Study of Harmonics Effects on Performance of Induction Motors

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Abstract: - With increasing the number of harmonics generating devices in power systems, the problem of their impact on the performance of system components like induction motors needs further consideration. Approximately, 60% of loads in all over the world are motor loads. More than 90% of these loads are consumed by three phase induction motors with a big utility factor between 0/7-0.9 in a day and most of them are used in industrial factories. So, study of their conditions under heavy harmonic polluted networks would be interesting for understanding of that how we should treat with the biggest electric load of the world. Harmonics measurement of an industrial unit is done to asset the power quality aspects in a typical factory. Then with using a lumped steady state and thermal model we analyzed the influences of different harmonics on motor temperature rise. The simulation was done with using Visual Basic linked with Excel program. The results of this simulation were compared with experimental results. New values for voltage harmonics are suggested to be considered in manufacturing procedures or in design of filter banks for induction motors. Using weighted harmonic distortion (WHD) seems to be more effective than THD that doesn't reveal the impact of individual harmonic, especially when the network has a THD bigger than IEEE criteria.

Key-Words: - Harmonics, Thermal Modeling, Induction Motors, Temperature Rise

1 Introduction

The application of nonlinear loads as a result of power electronic development is growing very fast. In general view, the shape of network voltage can't be imagined sinusoidal and motor manufacturers have to consider non-sinusoidal conditions in their designs. The harmonics of network voltage effect on operation of all electrical equipment like relays, that are the guards of power system, measurement equipment, and electric motors, that are the wheels of industries. In fact, all of these equipment have been designed to work in normal conditions, but in real networks the power is non-sinusoidal that reduces the motor efficiency and their lifetime [1].
Temperature rise of machines is the most effective parameter that decreases the age of insulation [2], and consequently the lifetime of the machine that depend on the health of its insulation. High temperature of the insulation declines its age exponentially according to the Arrehnius equation [3]. Many parameters like different load cycling, switching, working in hot weather, harmonics and unbalances are major reasons in temperature rise of the motors.

The motor losses consist of mechanical and electrical losses. Mechanical losses that caused by friction and windage are not affected by harmonics [4], but electrical losses that consist of Iron, Winding and stray load losses depend on order and magnitude of harmonics. Hystersis loss and eddy current loss that take place in the Iron vary with the square of the air-gap voltage. The harmonic currents are proportional to the magnitude of voltage harmonics, i.e. the stray load loss and winding loss vary with the square of the voltage harmonic.

2 Harmonic content measurement

The harmonic content were measured by an OIN7500 data logger at a feeder supplying a cooling room that have mostly 25 kW and 50 kW three phase induction motors. "Fig.1," shows the measurement done on this feeder.
As is shown in the figure, the voltage THD (9.244%) is more than IEC519 [5] standard and the current THD (145.7%) is over the standard value too. According to the measurements in different points (not presented here), we observed that the dominant voltage harmonics were 2nd, 3rd, 5th, 7th harmonics overall. 2nd, 5th harmonics not only do

they cause losses , but also produce opposite torques in the motor and may overload motor if their amplitude is very big, 7th harmonic causes more loss and consequently cause more temperature rise in the motor and its torque is in the same direction of first harmonic torque direction.

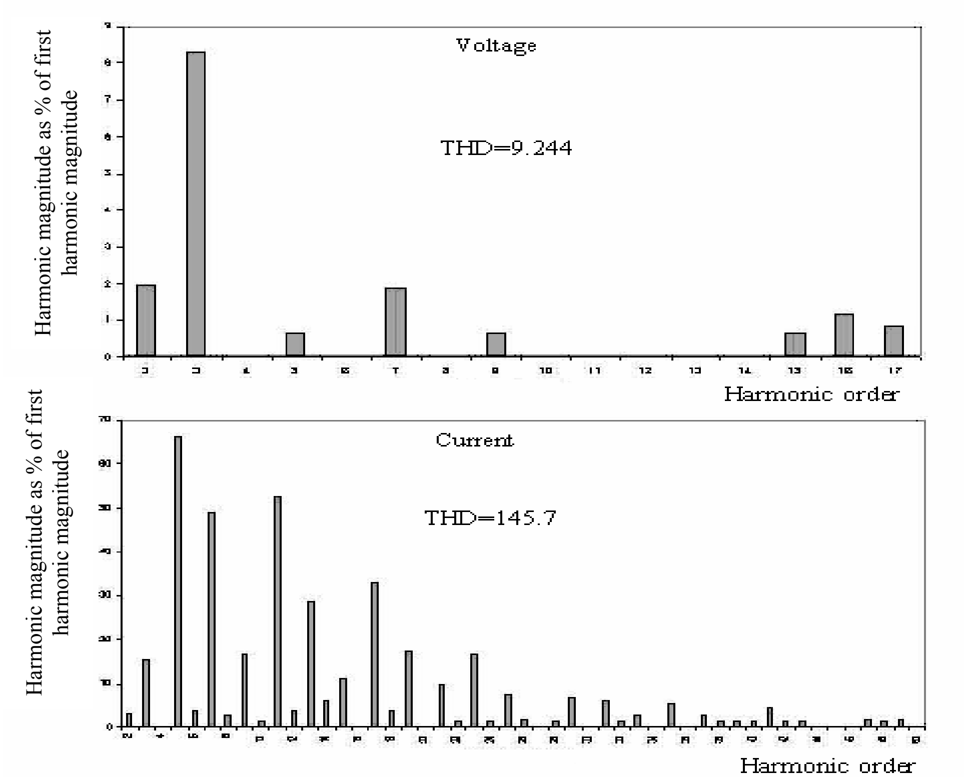

Fig.1 Harmonic content of the desired network

3 Motor losses

Iron, winding and stray load losses occur in induction motor at presence of the harmonics.

Iron loss

This loss comprises the Hystersis and eddy current loss and is calculated according to equation.1. We assume that superposition principle is accepted

$$P_{fe-h} = \left[k_h \left(\frac{1}{f_h} \right) + k_e \right] (B_{mh})^2 \qquad (1)$$

And

$$E_h = 4.44 N A f_h B_{mh} \qquad (2)$$

In which B_{mh}, E_h and f_h are maximum flux density of the core, air-gap voltage and frequency of a harmonic respectively. k_h and k_e depend on the properties of material. “A” is the cross sectional area of the core.

Winding loss

The winding loss in induction machines is related to series resistances in induction motor models and loss in the shunt resistance that changes with the square of voltage. The loss in shunt component because of skin effect and large value of shunt resistance for harmonics is neglected especially for large machines with big slot depth.

The winding loss is the summation of the winding loss of all harmonics that for each harmonic is equal to:

$$P_{cu-h} = (R_s + R_{rh}) I_h^{\,2} \qquad (3)$$

Where R_{rh} is the rotor resistance for a harmonic in stator side view and I_h is the harmonic current determined by:

$$I_h = \frac{V_h}{\left[(R_s + R_{rh})^2 + (X_s + X_{rh})^2 \right]^{1/2}} \qquad (4)$$

The series lumped model parameter of the rotor for different harmonic order should be calculated with locked rotor test that is supplied with harmonic frequency or with using the routine will be expressed in the next section. A precise method can evaluate these parameters with using finite element method for different shapes of slots [6, 7].

Stray load loss
This loss is proportional to square of flux density [8] and consequently (equation.2) can be expressed as:

$$\frac{P_{hstr}}{P_{str}} = \left(\frac{E_h}{E_1}\right)^2 \tag{5}$$

That P_{str} is the stray load loss of a harmonic.

4 Derating of induction motors

The derating of induction machines due to harmonics can be severe if the harmonics have big magnitude. The derating is determined by equation.6, so that the temperature-rise limit with or without harmonic in the supply for a specific insulation class should be kept constant. This can be done by using thermal modeling and calculating the output power with restriction in temperature rise limit (Sec.5).

$$D_h = 1 - \frac{P_{outh}}{P_{out}} \tag{6}$$

Where P_{outh} is the output of induction motor when supplied with nonsinusoidal voltage and P_{out} has the same concept with sinusoidal voltage.
The output power of the machine can be calculated by using the model of Fig.2. The parameters of this model are determined from no-load and locked rotor tests. Slip for different harmonics can be expressed in relation to fundamental harmonic.

$$s_h = \frac{h+1-s}{h} \tag{7}$$

in which “h” is the harmonic order and “s” is the slip of fundamental harmonic.

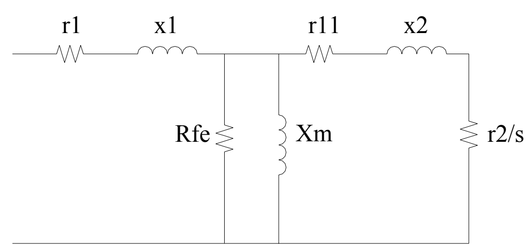

Fig.2 Harmonic model of induction motors

In this figure, r_{11} is a constant resistor that depicts the stray load loss of the induction motor. x_2, r_2 are the reactance and resistance of the rotor and for different harmonics are calculated according to curve depicted in Fig.3 where r_2 and x_2 for different harmonics are shown as per unit of first harmonic.

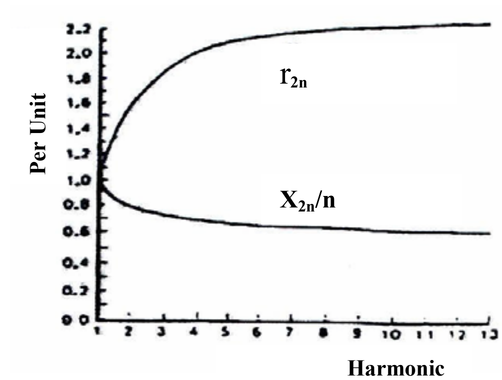

Fig.3 Dependence of rotor resistance and reactance to the harmonic order

The nonlinearity of Fig.3 is due to skin effect, and it rises as the frequency rises. At very high frequencies, the most current pass through the edge of the wire and current density in this area go to a saturation shape.

5 Temperature rise of induction motors due to harmonics

The lumped model of Fig.4 is considered for studying of harmonic impact on the motor temperature rise [9, 10]. Using finite element method for analyzing the thermal flow has better precision, but is more complicated and time consuming [11]. In finite element method by using two steps, the temperature of a spot can be calculated with small error. Step one: computation of temperature distribution with small number of nodes for detecting the hot spot. Step two: increasing the number of nodes near the hot spot and zooming on the area of this spot to find its temperature and location.
Resistances in the figure are thermal resistances, but capacitors show the delay in temperature rise and are proportional to thermal rating of materials. Induction motor normally has big thermal time constants that make them immune to significant levels of harmonics. Time constants for different spots can be calculated by using Norton equivalent circuit or analyzing the model with spice and observing the temperature rise.

The DC sources are losses determined theoretically in terms of machine specifications and dimensions. For a thermal resistance R_{th} with loss P_w, the temperature rise at a specific spot (j) is:

$$T_j = R_{th} \times P_w \tag{8}$$

By using the model and relation that were available, the temperature rise of a typical motor with known dimensions, specification and materials was calculated. Calculating of all thermal resistances is related to using coefficient factor of materials in stator and rotor like the coefficient of the frame, winding, iron so on. These calculations were performed with using Microsoft Visual Basic linked with Excel and "IMHD" is the software written for this purpose. Hot spot of a typical motor can be found by analyzing the Fig.4, with Spice software, but iteration ability and flexibility of the model will be lost and handling of a large number of inputs and outputs would be confusing.

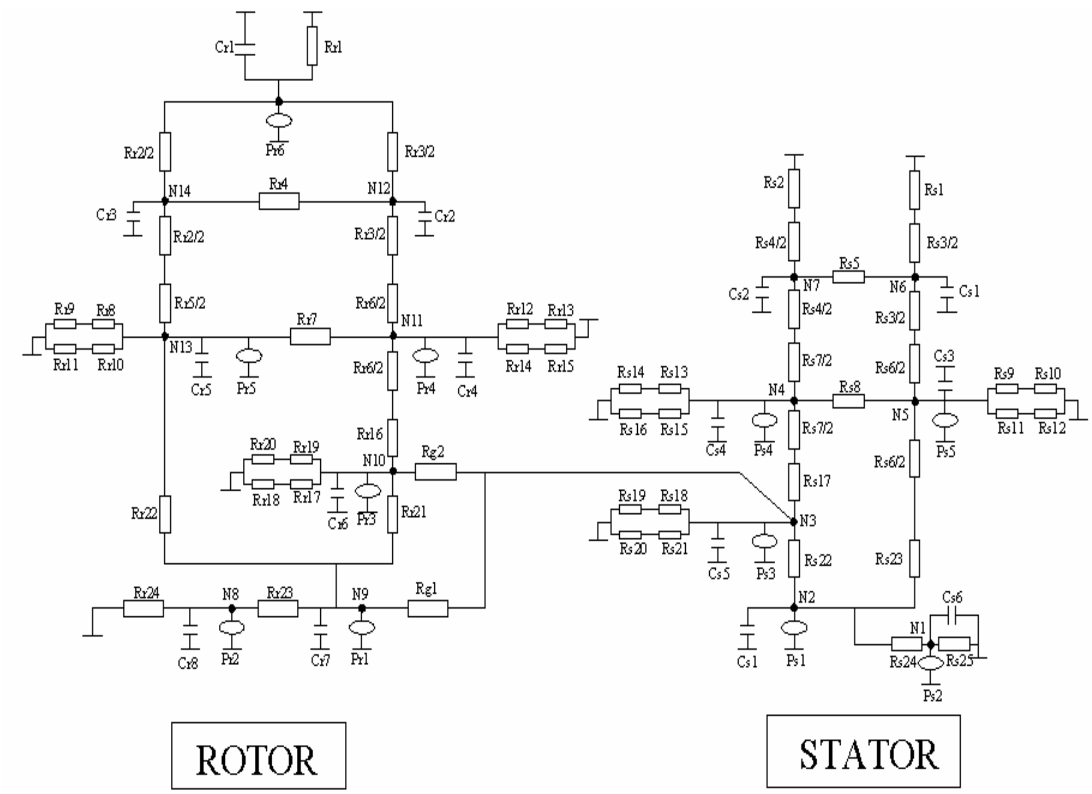

Fig.4 Thermal model used for induction motors

6 IMHD

Induction Motor Harmonic Debugger (IMHD) was jointed with Microsoft Excel to read the inputs and put the outputs from/in a database. IMHD gets the inputs like motor specifications and harmonics characteristic (like the order of the harmonics and their amplitude) from an Excel file and then it calculates the derating of the motor and its temperature rise related to each harmonic order. The output is again put in another Excel file for further calculations or reviews. In addition, the temperatures of different points will be shown on a figure similar to Fig.4, as an output and a new output form in Visual Basic, so that anyone can see the location of hot spot and can suggest a solution for decreasing the hot spot temperature. The result of this suggestion would be revealed with a re-running of the program.
The result of the running of the program on a typical three phase induction motor has been presented.

Motor specifications
28kW, cosΦ= 0.8, Efficiency= 80%, 50Hz, 4 pole

Temperature rise

The output of the IMHD for 1st, 3rd and 5th harmonics are presented in table I.

As is shown in the table I, 3rd, and 5th, voltage harmonics cause approximately 8% and 3% of total losses in the motor respectively.

TABLE I
Output of the IMHD for the selected motor and with harmonics shown in Fig.1

Harmonic order	1st	3rd	5^{th}
Losses (W)	5200	430	150
Temperature rise (°C)	52.4	4.7	1.9

7 Experimental results

Finally, we settled a test to compare our results with real conditions [12]. We used AD590 sensors that are current sources controlled by temperature, to measure the hot spot temperature. they were positioned between the stator phase windings and at the bottom of stator slot. The output of each sensor, a voltage signal, was polled out from the stator by a thin wire.

The load of this motor was a DC generator connected to a rheostat. We fed the motor together with a sinusoidal source and AC-DC-AC driver that produced desired harmonic. The temperatures were read after 35 minutes to account steady state condition. Table II shows result of the test for the selected induction motor.

Table II
Experimental results of the test
(Hot spot temperature)

Harmonic order	1st	3^{rd}	5^{th}
Temperature rise (°C)	50.6	3.5	1.3

There are slight differences between our results and the measurement, perhaps the hot spot occurred where we could not place a temperature sensor for measurement purpose.

8 Conclusion

We study the effect of harmonics on temperature rise of induction motors with using steady state model and thermal model. These works should be done as a part of design procedure in induction motor manufacturing factories to increase motor lifetime and its efficiency. In addition, it's better to think that sinusoidal network power assumption is no longer true and we have a network power that its voltage harmonics are as shown in table III.

The table III has been inferred from our measurement done in different locations of our case study and suggested values for harmonics are close enough to measured value. The 5% voltage THD for generating harmonic consumers is acceptable but for designing of electrical equipment, especially induction motors the values of table III should be considered after agreement. In fact, using weighted harmonic distortion (WHD) would be more useful than THD for some concepts like the matters related to machines.

Table III
Nominal harmonics that should be considered as constant harmonics of the network voltage

Harmonic order	Magnitude as % of first harmonic magnitude
2nd	2% (due to voltage unbalances)
3rd	7%
5th	4%
7th	2%
9th	1%
11th	0.5%

Temperature rise of induction motor due to harmonics is approximately between 4-6 °C, and this impact of harmonics on induction motors must be take into account in selecting the motor insulation class and life assessments. Fig.5 depicts the effect of harmonics on temperature rise of an induction motor. As shown in this figure, the harmonics below 5th have significant impact on temperature rise and can cause more loss of life.

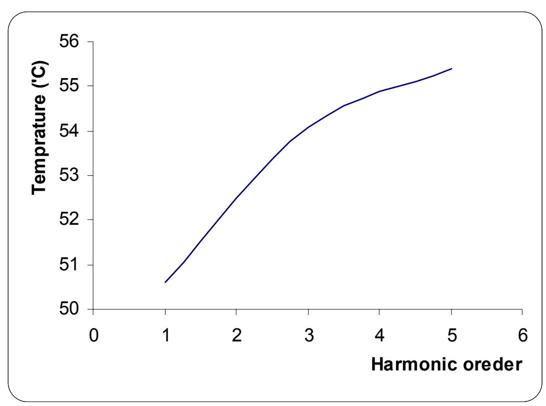

Fig.5 Temperature rise of induction motor due to different harmonics.

Like capacitor banks used for power factor correction of induction motors, filter banks should be selected to eliminate 2nd, 3rd, 5th of voltage harmonics form induction motor's supply unless this harmonics are considered in design procedure.

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