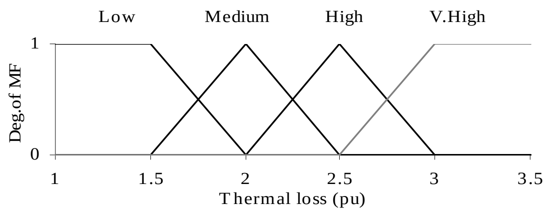


Figure 11: Membership function for thermal loss

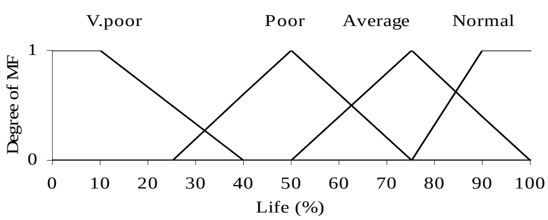


Figure 12: Membership function for estimated life

TABLE 2
RESULTS OF FUZZY EXPERT SYSTEM

| $f_s$ (kHz) | $V_p$ (pu) | N (per sec) | T (pu) | Life (%) |
|---|---|---|---|---|
| 1 | 1.74 | 18 | 2.11 | 75 |
| 5 | 2.12 | 25 | 2.18 | 58.5 |
| 8 | 2.19 | 36 | 2.22 | 51 |
| 11 | 2.26 | 75 | 2.26 | 43.8 |
| 15 | 2.43 | 100 | 2.32 | 32.4 |

## 6. CONCLUSION

The objective of this study was to develop a fuzzy expert system based on the inverse power law for life estimation of PWM fed induction motors in terms of the parameters responsible for accelerated insulation aging. PWM voltage results into increased voltage and thermal stresses; hence aging is accelerated. These stresses increase with the switching frequency. The results show increase in voltage peak (174 % to 243 %) and increase in rate of rise of voltage (5.2 kV/μsec to 7.2 kV/μsec). They result into voltage stress on the insulation in general and particularly on turn insulation. The highest voltage stress points are the first turns of the line end coil and the last turns of the coil group. Frequency of occurrence of high voltage spikes has also increased (18 to 100 per second). Voltage spikes increase the probability of partial discharges. Partial discharges gradually destroy the insulation. Increase in the thermal losses (211% to 232%) show increase in higher order harmonic in the voltage waveform and rise in the amplitude of these harmonic components. Therefore the insulation stress in PWM fed induction motors increases with the switching frequency resulting into decreased life.

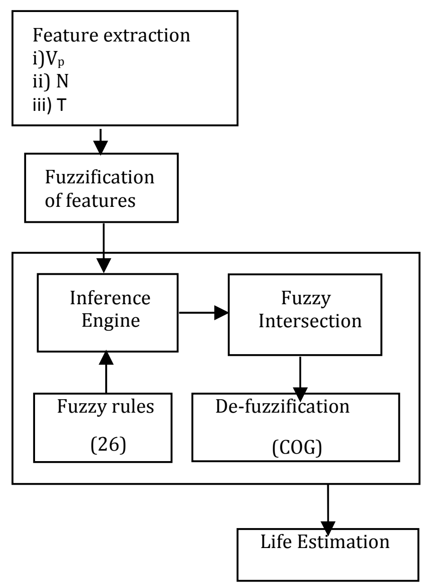


Figure 13: Schematic diagram for flow of information in fuzzy system

NEMA MG-1-1998 section IV part 30 publishes a specification for general purpose motors used with PWM drives that motors rated for operation at 600 volts or less should not be subjected to the voltage peaks that are higher than 1000 volts with a rise time less than 2 microseconds. The motor used in the experiment is rated for 440 volts. From the results it is observed that when it is driven with PWM drive the maximum peak voltage is more than 1000 volts and the rise time is less than 2 microseconds for all the switching frequencies. Therefore the insulation life reduces due to PWM voltage. The proposed method provides information quantitatively for the stress parameters responsible for accelerated insulation aging due to PWM voltage. The life estimation results obtained with the fuzzy expert system indicate a performance approaching that attainable for the life model based on the inverse power law. Hence the proposed method can be used for the life estimation of PWM driven induction motors.

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