International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:7, No:12, 2013

Life Estimation of Induction Motor Insulation under Non-Sinusoidal Voltage and Current Waveforms Using Fuzzy Logic

Triloksingh G. Arora, Mohan V. Aware, Dhananjay R. Tutakne

***Abstract*—**Thyristor based firing angle controlled voltage regulators are extensively used for speed control of single phase induction motors. This leads to power saving but the applied voltage and current waveforms become non-sinusoidal. These non-sinusoidal waveforms increase voltage and thermal stresses which result into accelerated insulation aging, thus reducing the motor life. Life models that allow predicting the capability of insulation under such multi-stress situations tend to be very complex and somewhat impractical. This paper presents the fuzzy logic application to investigate the synergic effect of voltage and thermal stresses on intrinsic aging of induction motor insulation. A fuzzy expert system is developed to estimate the life of induction motor insulation under multiple stresses. Three insulation degradation parameters, viz. peak modification factor, wave shape modification factor and thermal loss are experimentally obtained for different firing angles. Fuzzy expert system consists of fuzzyfication of the insulation degradation parameters, algorithms based on inverse power law to estimate the life and defuzzyficaton process to output the life. An electro-thermal life model is developed from the results of fuzzy expert system. This fuzzy logic based electro-thermal life model can be used for life estimation of induction motors operated with non-sinusoidal voltage and current waveforms.

***Keywords*—**Aging, Dielectric losses, Insulation and Life Estimation.

I. INTRODUCTION

INDUCTION MOTORS are the work horse of the industries. The energy consumption of all the motors is approximately 70% of the total energy produced in the power system. Any change in the technology which could reduce power consumption will result into major economic impact. Over the past few years, power electronics with improved speed control offered by inverter drives, have led to entirely new applications were induction motors were not used before. On the other hand the recent proliferation of power electronic controllers in industrial as well as domestic appliances has resulted into the increasing problem of power quality and premature failure of induction motors. The harmonic current injected in ac lines by power electronic controllers affect considerably the shape of voltage waveform at supply side. Harmonics have become very important issue in the design and operation of power electronic drives due to the restrictions imposed by regulations [1]. In general the effect of non-sinusoidal voltage and current waveforms is associated with insulation degradation due to thermal aging [2] but the effect of voltage peaks [3], rate of rise of voltage [4], rate of repetition of switching impulse [5] and wave shape [6] can also be predominant. The additional stresses caused by such voltages eventually lead to accelerated aging of the insulation in the motors [7], [8], to rotor and bearing failures and so on. These waveforms have sharp rise time which results into non-uniform voltage distribution in the windings [9], [10]. The frequency spectrum of these voltages reveals the presence of high frequency harmonics of non-negligible magnitude [11]. When exposed to the voltage waveforms containing high amount of harmonics, the heat generation, as a result of dielectric losses is larger as compared with the power frequency excitation [12]. This may result into decreased life or even failure of insulation due to the increased operating temperature or to thermal runaway. These types of voltages and their parameters have influence on the partial discharge (PD) mechanism and degradation processes in insulation systems [13], [14]. Processes occurring under non-sinusoidal voltages are different from the ones under conventional ac power frequency voltage. The rise time of the impulse like voltage influences the occurrence of PD. Hence the PD inception and extinction voltage reduce [15]. 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 [16]. A breakdown of the electrical insulation system causes catastrophic failure of the electrical machine and brings large process downtime losses. Therefore one of the rapidly expanding areas for both research and product development efforts is to develop the monitoring techniques to diagnose the condition of turn-to-turn insulation of low voltage machines [17]. Due to premature failure of many standard motors operated with power electronic controllers it becomes obvious that a detailed analysis of the wave shape and their impact on insulation life is necessary.

In this paper the effect of non-sinusoidal voltage and current on intrinsic aging (in the absence of partial discharges) of induction motor insulation is investigated. Mathematical analysis is carried out to extract the parameters of the non-sinusoidal voltage and current waveform responsible for insulation aging. The main factors, which are causing the

T. G. Arora is with the Electrical. Engineering Department, Shri Ramdeobaba College of Engineering and Management, Nagpur, India (e-mail: aroratg@rediffmail.com).

M. V. Aware is with the Electrical. Engineering Department, Visvesvaraya National Institute of Technology, Nagpur, India (e-mail: mva_win@yahoomail.com).

D. R. Tutakne is with the Electrical Engineering Department, Shri Ramdeobaba College of Engineering and Management, Nagpur, India (e-mail: dhananjaydrt@rediffmail.com).

excess insulation stress, include voltage peaks (V_p), rate of rise of the voltage (dV/dt), voltage transients, dielectric losses, current peaks (I_p) and harmonics present in the voltage waveform. They are experimentally obtained using power electronic voltage controller at different firing angles. The experimentally generated data is used to compute the stress factors. These stress factors are used as input to the fuzzy expert system for life estimation. An electro-thermal life model [18], [19] is obtained from the results of fuzzy expert system which can be used for life estimation of single phase induction motors operated with non-sinusoidal voltage and current waveforms.

II. INSULATION AGING AND LIFE MODELS

Electric motor life is a critical issue when discussing predictive maintenance and reliability programs. The primary question is: When will the motor fail? Unfortunately, this is not an easy question to answer, in particular as it relates to electric motor systems. Generally 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 the time-to-failure or time-to-breakdown, alternatively 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. When two or more stresses are present, the aging is much faster than if only a single stress was present Aging models that allow machine manufacturers to predict the capability of insulation under such multi-stress situations tend to be very complex and, to date, somewhat impractical. When the relationship between life and applied stresses is derived by simply resorting to experimental evidences of the insulation breakdown phenomenon, consisting of failure times obtained by accelerated life tests at given stress levels then, life models are referred to as phenomenological life models. Physical models are based on the description of specific degradation mechanisms assumed as predominant within proper ranges of applied stresses. Insulation aging model based on Design of Experiment (DoE) method has also been proposed [20]. Artificial intelligence based decision making techniques and advanced data processing techniques for life estimation and diagnostic of induction motor have also been proposed in the last decade [21]. Additional information on insulation aging and life models may be found in [22], [23].

III. FUZZY LOGIC

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. Most tools for working with fuzzy expert systems allow more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the rule base or knowledge base. The general inference process proceeds in three steps. Under FUZZIFICATION, the membership functions defined on the input variables are applied to their actual values to determine the degree of truth for each rule premise.

Under INFERENCE, the truth value for the premise of each rule is computed and applied to the conclusion part of each rule.

Finally is the DEFUZZIFICATION, which is used to convert the fuzzy output set to a crisp number. There are many defuzzification techniques. Two of the more common techniques are the CENTROID and MAXIMUM methods.

Insulation failure is a stochastic phenomenon, thus, in order to determine life model parameters, life test results at various test stress levels are processed resorting to proper statistical methods and failure probability distribution functions. Using the probability distribution function life model can be obtained. Fuzzy logic is a form of many valued logic or probabilistic logic. Fuzzy logic and probabilistic logic are mathematically similar; both have truth values ranging between 0 and 1 but conceptually distinct, due to different interpretations. Fuzzy logic corresponds to “degree of truth”, while probabilistic logic corresponds to “probability, likelihood". As these differ, fuzzy logic and probabilistic logic yield different models of the same real-world situations. 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. Artificial intelligence (AI) techniques, particularly the fuzzy logic 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. Additional information on fuzzy logic theory and applications may be found in [24].

It is the intent of this paper to apply fuzzy logic to study the synergic effect of voltage and thermal stresses on insulation life of single phase induction motor under non-sinusoidal voltage and current waveforms. Insulation stress parameters are experimentally computed for the power electronic controlled single phase induction motor for different firing angles. This data is processed by the fuzzy expert system to estimate the life in percentage. Estimated life at different firing angles is used to develop the electro-thermal life model for single phase induction motor under non-sinusoidal voltage and current waveforms.

IV. MATHEMATICAL ANALYSIS

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

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

n is harmonic no., V_n is the peak value of the nth harmonic, Ψ_n is phase shift of the harmonic being considered, ω_1 is the fundamental frequency and N is no of harmonics being considered. The main factors, which stress the insulation, are; voltage peaks, waveform slope (dV/dt) and thermal stress. From (1) it can be shown that;

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

Hence for fundamental;

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

Equations (2) and (3) show the slopes for non-sinusoidal and sinusoidal waveform respectively. Dividing (2) by the derivative of a purely sinusoidal wave at supply frequency of 50 Hz, having the same magnitude of the fundamental component of the distorted waveform following equation is obtained.

$$K_s = \sqrt{\sum_{n=1}^{N} n^2 \left[\frac{V_n}{V_1}\right]^2} \tag{4}$$

K_S is called as wave shape modification factor. This factor indicates how the wave shape is getting distorted from sinusoidal to non-sinusoidal. This depends on harmonic order as well as magnitude of the harmonic voltage.

The other factor, which is considered to take into account the effect of voltage stress is the peak modification factor; K_P. It is given as;

$$K_p = \frac{V_p}{V_{1p}} \tag{5}$$

where; Vp is peak of the distorted voltage and V_1p is the peak of the reference sinusoidal voltage wave. The RMS modification factor is defined as;

$$K_r = \frac{V_{rms}}{V_{1rms}} \tag{6}$$

where; V_{rms} is rms voltage of the distorted voltage and V_{1rms} is the rms voltage 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;

$$P = \omega E^2 \varepsilon_0 \varepsilon_r \tan\delta \tag{7}$$

where ω is the angular frequency given by;

$$\omega = 2\pi f \tag{8}$$

$tan\delta$ is the loss factor and E is the electric field given by;

$$E = V/d \tag{9}$$

Therefore for a given insulating material it can be shown;

$$P = Kf(V)^2 \tag{10}$$

K may be assumed constant for the given insulation. It is given as;

$$K = 2\pi \frac{\varepsilon_0 \varepsilon_r}{d^2} \tan\delta \tag{11}$$

Hence for sinusoidal waveform;

$$P = Kf(V_1)^2 \tag{12}$$

and for non-sinusoidal waveform;

$$P = K\sum_{n=1}^{N} f_n (V_n)^2 \tag{13}$$

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. Dividing (13) by (12) gives the increase in dielectric power loss, ΔP. The heat generated in the winding conductor is given by;

$$H = (I)^2 R_w t \tag{14}$$

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

$$H = \sum_{j=1}^{J} I_j^2 R_w t \tag{15}$$

j shows the number of samples of current wave over one cycle. Hence higher the peak value of the current (Ip) and higher the harmonic content in the wave, more will be the heat generated in the winding. Dividing (15) by (14) gives the increase in heat generation, ΔH. Hence the total increase in thermal loss (T) may be estimated as;

$$T = (\Delta P + \Delta H) \tag{16}$$

When a single stress; say voltage; is applied to the insulation; the life model based either on inverse power law (IPL);

$$L = C_1 E^{-n} \tag{17}$$

or on the exponential law;

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

can be 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 [18]. Equations (17) and (18) provide straight lines in log-log or semi log coordinate systems, respectively with slopes -1/n and -1/h. E is the abscissa and log (L) is the ordinate. Coefficient n (or h) is called voltage endurance coefficient (VEC).

Power electronic controlled induction motor insulation is subjected to multiple stresses due to non-sinusoidal voltage and current waveforms. With such waveforms following electro-thermal life model (which includes all the significant aging factors and uses the Arrhenius model) has been proposed [18].

$$L = L_0 K_p^{-n_p} K_s^{-n_s} K_r^{-n_r} \quad (19)$$

where L_0 is life under reference sinusoidal condition, K_s, K_p and K_r are wave shape, peak and rms modification factor given in (4), (5) and (6) respectively. All three factors are associated with the voltage waveform. For the power electronic controlled induction motors the non-sinusoidal voltage and current increase the dielectric loss and heat loss. Therefore in (19) *Kr* is replaced by thermal loss; *T*. Hence the proposed electro-thermal life model is;

$$L = L_0 K_p^{-n_p} K_s^{-n_s} T^{-n_t} \quad (20)$$

Equation (19) can be converted to the first order log-log life model as under:

$$\ln L = L_0 - n_p \ln K_p - n_s \ln K_s - n_t \ln T \quad (21)$$

The stress factors K_P, K_S and T enter into the model equations with proportionality coefficients n_p, n_s and n_t respectively which provide a measure of the extent of the dependence of life on these factors. Therefore, the relationship between the logarithm of life L and logarithm of stress characteristic parameters fits a linear law. In this paper the stress factors K_P, K_S and T are experimentally computed for the power electronic controlled single phase induction motor for different firing angles. This data is processed by the fuzzy expert system to estimate the life. Estimated life at different firing angles is used to compute the proportionality coefficients n_p, n_s and n_t. Hence fuzzy logic based electro-thermal life model for single phase induction motor under non-sinusoidal voltage and current waveforms is developed.

V. EXPERIMENTAL

A. Experimental Setup

Experimental set up is shown in Fig. 1. A single phase, 230 volts, 50 Hz, 600 watts, 1410 rpm induction motor (IM) with exhaust fan blades as load is controlled by the thyristor based voltage regulator (VR). The firing angle (α) of the voltage regulator is varied from zero degree to 90 degrees. This results into speed variation from rated to 35% of the rated speed. The voltage and current applied to the motor no longer remain sinusoidal under this condition. Current and voltage signals are measured by Digital Storage Oscilloscope (DSO) using small shunt (1 ohm) and potential divider (1 k: 50 k) respectively. FFT of voltage and current waveforms for various firing angles is obtained by the DSO. Back-to-back zener diodes (Zener) are connected to protect the DSO from voltages transients.

B. Experimental Results

The experimental results are shown for different values of the firing angle (α) of electronic regulator in Table I. The reference is taken when firing angle is zero and the voltage and current waveforms are sinusoidal. This corresponds to the rated speed. Figs. 2 (a) and (b) show the voltage waveform for firing angle of 30 and 90 degrees respectively. The waveforms are non-sinusoidal with spikes. It is observed that the amplitude of the voltage spikes is increasing with the firing angle. Fig. 3 shows the expanded view of the voltage spike when firing angle is 90 degree. This shows impulse type of voltage is appearing due to switching operation of thyristors resulting in high rate of rise of the voltage (dV/dt*)*. Figs. 4 (a) and (b) show the FFT of voltage waveforms for firing angle of 30 and 90 degree respectively. From the FFT it is observed that the amplitude of harmonic voltages is increasing with the firing angle. This results into increased dielectric losses. Current peaks are also increasing resulting in increased heat losses. Hence from the results it is obvious that the voltage and thermal stresses are increasing with firing angle. The synergic effect of this is accelerated insulation aging; hence reduction in life.

TABLE I
EXPERIMENTAL RESULTS

Firing angle *α* (deg).	Speed *S* (rpm)	Voltage peak V_p (Volts)	*dV/dt* (V/μsec)	Current peak I_p (Amp)
0	1410	322.22	22.65	2.92
15	1250	452.11	199	3.72
30	1100	580	237	4.56
45	950	626.4	283	5.2
60	800	649.6	305	5.52
75	650	672.8	328	5.6
90	500	680	339	5.65

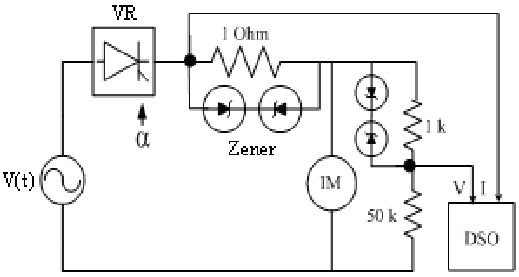

Fig. 1 Circuit diagram

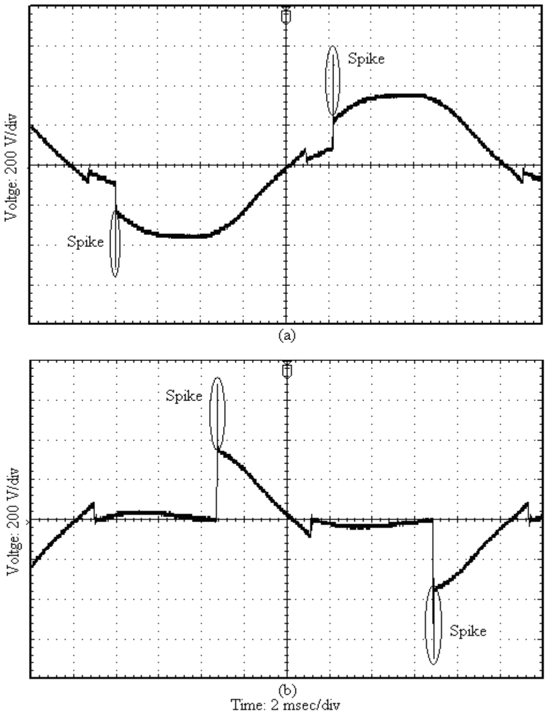

Fig. 2 Effect of firing angle on voltage waveform: (a) $\alpha = 30^0$ and (b) $\alpha = 90^0$

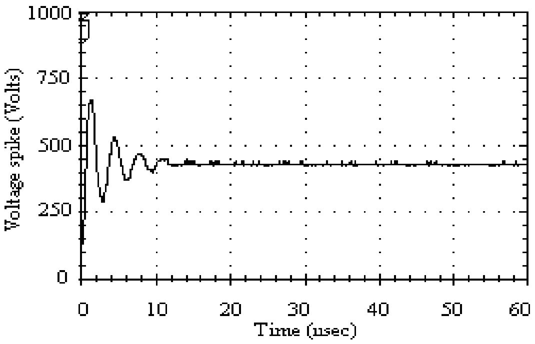

Fig. 3 Expanded view of voltage spike

VI. STRESS FACTORS

On the basis of experimental results insulation stress factors, viz, wave shape modification factor (K_S), peak modification factor (K_P) and increased thermal loss (T) are computed using (4), (5) and (16) respectively. The stress characteristic parameters with non-sinusoidal voltage and current waveforms due to electronic regulator are compared with sinusoidal waveforms. In all the cases the firing angle is taken along x–axis and stress parameter along y–axis. Fig. 5 shows the variation of peak modification factor (K_P). It indicates increase in voltage spike magnitude with the firing angle. Fig. 6 shows the variation of wave shape modification factor (K_S). It shows remarkable change in the wave shape at moderate and high speeds indicating introduction of higher order harmonics of non-negligible magnitude. This increases the dielectric power loss. Fig. 7 shows the variation of the thermal loss (T). This shows continuous increase in the thermal stress. The results show that the voltage and thermal stresses are increasing with the firing angle. They result into accelerated insulation aging; hence the life is reduced.

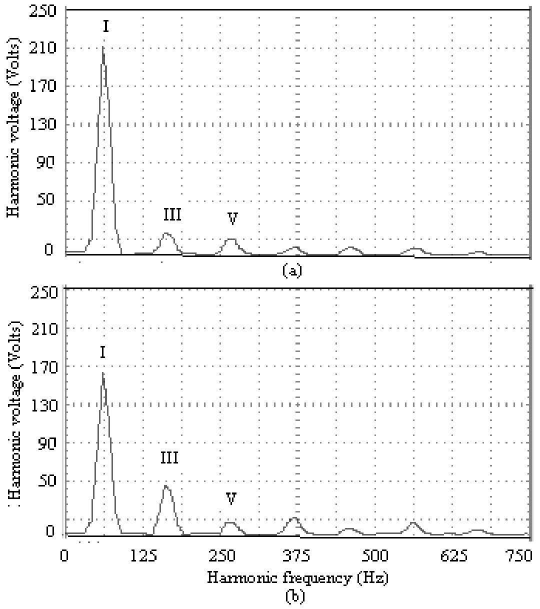

Fig. 4 FFT of the voltage waveform: for (a) $\alpha = 30^0$ and (b) $\alpha = 90^0$

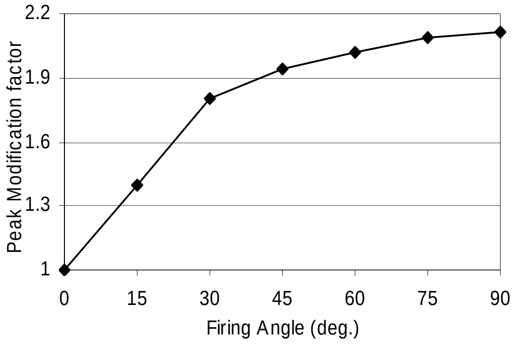

Fig. 5 Variation of peak modification factor (K_P)

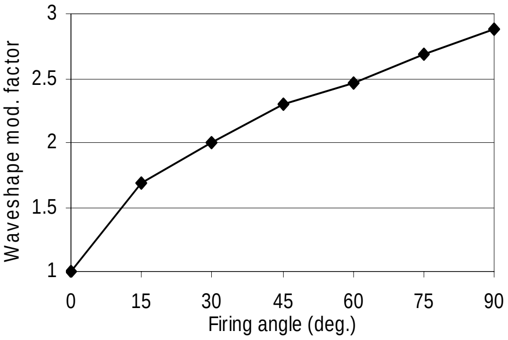

Fig. 6 Variation of wave shape modification factor (K_S)

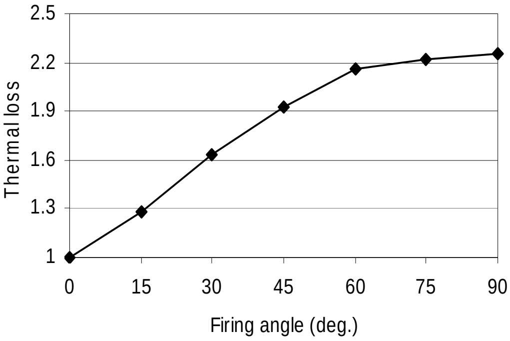

Fig. 7 Variation of Thermal loss (*T*)

VII. Fuzzy Logic based Life Model

A fuzzy expert system is developed to study the insulation aging due to non-sinusoidal voltage and current. Three insulation stress parameters; peak modification factor (K_P), wave shape modification factor (K_S) and thermal loss (T) are taken as inputs. The fuzzification process is accompanied by generalizing the crisp number set and sub set of all the input values. A fuzzy set is described by a membership function, which assumes values in the interval [0, 1]. The basic principles and the design guidelines for the fuzzy expert system are as under:

1. Stress factor threshold (i.e. the value below which no degradation due to a given mechanism takes place) is considered under "Low" value of the membership function. Corresponding life is 100%.
2. The maximum value of stress factors is taken when the breakdown of the insulation occurs.
3. The range for the membership functions of the inputs is decided from the experimentally obtained data. The stress input parameters are classified as low, medium, high and very high according to their magnitudes.
4. The membership functions and the rules are framed with reference to the life model based on inverse power law (IPL).
5. Total 21 rules are framed considering all the possible combinations of the inputs from the experimental results with non-sinusoidal voltage and current. The rules are given in Table III appendix.
6. Life is assumed normal when the input is sinusoidal. The life is classified as very poor, poor, average and normal. To present the effect of insulation aging due to non-sinusoidal voltage and current, life is estimated as percentage of normal life.
7. The defuzzification of the resultant membership function is performed using center of gravity algorithm.

The membership functions for the peak modification factor, wave shape modification factor and thermal loss are shown in Figs. 8, 9 and 10 respectively. The membership function for the output (life in percentage) is given in Fig. 11. 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. Under sinusoidal voltage and current the life is assumed 100%. The results of the fuzzy expert system are presented in Table II. Fig. 12 shows the variation of the estimated life (life curve) as a function of the firing angle. This characteristic is following the inverse power law.

On the basis of the estimated life by fuzzy expert system the proportionality coefficients of the first order log-log electro-thermal life model for multiple stresses due to non-sinusoidal voltage and current waveforms given in (21) are computed. The electro-thermal life model developed from the fuzzy expert system is as under:

$$\ln L = 4.7495 - 0.5889 \ln K_p - 0.1496 \ln K_s - 0.288 \ln T$$

This electro-thermal life model can be used to investigate the synergic effect of multiple stresses on the life of induction motor.

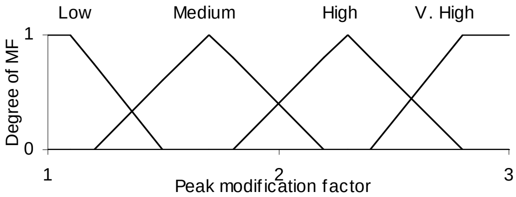

Fig. 8 Membership function for peak modification factor (K_P)

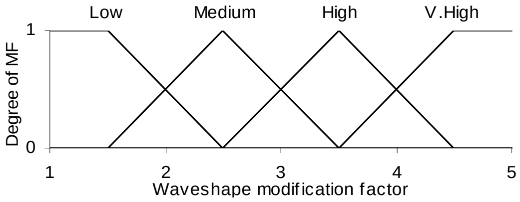

Fig. 9 Membership function for wave shape modification factor (K_S)

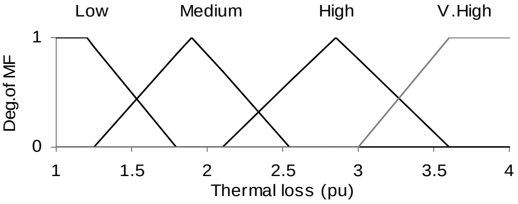

Fig. 10 Membership function for thermal loss (*T*)

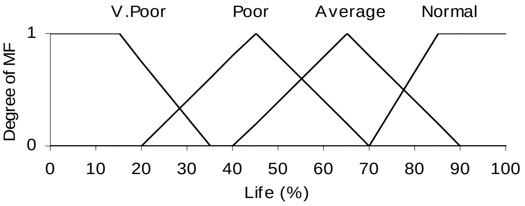

Fig. 11 Membership function for estimated life in percentage (%*L*)

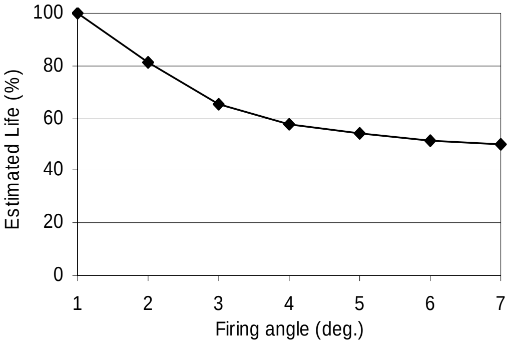

Fig. 12 Variation of estimated life in percentage of normal life (%*L*)

TABLE II
INPUTS AND OUTPUT OF FUZZY LOGIC MODEL AT DIFFERENT SPEEDS AND FIRING ANGLES

Firing angle, α (deg).	Speed, S (% of rated)	K_P	K_S	T	Life, L (% of Normal)
0	100	1	1	1	100
15	88.65	1.4	1.68	1.28	81.2
30	78.01	1.8	2	1.63	65
45	67.37	1.94	2.3	1.92	57.9
60	56.74	2.02	2.47	2.16	54
75	47	2.09	2.68	2.22	51.1
90	35.46	2.11	2.88	2.25	50.3

VIII. CONCLUSION

The objective of this study was to investigate the synergic effect of voltage and thermal stresses on intrinsic aging of induction motor insulation under non-sinusoidal voltage and current waveforms. The experimental results obtained with the power electronic voltage regulator show more than two times increase in voltage peaks (2.11) and thermal loss (2.25). Insulation is continuously subjected to impulsive type voltage transients due to switching of thyristors. FFT shows considerable increase in harmonic contents of the voltage and current waveforms. Therefore the insulation is subjected to multiple stresses resulting into accelerated aging. This results into premature failure of the induction motor. A fuzzy logic based first order log-log electro-thermal life model to estimate the life of induction motor under non-sinusoidal voltage and current waveforms is obtained. The proposed model relates three stress parameters viz. peak modification factor, wave shape modification factor and thermal loss to life. These stress parameters enter into the life model equation with proportionality coefficients which provide a measure of the extent of dependence of life on these terms. It follows from the life model equation that the effect of peak voltage is predominant, while the effect of thermal loss seems slightly more significant than that of wave shape parameter. The relationship between the logarithm of life and logarithm of stress parameters fits a linear law with correlation coefficient of 0.98. The proposed fuzzy logic based electro-thermal life model can be used to estimate the life of single phase induction motors under non-sinusoidal voltage and current waveforms.

APPENDIX

TABLE III
RULES FOR THE FUZZY LOGIC MODEL

Rule No.	K_P	K_S	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 Transaction on Industrial Electronics*, vol.56, pp. 408-417, Feb. 2009.

[2] 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 Transaction on Dielectrics & Electrical Insulation*, vol.17, pp 1378-1384, Dec-2010.

[3] J. P. Bellommo, P. Casteian and T. Lebey, “The Effect of Pulsed Voltage on Dielectric Material Properties”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.6, pp 20-26, Feb-1999.

[4] Juha – Pecca Strom, Juhamatti M. Korhonen, Juho Tyster and Pertti Silventoinen, “Active du/dt-New Output-Filtering Approach for Inverter-fed Electric Drives”, *IEEE Transaction on Industrial Electronics*, vol.58, pp 3840-3847, Sept-2011.

[5] S .P. Balaji, I. P. Merin Sheema, G. Krithika and S. Usa, “Effect of Repeated Impulses on Transformer Insulation”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.18, pp. 2069-2078, Dec-2011.

[6] 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”, *International IEEE Symposium on Diagnostic for Electrical Machines and Power Electronic Drives*, pp 288-293, 2011.

[7] D. Fabiani, A. Cavallini and G. C. Montanari, “Aging Investigation of Motor Winding Insulation Subjected to PWM Supply”, *IEEE Conference on Electrical Insulation & Dielectric Phenomenon*, pp 434-457, 2005.

[8] T. G. Arora, M. V. Aware and D. R. Tutakne, “Accelerated Insulation Aging in Phase Angle Controlled Single Phase Induction Motors”, *IEEE International Region Ten conference*, 2009.

[9] F. Castelli–Deza and M. M. Maglio, “A Coil Model for Voltage Distribution and Electrical Insulation Analysis”, *International IEEE Symposium on Diagnostic for Electrical Machines and Power Electronic Drives*, pp 444-450, 2011.

[10] S. U. Haq, S. H. Jayaram and E. A. Cherney, (Dec- 2007) “Evaluation of Medium Voltage Enameled Wire Exposed to Fast Repetitive Voltage Pulses”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.1, pp194-203, Dec- 2007.

[11] A. Cavallini and G. C. Montanari, “Effect of Supply Voltage Frequency on Testing of Insulation System”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.13, pp 111-121, Dec-2006.

[12] S. M Gubanski, B. Sonerud., T. Bengtsson and J. Blennow, “Dielectric Heating in Insulating Materials Subjected to Voltage Waveforms with High Harmonic Content*”, IEEE Transaction on Dielectrics & Electrical Insulation*, vol. 16, pp 1926-1931, August-2009.

[13] H. Okubo, N. Hayakawa and G. C. Montanari, “Development on PD Measurement & Electrical Insulation Techniques for Low Voltage Motors Driven by Voltage Inverters”, *IEEE Transaction on Dielectrics & Electrical Insulation,* vol.6, pp 1516-1530, Dec-2007.

[14] G. C. Montanari, A. Cavallini and A. Caprava, “Partial Discharge Activity and Aging of Power Electronics Controlled Motors”, *IEEE International Symposium on Electrical Insulating Materials*, pp. 168-171, 2005.

[15] E. Lindell, T. Bengtsson1, J. Blennow and S. M. Gubanski, “Influence of Rise Time on Partial Discharge Extinction Voltage at Semi-square Voltage Waveforms”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.17, pp 141-148, Feb-2010.

[16] A. Tzimas., S. Rowland., L. A. Dissado, M. Fu and U.H. Nisson, “Effect of Long Time Electrical and Thermal Stresses upon the Endurance Capability of Cable Insulation Material”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.6, pp 1436-1443, Oct-2009.

[17] 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 Transaction on Industrial Electronics*, vol.55, pp 4127-4136, Dec- 2008.

[18] G. C. Montanari, G. Mzzanti and A. Cavallini, “Progress in Electro-thermal Life Modeling of Electrical Insulation during the Last Decades”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.9, pp 1730-1741, Oct-2002.

[19] G. C. Montanari and D. Fabiani, “The Effect of Non-sinusoidal Voltage on Intrinsic Aging of Cable & Capacitor Insulating Materials”, *IEEE Transaction on Dielectrics & Electrical Insulation*, vol.6, pp 798-802, Dec-1999.

[20] Nadine Lahoud., Jerome Faucher, David Malec and Pascal Maussion, “Electrical Aging Modeling of the Insulation of the Low Voltage Rotating Machines fed by Inverters with the Design of Experiments Method”, *IEEE Symposium on Diagnostic for Electrical Machines and Power Electronic Drives*, pp 272-277, 2011.

[21] A. Bellini, A. F. Filippetti, C. Tassoni, and G. A. Capolino, “Advances in Diagnostic Techniques for Induction Machines”, *IEEE Transaction on Industrial Electronics*, vol.55, pp 4109-4126, Dec- 2008.

[22] G. C. Montanari and L. Simoni, *Fundamentals of Endurance of Electrical Insulating Materials*, CLUEB, Bologna, Italy, 1994.

[23] 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

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

Triloksingh G. Arora was born in Nagpur, India, on June 20, 1961. He received the B.E. degree in electrical engineering from the Government College of Engineering, Amravati, Maharashtra, India, in 1983 and M.Tech. degree from Visvesvaraya Regional College of Engineering, Nagpur, Maharashtra, India, in 1985. He is currently pursuing the Ph.D. degree in the area of high voltage engineering in Electrical Engineering Department of Shri Ramdeobaba College of Engineering and Management, Nagpur, Maharashtra, India.

From 1985 to 1986, he was a Research Assistant with the Visvesvaraya Regional College of Engineering, Nagpur. Since 1986, he is a Associate Professor in Electrical Engineering Department of Shri Ramdeobaba College of Engineering and Management, Nagpur, India. He has published 10 articles. His research interests include insulation breakdown and discharges under non-sinusoidal waveforms.

Prof. T. G. Arora is the fellow of Institution of Engineers (India) and life member of Indian Society for Technical Education.

Mohan V. Aware was born in Amravati, India, on August 26, 1958. He received the B.E. degree in electrical engineering from the Government College of Engineering, Amravati, Maharashtra, India, in 1980, M.Tech. degree from the Indian Institute of Technology, Bombay, Maharashtra, India, in 1982, and the Ph.D. from Visvesvaraya Regional College of Engineering, Nagpur, Maharashtra, India, in 2002.

From 1982 to 1989, he was Design Officer with Crompton Greaves Ltd., Nasik, India. From 1989 to 1991, he was Development Engineer with Nippon Denro Ispat, Nagpur, India. In 1991, he joined the Electrical Engineering Department, Visvesvaraya Regional College of Engineering, as a Lecturer. From 1994 to 2001, he was with the Power System Research Laboratory in the same Institute as Scientist “C.” From 2001 to 2003, he was a Research Associate with the Electrical Engineering Department, Hong Kong Polytechnic University, Kowloon, Hong Kong. Presently, he is working as a Professor and Head of the Electrical Engineering Department at Visvesvaraya National Institute of Technology, Nagpur, India. He has published more than 40 articles.

Prof. M. V. Aware is member of Bureau of Energy Efficiency (BEE) and also certified Energy Auditor. His research interests include electrical insulation, power electronics, and electric drives.

Dhananjay R. Tutakne was born in India, on July 7, 1956. He received B.E. degree in electrical engineering from Govt. College of Engineering and Technoolgy Raipur, Madhya Pradesh, India in 1977 and M.Tech. degree in electrical engineering from Maulana Azad College of Technology,Bhopal, Madhya Pradesh in 1980, and Ph.D. from RTM Nagpur University, Nagpur, Maharashtra, India, in 2007 in the field of Power Electronic Drives.

From 1980 to 1985, he was a design and development engineer in industry in Nagpur, India. From 1985 to 2009, he was with the research laboratory of Visvesvaraya National Institute of Technology, Nagpur, India. Presently he is an Associate Professor in Shri Ramdeobaba College of Engineering and Management, Nagpur, India. He has published more than 20 articles. His research interests include Power Electronic drives and instrumentation.

Prof. D. R. Tutakne has a Patent for invention of Human safety device (Electronic High Sensitivity Electric Shock-Preventer; 2mA sensitivity).