FUZZY LOGIC BASED ELECTROTHERMAL LIFE MODEL FOR INDUCTION MOTOR INSULATION UNDER NON-SINUSOIDAL VOLTAGE AND CURRENT WAVEFORMS

Triloksingh G. ARORA
Shri Ramdeobaba College of Engineering and Management, Nagpur (India)
Email: aroratg@rediffmail.com

Mohan V. AWARE
Visvesvaraya National Institute of Technology, Nagpur (India)
Email: mva_win@yahoomail.com

Dhananjay R. TUTAKNE
Shri Ramdeobaba College of Engineering and Management, Nagpur (India)
Email: dhananjaydrt@rediffmail.com

Abstract: *Power electronic voltage regulators used for speed control of induction motors give rise to non-sinusoidal voltages and currents. This leads to increase in voltage and thermal stresses which result into accelerated insulation aging and premature failure of the motors. With increase in number of stresses the life models that help in predicting the capability of insulation become complex and ambiguous. In this paper an electrothermal life model is derived using fuzzy logic to investigate the synergic effects of voltage and thermal stresses on intrinsic aging of induction motor insulation. Three parameters, voltage stress factor, waveform slope stress factor and thermal stress factor are proposed to describe the insulation stresses due to non-sinusoidal waveforms. They are computed from the experimental results and used in fuzzy logic based life estimation algorithms. Accelerated aging test is also performed on solid insulating material samples with the same non-sinusoidal voltages. Insulation life computed by the fuzzy expert system is in close agreement with the results of the accelerated aging test. An electrothermal life model is derived from the fuzzy logic results which can be directly used for the life estimation of any single phase induction motor insulation under non-sinusoidal voltage and current waveforms.*

Key words: *Aging, dielectric losses, insulation, life estimation, stress.*

I. Introduction

Standard induction motors that have been designed to operate from fixed frequency sinusoidal power are being extensively used with power electronic controllers in industrial as well as domestic appliances. The non-sinusoidal voltages generated by these controllers result into voltage spikes, increased rate of rise of voltage and harmonics of non-negligible magnitude [1-5]. Voltage harmonics increase the dielectric power loss [6-8]. Sharp rise time impresses switching impulse in the winding which leads to non-uniform voltage distribution in the winding [9], [10]. The rate of repetition of switching impulse influences the partial discharge (PD) mechanism, therefore PD inception voltage reduces [11], [12]. This may result into decreased life or even failure of insulation [13], [14]. 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 materials [15]. The additional voltage and thermal stresses caused by such waveforms eventually lead to accelerated aging of the insulation in the motors as well as rotor and bearing failures. Due to premature failure of many standard motors operated with such controllers it becomes necessary to analyze the waveform in detail, devise the factors to quantify the stresses and develop a life model to investigate the synergic effect of voltage and thermal stresses on the insulation aging. Achievements on the aspects of life modeling and aging process investigations have been discussed in [16-18]. Insulation aging models based on Design of Experiments method have been proposed in [19-21]. In the work done so far statistical methods and failure probability distribution functions have been extensively used to determine the life model parameters for the insulating materials. When two or more stresses are present, the aging is much faster than if only a single stress is present and the insulation aging models under such multi-stress situations tend to be very complex and ambiguous. Artificial intelligence (AI) techniques, particularly the fuzzy logic [22], are powerful mathematical tools for modeling uncertain systems and complex phenomena. Fuzzy logic is a vast discipline and the basic technology has advanced tremendously in recent years; therefore its application can be explored for aging process investigations and life modeling of insulation under multiple stresses [23].

It is the intent of this paper to propose the fuzzy logic application to investigate the effect of multiple stresses due to non-sinusoidal voltage and current waveforms on intrinsic aging (in the absence of PD) of single phase induction motor insulation. The factors which cause the insulation stress are; voltage spikes, rate of rise of the voltage, current spikes and harmonics present in the voltage waveform. They are experimentally obtained using phase angle voltage controller for the wide motor speed range. Three parameters, viz. voltage stress factor (K_V), waveform slope stress factor (K_S) and thermal stress factor (K_T) are proposed to compare the effect of non-sinusoidal waveforms with the 50 Hz sinusoidal waveforms of the same magnitude on the insulation stresses. They are mathematically derived for non-sinusoidal waveforms, computed from the experimental results and used in fuzzy logic based life estimation algorithms. The results of the fuzzy system are verified by performing the accelerated aging test with the same non-sinusoidal voltage waveforms on insulation papers which are used for the motor winding. An electrothermal life model is derived from the fuzzy logic results which can be directly used for the life estimation of any single phase induction motor insulation under non-sinusoidal voltage and current waveforms.

II. Mathematical Analysis

When voltage waveform applied across the insulation becomes non-sinusoidal; the Fourier decomposition of the voltage is given as

$$v(t) = \sum_{n=1}^{N} V_{pn} \sin\left(n\omega_1 t + \psi_n\right). \tag{1}$$

where n is harmonic order, V_{pn} is the peak voltage of the nth harmonic, ω_1 is fundamental frequency, Ψ_n is phase shift of the nth harmonic with respect to the fundamental and N is the number of harmonics being considered.

To describe the effect of voltage spikes, rate of rise of voltage and thermal stress on insulation due to non-sinusoidal waveforms the parameters proposed are voltage stress factor, waveform slope stress factor and thermal stress factor respectively. The voltage stress factor is given as

$$K_V = \frac{V_s}{V_{p1}} \tag{2}$$

where V_s is the magnitude of the voltage spike of the non-sinusoidal waveform and V_{p1} is the peak voltage of the sinusoidal voltage waveform. From (1), the rms value of the waveform slope for non-sinusoidal voltage can be derived as

$$\frac{dv(t)}{dt} = \frac{\omega_1}{\sqrt{2}} \sqrt{\sum_{n=1}^{N} n^2 V_{pn}^2} \tag{3}$$

Hence for the sinusoidal wave (3) can be written as

$$\frac{dv(t)}{dt} = \frac{\omega_1 V_{p1}}{\sqrt{2}} \tag{4}$$

Waveform slope stress factor is obtained by dividing (3) by (4) as under:

$$K_S = \sqrt{\sum_{n=1}^{N} n^2 \left[\frac{V_{pn}}{V_{p1}}\right]^2} \tag{5}$$

Thermal stress is developed due to dielectric losses in the insulation and the resistive losses in the winding conductor. The dielectric loss in the insulation is given as

$$P_{di} = \omega E^2 \varepsilon_0 \varepsilon_r \tan\delta \qquad (6)$$

where $\omega = 2\pi f$ is the angular frequency, ε_r is the relative permittivity of the insulation material, $\tan\delta$ is the loss factor $E = \frac{V}{d}$ is the magnitude of the electric field, V is the RMS value of the applied voltage, d is the thickness of the insulation and f is the frequency of the applied voltage. Therefore (6) can be written as

$$P_{di} = K(V)^2 f \qquad (7)$$

where K is constant for the given insulation and it is given as

$$K = 2\pi\left(\frac{1}{d}\right)^2 \varepsilon_0 \varepsilon_r \tan\delta \qquad (8)$$

Therefore for the sinusoidal waveform

$$P_{di} = K(V_1)^2 f_1 \qquad (9)$$

and for the non-sinusoidal waveform

$$P_{di} = K\sum_{n=1}^{N}(V_n)^2 f_n \qquad (10)$$

f_n and V_n for n = 1 to N can be obtained from the FFT of the voltage waveform. Change in dielectric power loss (ΔP_{di}) is obtained by dividing (10) by (9) and it is given as

$$\Delta P_{di} = \sum_{n=1}^{N}\left[\frac{V_n}{V_1}\right]^2 \frac{f_n}{f_1} \qquad (11)$$

The resistive power loss in the winding conductor (P_{cu}) is given as

$$P_{cu} = (I)^2 R \qquad (12)$$

where I = RMS value of the current and R = winding resistance. For non-sinusoidal waveform (12) is expressed as

$$P_{cu} = \sum_{j=1}^{k} i_j^2 R \qquad (13)$$

j = 1 to k shows the instantaneous values of the current over one cycle. Change in winding power loss (ΔP_{cu}) is obtained by dividing (13) by (12) and it is given as

$$\Delta P_{cu} = \sum_{j=1}^{k}\left[\frac{i_j}{I}\right]^2 \qquad (14)$$

Therefore the total thermal loss (T) is given as

$$T = P_{di} + P_{cu} \qquad (15)$$

Thermal stress factor is given as

$$K_T = [\Delta P_{di} + \Delta P_{cu}] \qquad (16)$$

The stress factors in (2), (5) and (16) show per unit increase in voltage, waveform slope and thermal stress due to non-sinusoidal waveforms with respect to the sinusoidal waveforms.

The stresses which mostly age and cause failure of electrical insulation system are voltage and thermal stresses. For single stress the life models based either on inverse power law (IPL) or on the exponential law have been proposed in [16]. They are given by (17) and (18) respectively.

$$L = C_1 E^{-h} \qquad (17)$$

$$L = C_2 \exp(-hE) \qquad (18)$$

where C_1, C_2 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.

Insulation of power electronic controlled induction motors is subjected to multiple stresses due to non-sinusoidal voltage and current waveforms. The electrothermal life model for insulating materials under non-sinusoidal voltage waveforms has been derived by Design of Experiments method in [20]. The general form of this electrothermal life model is given as

$$L = L_0 K_p^{-n_p} K_s^{-n_s} K_{rms}^{-n_{rms}} \qquad (19)$$

where L_0 is life under reference sinusoidal condition; K_P, K_s and K_{rms} are peak, wave shape and RMS modification factor respectively and n_p, n_S and n_{rms} are the proportionality coefficients. In this model all three factors are related with the voltage waveform. For the induction motors fed with non-sinusoidal voltage and current waveforms thermal stress becomes considerable. Hence the following electrothermal life model is proposed:

$$L = L_0 K_V^{-n_V} K_s^{-n_s} K_T^{-n_T} \qquad (20)$$

where K_V, K_S and K_T are the voltage, waveform slope and thermal stress factors given in (2), (5) and (16) respectively. The proportionality coefficients n_V, n_S and n_T provide a measure of the extent of the dependence of insulation life on these stress factors. This model includes the effect of voltage as well as thermal stresses; hence provides complete information related with the insulation aging. Equation (20) can be converted to the first order log-log life model as under:

$$\ln L = \ln L_0 - n_V \ln K_V - n_S \ln K_S - n_T \ln K_T \quad (21)$$

This electrothermal model can be directly used for life estimation of any single phase induction motor insulation operated with non-sinusoidal voltage and current waveforms.

III. Experimental Setup

The experimental set up is shown in Fig. 1. A 1000 watt phase angle controlled voltage regulator (VR) is used for speed control of single phase, 230 volts, 50 Hz, 600 watts, 1410 rpm induction motor (IM) with fan load. The switching angle (α) of the voltage regulator is varied from 0 to 90 degree in step of 15 degree. This gives speed variation from rated to 35% of the rated speed. The voltage and current applied to the motor become non-sinusoidal under these conditions. The waveforms are recorded by Digital Storage Oscilloscope (DSO).

IV. Experimental Results

The experimental results are shown in Table 1 for different switching angle (α) of the phase angle controlled voltage regulator. The reference is taken when switching angle is zero and the voltage and current waveforms are sinusoidal. This corresponds to the rated speed. Fig. 2 (a) and (b) show the voltage waveforms for switching angle of 30^0 and 90^0 respectively. These waveforms are non-sinusoidal containing spikes. The spike magnitude increases with rise in the switching angle. Fig. 3 shows the enlarged view of the voltage spike. Fig. 4 (a) and (b) show the FFT of the voltage waveforms for switching angle of 30^0 and 90^0 respectively. The magnitude of harmonic voltages is increasing with rise in the switching angle. From the experimental results all the stress factors K_V, K_S and K_T are computed using (2), (5) and (16) respectively. The variation of these stress factors with the switching angle is shown in Fig. 5, 6 and 7 respectively. The stress factors are unity when the waveforms are sinusoidal and they are increasing with the switching angle.

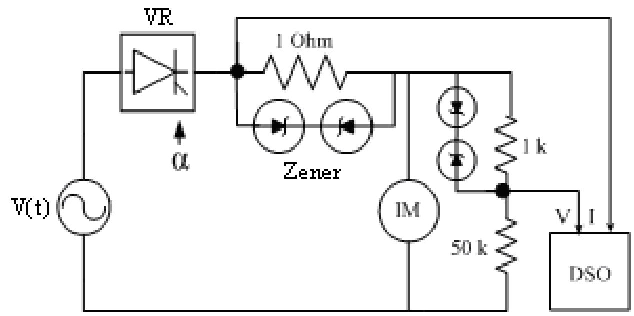

Fig. 1 Experimental Setup

Table 1
Experimental Results

Switching angle $(\alpha)^0$	Speed (*N*) rpm	Voltage spike (V_s) Volts	Current spike (I_s) Amp	Thermal loss (*T*) Watts
0	1410	322.22	2.92	41
15	1250	422.11	3.72	52.5
30	1100	580	4.56	66.8
45	950	626.4	5.2	78.7
60	800	649.6	5.52	89.7
75	650	672.8	5.6	91
90	500	680	5.65	92.5

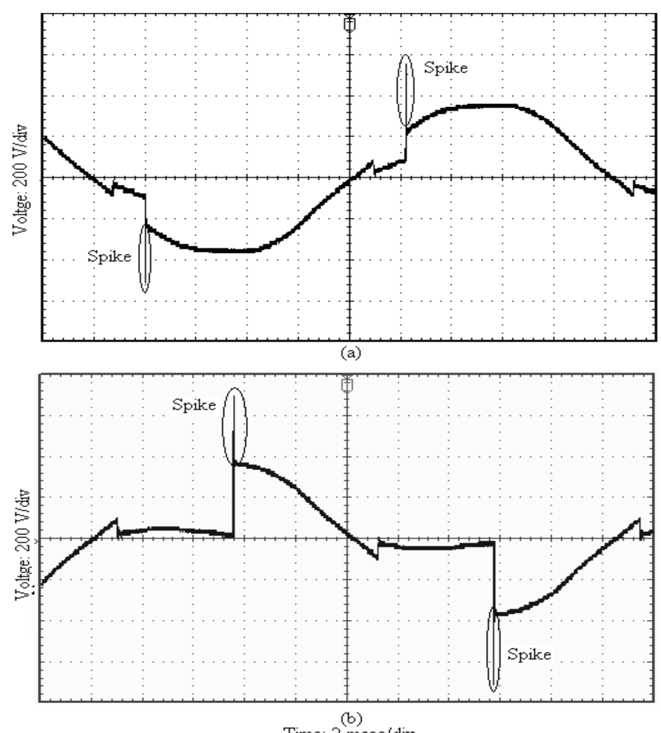

Fig. 2 Voltage waveform: (a) α = 30^0 and (b) α = 90^0

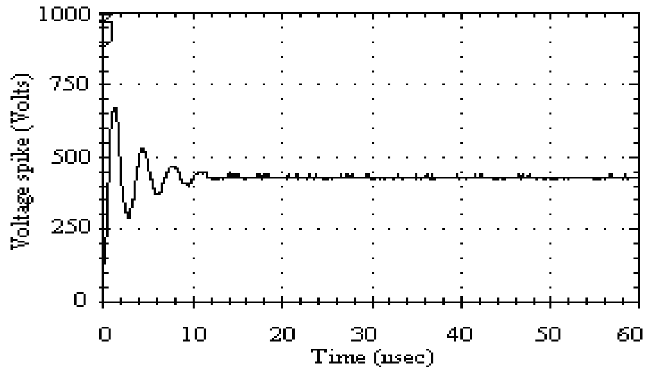

Fig. 3 Enlarged view of the Voltage Spike

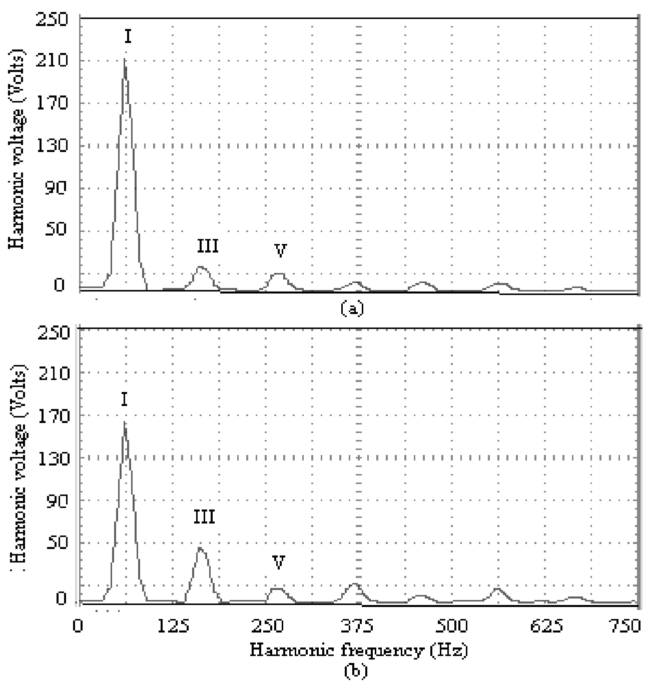

Fig. 4 FFT of the Voltage waveform: (a) $\alpha = 30^0$, (b) $\alpha = 90^0$

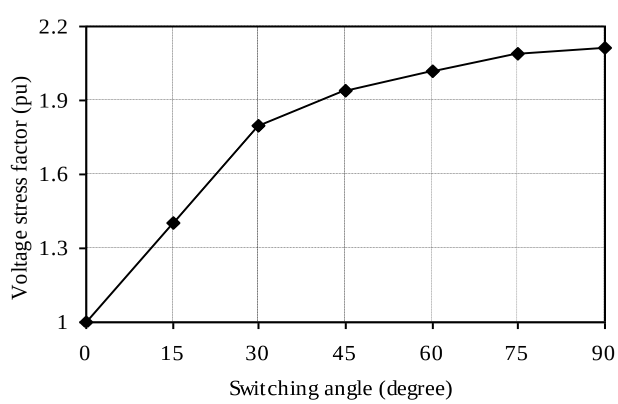

Fig. 5 Variation of voltage stress factor with switching angle

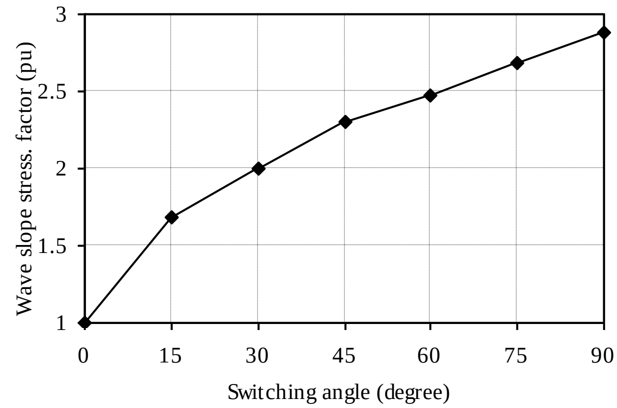

Fig. 6 Variation of wave slope stress factor (K_S) with switching angle (α)

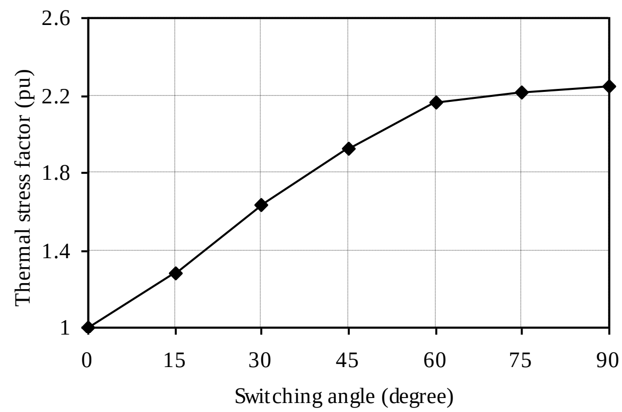

Fig. 7 Variation of thermal stress factor (K_T) with switching angle (α)

V. Fuzzy Logic Application for Life Estimation

Mamdani type fuzzy inference system is developed for the life estimation. For fuzzy logic model three stress factors are taken as inputs. These factors are defined low, medium, high and very high according to their magnitudes. Stress factor threshold i.e. the value below which no degradation takes place is considered as “Low” value of the membership function. The highest value of these parameters is taken when the break down of the insulation has occurred. The estimated life is classified as very poor, poor, average and normal. 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 for the stress factors and the life are shown in Fig. 8.

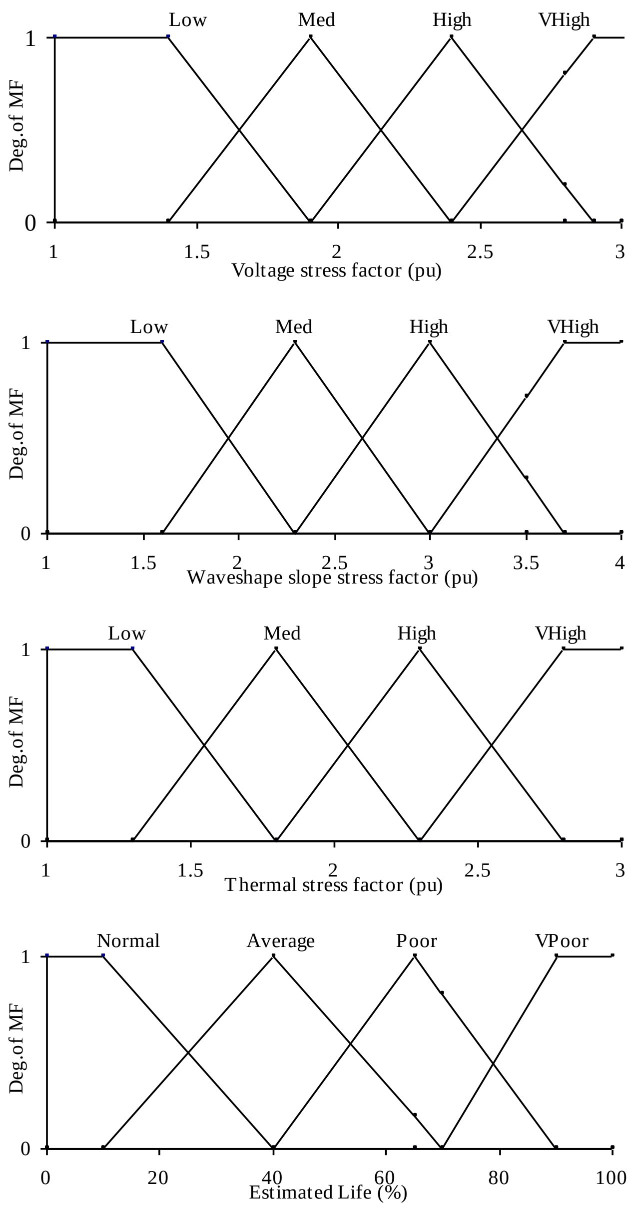

Fig. 8 Membership functions for fuzzy logic model

The membership functions and the rules are framed with reference to the life model based on inverse power law and considering all the possible combinations of the inputs computed from the experimental results with non-sinusoidal voltage and current. Total twenty one rules are framed. They are given in the appendix.

Defuzzification of the resultant membership function is performed using center of gravity algorithm. When voltage and current waveforms are sinusoidal, insulation life is assumed 100%. For non-sinusoidal waveforms this life is computed in percentage of the life under reference sinusoidal input condition. The stress parameters, speed in percentage of the rated speed and the estimated life in percentage (%*L*) for different switching angles are presented in Table 2. From the results it is obvious that as the switching angle increases, the stress parameters increase and the insulation life reduces.

Schematic diagram for the flow of information for fuzzy logic model is given in Fig. 9.

Table 2
Fuzzy Logic Inputs and Output

Switching angle $(\alpha)^0$	% Speed (% *N*)	K_V (pu)	K_S (pu)	K_T (pu)	% Life (% *L*)
0	100	1	1	1	100
15	88.65	1.4	1.68	1.28	89.1
30	78.01	1.8	2	1.63	68.3
45	67.38	1.94	2.3	1.92	61.4
60	56.77	2.02	2.47	2.16	56.3
75	46.10	2.09	2.68	2.22	49.7
90	35.46	2.11	2.88	2.25	44.7

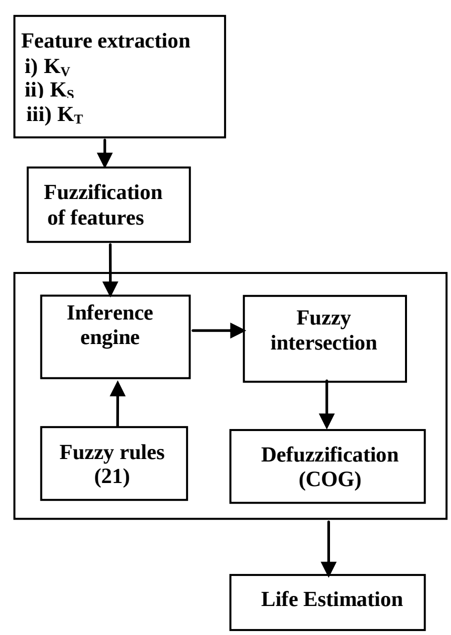

Fig. 9 Schematic diagram for information flow in fuzzy logic model

VI. Validation of the Fuzzy Logic Model

The accelerated aging tests are usually performed to study multi-stresses. These tests also give insight into the failure modes of the products and their life characteristic in short time. There are several methods to accelerate the aging process. The most popular are with the experiments performed on insulating materials at voltages and temperatures higher than normal operating conditions. There are two methods to apply voltage stress. In the first method, the voltage is held constant until sample ages and breaks down. In the second method, the voltage stress is increased until breakdown of the sample occurs. For both the methods, when breakdown occurs experimental data are noted for calculation of life models. In this study the second method is used for validation of the fuzzy logic model.

Accelerated aging test is performed with the same non-sinusoidal voltages on the insulation papers used in the induction motors. For the switching angles shown in table II; ten samples; each of PVC paper (0.2 mm thickness) and lathoride paper (0.3 mm thickness) are tested with the stainless steel electrodes made according to Rogowski profile of standard dimensions to avoid breakdown at edges. Table 3 shows the RMS breakdown voltage (BDV) for these insulation papers at confidence interval of 90% with 63% failure probability. As the stress factors K_V, K_S and K_T are in per unit, their values corresponding to the switching angles of Table 3 are same as those shown in Table 2.

Breakdown voltages of both the insulation papers in percentage of the reference sinusoidal breakdown voltage are compared with the insulation life computed using fuzzy logic model. Fig. 10 and 11 show the comparison of fuzzy logic result and experimentally obtained results for the PVC paper and lathoride paper respectively. The experimental results of accelerated aging test for both the insulation papers and the results from the fuzzy expert system are in close agreement. Therefore on the basis of the estimated life by fuzzy expert system the proportionality coefficients of the electrothermal life model given in (21) are computed. The electrothermal life model derived is as under:

$$\ln L = 5.01 - 0.67\ \ln K_V - 0.46\ \ln K_S - 0.15\ \ln K_T \quad (22)$$

This electrothermal life model can be directly used for the life estimation of any single phase induction motor insulation under non-sinusoidal voltage and current waveforms

Table 3
RMS Breakdown Voltage of Insulation Papers at Confidence Interval of 90% with 63% Failure Probability

Switching angle $(\alpha)^0$	BDV for PVC paper (kV)	BDV for Lathoride paper (kV)
0	10	6.9
15	9.2	6
30	7.1	5
45	6.4	4.4
60	5.7	4.1
75	5.1	3.6
90	4.6	3.2

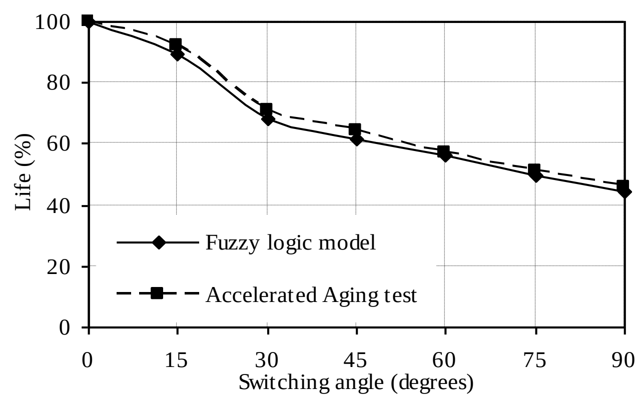

Fig. 10 Comparison of insulation life with fuzzy logic model and accelerated aging test for PVC paper

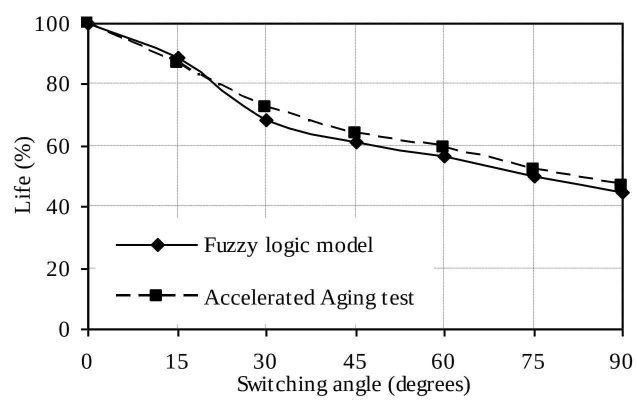

Fig. 11 Comparison of insulation life with fuzzy logic model and accelerated aging test for lathoride paper

VII. Conclusion

A fuzzy logic based electrothermal life model to investigate the synergic effects of voltage and thermal stresses on intrinsic aging of induction motor insulation under non-sinusoidal voltage and current waveforms is developed. For non-sinusoidal waveforms distortion factor or total harmonic distortion does not provide complete information concerning insulation stresses. In this paper three parameters viz. voltage stress factor, waveform slope stress factor and thermal stress factor are proposed which give exhaustive information regarding insulation stresses due to non-sinusoidal waveforms. These parameters are used in fuzzy logic based life estimation algorithms. The experimental results obtained with the phase angle controlled single phase induction motor at different switching angles show more than two times increase in voltage and thermal stresses and significant increase in the waveform slope. The enlarged view of the voltage spike shows the switching type impulse is impressed across the winding. For this impulse the rise time is small hence it results into non-uniform voltage distribution in the winding. The overall effect is to accelerate the insulation aging process and reduce the insulation life.

Accelerated insulation aging test performed on two different insulation papers also show decline in the endurance capability of the insulation papers as the waveform becomes more distorted. In this test the effect of heat generated due to winding loss does not appear, hence the insulation life is slightly higher than that computed by the fuzzy logic model. An electrothermal life model is derived from the results of fuzzy expert system. It follows from the life model equation that the effect of voltage stress is most predominant, followed by the effect of waveform slope and thermal stress respectively. The results computed with the fuzzy logic model and obtained with the accelerated insulation aging test are in close agreement. Therefore the proposed fuzzy logic based electrothermal life model can be directly used to estimate the life of any single phase induction motor insulation under non-sinusoidal voltage and current waveforms.

Appendix

Rules for the fuzzy logic model

Rule No.	K_V	K_S	K_T	Life
1	Low	Low	Low	Normal
2	Low	Low	Medium	Normal
3	Low	Medium	Medium	Average
4	Low	Medium	High	Average
5	Medium	Medium	Medium	Average
6	Medium	Medium	High	Poor
7	Medium	Medium	V. high	Poor
8	Medium	High	Medium	Average
9	Medium	High	High	Poor
10	Medium	High	V. high	Poor
11	High	Medium	Medium	Poor
12	High	Medium	High	Poor
13	High	Medium	V. high	V. poor
14	High	High	High	Poor
15	High	High	V. high	V. poor
16	High	V. high	High	Poor
17	High	V. high	V. high	V. poor
18	V. high	High	High	Poor
19	V. high	High	V. high	V. poor
20	V. high	V. high	High	V. poor
21	V. high	V. high	V. high	V. poor

References

[1] P. Lezana, J. Rodriguez, M.A. Perez. and J Espinoza. "Input current harmonics in a regenerative multi cell inverter with single-phase PWM rectifiers," IEEE Trans. on Industrial Electronics, vol. 56, no. 2, pp. 408-417, Feb. 2009.

[2] H. Akagi and I. Matsumura, "Over voltage mitigation of inverter-driven motors with long cables of different lengths," IEEE Trans. on Industrial Electronics Applications, vol. 47, no. 4, pp. 1741-1748, July. 2011

[3] A. Cavallini, G. C. Montanari, D. Fabiani and M. Tozzi, "The influence of PWM waveform on induction motor insulation system; perspective for the end users," in Proc. SDEMPED, 2011, Bologna, Italy, pp. 288-293.

[4] J. P. Strom, J. Korhonen, J. Tyster and P. Silventoinen, "Active du/dt-new output-filtering approach for inverter-fed electric drives," IEEE Trans. on Industrial Electronics, vol. 58, no. 9, pp. 3840-3847, Sept. 2011.

[5] S. U. Haq, S. H. Jayaram and E. A. Cherney, "Evaluation of medium voltage enameled wire exposed to fast repetitive voltage pulses," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 14, no. 1, pp. 194-203, Feb. 2007.

[6] E. Sharifi, S. H. Jayaram and E. A. Cherney, "Analysis of thermal stresses in medium-voltage motor coils under repetitive fast pulse and high-frequency voltages," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 17, no. 5, pp. 1378-1384, Oct. 2010.

[7] B. Sonerud., T. Bengtsson, J. Blennow and S. M Gubanski., "Dielectric heating in insulating materials subjected to voltage waveforms with high harmonic content," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 16, no. 4, pp.926-933, Aug. 2009.

[8] A. Cavallini and G. C. Montanari, "Effect of supply voltage frequency on testing of insulation system," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 13, no. 1, pp. 111-121, Feb. 2006.

[9] F. C. Deza and M. M. Maglio, "A coil model for voltage distribution and electrical insulation analysis," in Proc. SDEMPED, 2011, Bologna, Italy, pp. 444-450.

[10] S. Grubic, J. M. Aller , B. Lu and T. G. Habetler, "A survey on testing and monitoring methods for stator insulation systems of low voltage induction machines focusing on turn insulation problem," IEEE Trans. on Industrial Electronics, vol. 55, no. 12, pp. 4127-4136, Dec. 2008.

[11] P. Wang, A. Cavallini, G. C. Montanari and W. Guangning, "Effect of rise time on PD pulse features under repetitive square wave voltages," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 20, no. 1, pp. 245-254, Feb. 2013.

[12] S. P. Balaji, I. P. Merin Sheema, G. Krithika and S. Usa, "Effect of repeated impulses on transformer insulation," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 18, no. 6, pp. 2069-2073, Dec. 2011.

[13] H. Okubo, N. Hayakawa and G. C. Montanari, "Technical development on PD measurement & electrical insulation technique for low voltage motors driven by voltage inverters," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 14, no. 6, pp. 1516-1530, Dec. 2007.

[14] E. Lindell, T. Bengtsson, J. Blennow and S. M. Gubanski, "Influence of rise time on partial discharge extinction voltage at semi-square voltage waveforms," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 17, no. 1, pp. 141-148, Feb. 2010.

[15] A. Tzimas., S. Rowland., L. A. Dissado, M. Fu and U. H. Nilsson, "Effect of long time electrical and thermal stresses upon the endurance capability of cable insulation material," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 16, no. 5, pp. 1436-1443, Oct. 2009.

[16] G. C. Montanari, G. Mazzanti and L. Simoni, "Progress in electrothermal life modeling of electrical insulation during the last decades," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 9, no. 5, pp. 730-745, Oct. 2002.

[17] G. C. Montanari and L. Simoni, Fundamentals of endurance of electrical insulating materials, Clueb, Bologna, Italy, 1994.

[18] G. C. Stone, E. A. Boulter, I. Culbert and H. Dhirani; Electrical Insulation for Rotating Machines, IEEE Press series on Power Engineering, Piscataway N J, 2004.

[19] N. Lahoud, J. Faucher, D. Malec and P.l Maussion, "Electrical aging modeling of the insulation of the low voltage rotating machines fed by inverters with the design of experiments method," in Proc. SDEMPED, 2011, Bologna, Italy, pp. 272-277.

[20] G. C. Montanari and D. Fabiani, "The effect of non-sinusoidal voltage on intrinsic aging of cable and capacitor insulating materials," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 6, no. 6, pp. 798-802, Dec. 1999.

[21] N. Lahoud, J. Faucher, D. Malec and P.l Maussion, "Electrical aging of the insulation of low-voltage machines: model definition and test with the design of experiments," IEEE Trans. on Industrial Electronics, vol. 60, no. 5, pp. 4147-4155, Sept. 2013.

[22] The Fuzzy System Handbook, E. Cox, A. P. Professional Press, Cambridge M.A., 1994. Biographies.

[23] T. G. Arora, M. V. Aware and D. R. Tutakne, "Fuzzy Logic Application to Life Estimation of Phase Angle Controlled Induction Motors," in Proc. SDEMPED, 2009, Cargese, France, pp. 1-5.