International Journal of Science, Engineering & Environmental Technology (IJOSEET), 3(8): 55-62, 2018
ISSN 0794-9650
www.repcomseet.com

Determining the Effect of Voltage Variation on Lifetime Expectancy of Induction Motor Using Arrhenius Equation

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Abstract – ***Induction motors are currently the most widely used electromechanical devices in production industries due to its ruggedness; its reliability has become a very important issue. Precise determination of the life expectancy of an induction motor is one way of improving its reliability, efficiency and replacement schedule in production industries. This paper presents and discusses the theoretical and experimental results of the change in induction motor parameters like winding current and temperature when subjected to overvoltage and under voltage. Arrhenius mathematical model is used in life time estimation of induction motor using data acquired by PIC18f4550 microcontroller based data acquisition system. The experimental results were satisfactory with the theoretical results. Operating an induction motor at voltage higher than designed voltage will reduce useful life of the machine.***

Keywords: Arrhenius Model, Current, Life Expectancy, Microcontroller, Induction Motors, Temperature,

1. Introduction

Motor reliability, performance and life expectancy are key factors of a successful motor application when viewed from consumer's perspective. The best life and most efficient operation occur when motors are operated at voltages close to the nameplate ratings (Austin, 1998). Condition monitoring schemes have focused on three phase induction motor components: the stator, rotor and bearings. Little attention has been paid to voltage unbalance in the motor supply (Mirabbasi *et al.* 2009) and condition monitoring of single phase induction motor. Induction Motor speed and temperature are more affected by high amplitudes of voltage fluctuations, whilst the torque and efficiency are more affected for middle and high amplitudes (Zhao *et al.*, 2012).

A study of the effects of these abnormal conditions in the machine is of great importance in industrial economy and interaction of induction motor with the power grid. The economic loss from premature motor failure due to unbalanced voltages can be devastating.

1.1. Causes of Unbalanced Voltage in Power Systems

Voltage imbalance (also called *voltage unbalance*) is defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent (Dugan et *al.*, 1996). That is, where voltage in one or three phases gets increased or decreased in phase and magnitude above or below tolerance limit and this can exist anywhere in a power distribution system (Rajashree and Chaudhar, 2015). The percentage voltage unbalance factor (% VUF), is given by equation 1 (Pillay and Manyage, 2001).

$$\%VUF = \frac{V_{ns}}{V_{ps}} \times 100 \quad (1)$$

where V_{ns} is the negative sequence voltage component and V_{ps} is the positive sequence voltage component. A good approximation to the definition when analyzing induction motor behaviour under unbalanced conditions is given as equation 2 (Pillay and Manyage, 2001);

$$\%\, Voltage\ Unbalance = \frac{82.\sqrt{V_{abf}^2 + V_{bcf}^2 + V_{caf}^2}}{Average\ line\ voltage} \quad (2)$$

where V_{abf} is difference between the line voltage V_{ab}, V_{bcf} is difference between the line voltage V_{bc} and V_{caf} is difference between the line voltage V_{ca}. Unbalance voltage can occur due to intermittent load or strong fluctuations in power demand (Zhao *et al.*, 2012), presence of larger single-phase consumers, asymmetrical capacitor banks with damage or capacitors that are switched off due to the fuse burning only in one phase and presence of higher harmonics in the supply voltage (Miloje, 2012)

1.2. Voltage Conditions

A motor is designed such that the optimum performance is obtained when the voltage applied is that which is indicated on the nameplate referred to as the rated voltage (Brown, 2015). National Electrical Manufacturers Association (NEMA) provides a forum for the standardization of electrical equipment, enabling consumers to select from a range of safe, effective, and compatible electrical products. The condition of induction motors voltages are as follows according to NEMA MG 1 2009;

(i) Voltage Ratings

Single phase motors.

The voltage ratings of single phase motors shall be;

(a) 60Hz-115 and 230 volts

(b) 50Hz- 110 and 220 volts

Poly phase induction motors.

The voltage ratings of poly phase motors shall be;

(a) 60Hz -200, 230, 460, and 575 volts

(b) 50Hz -220, and 380 volts

(ii) Variation from Rated Voltage

Alternating-current motors shall operate successfully under running conditions at rated load with a variation in the voltage or the frequency up to the following:

(a) Plus or minus 10 percent of rated voltage, with rated frequency for induction motors.

(b) Plus or minus 5 percent of rated frequency, with rated voltage.

(c) A combined variation in voltage and frequency of 10 percent (sum of absolute values) of the rated values provided the frequency variation does not exceed plus or minus 5 percent of rated frequency'.

Performance within these voltage and frequency variations will not necessarily be in accordance with the standards established for operation at rated voltage and frequency.

1.3. Effects of Voltage Variations on the Performance of Induction Motor

An overvoltage is an increase in the root mean square (rms) ac voltage greater than 110 percent at the power frequency for duration longer than 60 seconds (Dugan et al., 1996). A high voltage on a motor makes the magnetic portion of the motor saturate quickly. This causes the motor to draw excessive current in an effort to magnetize the iron core beyond the point to which it can easily be magnetized and heat up quickly (Cyndi, 2000). An undervoltage is a decrease in rms ac voltage to less than 90 percent at the power frequency for duration longer than 60 seconds (Dugan et al., 1996). Low voltage supply is dangerous because less flux produced in the iron will cause the starting torque and efficiency to fall

(Cyndi, 2000). When voltage gets low, the current must get higher to provide the same amount of power to run the motor, therefore, it develops more heat.

1.4. Motor Temprature

The motor temperature depends on bearing friction, windage, core loss (eddy and hysteresis losses), I^2R and stray losses. Only stray and I^2R losses vary with motor load (Emanuel, 1992). If the temperature goes up, this is a clear indication that the ambient has increased or the load has increased or faults has actually occurred. A simple way to protect induction motor is to monitor the winding temperature by means of sensors

The total winding temperature rise

$$T = C_T - A_T \quad (3)$$

where C_T sensor measured winding temperature and A_T is ambient temperature. The NEMA allowable temperature rise for different classes of insulation is as shown in table 1

1.5 Thermal Aging

Aging is a deleterious, irreversible physicochemical change in insulating materials or systems, which may subsequently degrade the dielectric properties of these systems by increasing the electrical conductivity or dissipation factor (Jakub *et al.,* 2017). Many factors, such as temperature, electrical and mechanical stresses, vibration, deleterious atmospheres and chemicals, moisture, dirt and radiation affect the insulation of electrotechnical products (Indian, 1986)

Insulation does not deteriorate electrically until it has lost all the mechanical strength by tearing and bursting. The reasonable life of insulation can be estimated by determine the rate of deterioration of its mechanical properties at different temperatures. The rate increases as the temperature increases and eventually renders the insulation unfit to provide both electrical and mechanical strength (Montsinger, 1930). Aging is a function of both time and temperature and goes on at all temperatures, even at room temperatures. Montsinger thermal aging model given by equation (4) is empirical; it does not describe the insulation system in terms of physicochemical processes (Jakub *et al.,* 2017).

$$Y = Be^{-m\tau} \quad (4)$$

where *Y* is the life in units of time (min, hr, *etc.)*,B is a constant, e is the base of Naperian logarithm, m is constant = (0.088) and τ is temperature in degree centigrade.

The disadvantage of Montsinger thermal aging model was addressed by Dakin (1948) and postulated that the rate of thermal ageing of insulation obeyed the Arrhenius chemical rate equation shown in equation (5) (Dakin, 1948)

$$L = \lambda exp\left(\frac{\phi}{kT}\right) \quad (5)$$

where *L* is the life in units of time (min, hr, *etc.), λ* is a constant that is usually determined experimentally, ϕ is the activation energy (eV) , T *i*s the absolute temperature (Kelvin), and k = 0.8617 x 10^{-4} (eV/K) the Boltzmann constant.

Arrhenius chemical rate equation describes the dependence of thermal aging of insulation material on the temperature; increase of temperature must inevitably increase the reaction rate. Using this basic concept, the life of insulation aged at elevated temperatures was expressed as follows

$$lnL = ln\lambda + \frac{\phi}{kT} \quad (6)$$

$$lnL_{ET} = ln\lambda + \frac{\phi}{kT_{ET}} \quad (7)$$

$$lnL_{HS} = ln\lambda + \frac{\phi}{kT_{HS}} \quad (8)$$

$$ln\frac{L_{ET}}{L_{HS}} = \frac{\phi}{k}\left(\frac{1}{T_{ET}} - \frac{1}{T_{HS}}\right) \quad (9)$$

where L_{ET} and L_{HS} are the life in units of time (min, hr, *etc.*) at elevate temperature, T_{ET} and T_{HT} are elevate and hot spot temperature respectively. The hot spot temperature, activation energy and expected life in years at hot spot temperature of common insulation classes are given in Table 1.

Table 1; Insulation Classes and Its Hot Spot, Activation Energy. (Emanuel, 1992)

Class	Hot Spot / ^0C	ϕ /eV	Expected Life/Yr
A	105	0.6	2.3
B	130	0.80	2.3
F	155	1.05	2.3
H	180	1.38	2.3
H	220	1.27	2.3

2. Materials and Methods

This research aims to investigate the effect of voltage variation on the life expectancy of induction motor. A dedicated induction motor test bed was developed in order to simulate different voltage levels. The block diagram of experimental setup for measurement of stator current and temperature at different voltage levels is shown in Figure 1. It consists of a 1.5 Hp, 6.5A, 220V, class B single phase squirrel cage induction motor, an embedded system and a variac.

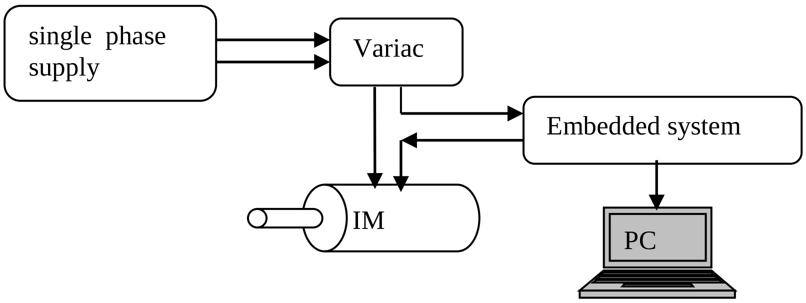

Figure 1; Experimental Setup Block Diagram

Data were measured and acquired from the running motor using developed embedded system based on PIC18f4550 microcontroller at intervals of 30 seconds for 20 minutes for normal voltage, overvoltage and undervoltage conditions. The PIC18f4550 acquire, process and display the magnitudes of monitored and measured signals on LCD display. A USB was used for data streaming from PIC18f4550 to personal computer (PC) in order access the measured quantities and stored in Microsoft excel file for further analysis.

3. Results and Discussion

Measured stator winding current and temperature, motor casing temperature, ambient temperature and humidity were displayed on the designed Motor monitoring interface via PC and also stored in the Microsoft excel file for further analysis as shown in table 2. Summary of the data captured when the motor was operated for twenty minute at 180V, 220V, 240V, and 260V is as shown in table 3. Computed motor life expectancy (class B insulation) at elevate temperature is as shown in Table 4.

Table 2: Experimental Results at 220V

Date	Time	Motor Current/ A	Motor External Temp / ^{O}C	Motor internal Temp / ^{O}C	Ambient Temp / ^{O}C	Ambient Humidity /%
21 June 2018	17:34:52	0.00	27.6	26.3	26.7	72.2
21 June 2018	17:35:22	7.77	27.6	31.1	26.8	72.9
21 June 2018	17:35:52	7.62	27.8	34.8	26.8	72.3
21 June 2018	17:36:22	7.70	28.0	37.3	26.8	72.0
21 June 2018	17:36:52	7.70	28.2	39.3	26.8	72.1
21 June 2018	17:37:22	7.70	28.5	40.7	26.9	72.0
21 June 2018	17:37:52	7.70	28.8	41.9	26.9	70.9
21 June 2018	17:38:22	7.62	29.1	43.0	27.0	70.9
21 June 2018	17:38:52	7.70	29.5	43.8	27.0	70.7
21 June 2018	17:39:22	7.77	29.9	44.7	27.1	70.4
21 June 2018	17:39:52	7.85	30.2	45.4	27.1	69.5
21 June 2018	17:40:22	7.70	30.6	46.2	27.2	68.9
21 June 2018	17:41:02	7.70	31.1	47.0	27.2	69.1
21 June 2018	17:41:32	7.70	31.4	47.6	27.3	68.7
21 June 2018	17:42:02	7.77	31.8	48.0	27.3	68.2
21 June 2018	17:42:32	7.77	32.2	48.5	27.4	68.5
21 June 2018	17:43:02	7.70	32.4	49.0	27.5	67.9
21 June 2018	17:43:32	7.77	32.8	49.4	27.5	67.9
21 June 2018	17:44:02	7.70	33.1	49.9	27.6	68.0
21 June 2018	17:44:33	7.62	33.5	50.3	27.7	68.0
21 June 2018	17:45:03	7.77	33.8	50.6	27.7	68.0
21 June 2018	17:45:33	7.70	34.2	51.0	27.8	68.1
21 June 2018	17:46:03	7.70	34.6	51.4	27.9	68.0
21 June 2018	17:46:33	7.55	34.9	51.8	27.9	68.0
21 June 2018	17:47:03	7.70	35.2	52.1	28.0	67.4
21 June 2018	17:47:33	7.55	35.4	52.4	28.0	67.0
21 June 2018	17:48:03	7.70	35.7	52.7	28.1	66.4
21 June 2018	17:48:33	7.70	36.0	53.2	28.1	66.1
21 June 2018	17:49:03	7.77	36.3	53.6	28.2	65.8
21 June 2018	17:49:33	7.70	36.5	53.9	28.2	65.7
21 June 2018	17:50:03	7.55	36.9	54.2	28.3	65.6
21 June 2018	17:50:33	7.55	37.1	54.4	28.3	65.8
21 June 2018	17:51:03	7.62	37.4	54.7	28.4	65.8
21 June 2018	17:51:33	7.70	37.6	55.1	28.4	65.8
21 June 2018	17:52:03	7.55	37.9	55.4	28.4	65.5
21 June 2018	17:52:33	7.55	38.2	55.6	28.5	65.4
21 June 2018	17:53:03	7.62	38.4	55.9	28.5	65.0
21 June 2018	17:53:33	7.55	38.6	56.2	28.6	64.9
21 June 2018	17:54:03	7.55	38.9	56.4	28.6	64.6
21 June 2018	17:54:33	7.55	39.2	56.6	28.6	64.5

Table 3: Summary of Results

Voltage/ Volt	Running Current/ A.	Temp. rise After 10 minutes / ^{O}C	Temp. rise After 20 minutes / ^{O}C
180	5.46	12.7	18.9
220	7.62	24.1	30.4
240	8.57	30.0	36.8
260	10.39	39.1	45.1

Table 4: Motor Life of Class B Insulation at Elevate Temperature

Stator Winding Temperature / ^{O}C	Motor Life/ Years
90	54.98537575
95	31.949126
100	19.59970742
105	12.59652095
110	8.427642224
115	5.839011789
120	4.171124715
125	3.060933487
130	2.300345218
135	1.765719994
140	1.381197353
145	1.098869002
150	0.887680669
155	0.727021991
160	0.60291718
165	0.505701719

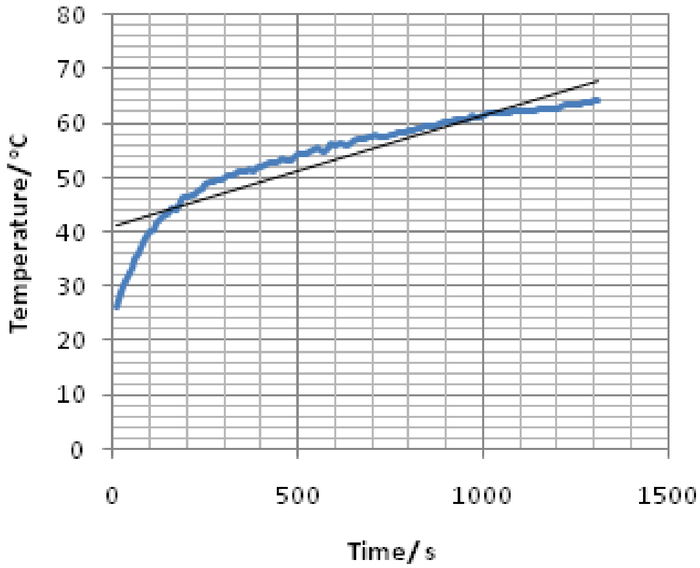

Figure 2: Plot of Winding Temperature versus Time

As revealed by Table 3 and Figure 2, the experimental results were deemed satisfactory. The running current increases with increase in input voltage and temperature also increases with increase current and time. Therefore, stray and I^2R losses will increase with increase in input voltage and load. From table 4, motor life decreases with increase in temperature, therefore, operating the motor at voltage higher than the rated voltage will reduce the useful life of the motor. Thermal ageing also occur at any temperature (ambient temperature) and this shows that aging is function of time because the machine will ever be subjected to ambient temperature.

The major impact of this work is the confirmation of the life sensitivity of motors to a relatively change in applied voltage. The temperature rise after 20 minutes when the motor is operating at normal voltage of 220V is 30.4^0C and at overvoltage of 260V is 45.1^0C. If temperature difference 14.7^0C (45.1^0C -30.4^0C) is maintained, the expected life of the motor will be quartered if Mont singer rule is applied. A continuous running of motor on high voltages will reduce the expected life.

4. Conclusion

The result of applying over voltage to induction motor input is high increase in temperature due to high current flowing through stator windings; that is 10.39Amp flows at 260Volt and 7.62Amp at 220Volt in the stator winding of motor under test. This paper has shown definitive effects of voltage variation on the life expectancy of induction motor by estimating motor life at various temperatures. Operating an induction motor at voltage higher than designed voltage will reduce useful life of the machine.

The use of induction motor input voltage stabilising system to keep the input voltage constant during operation, or voltage monitoring system that will isolate the machine if set threshold value is exceeded has to be encouraged. This will ensure perfect operation of motor and fulfil the life expectancy predicted by the manufacturers.

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