Experimental Study of the Effect of Positive Sequence Voltage on the Derating of Induction Motors under Voltage Unbalance

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***Abstract* – This paper presents the results of an experimental study on derating of an induction motor under different voltage unbalanced conditions and its comparison with the NEMA standard MG1 voltage unbalance derating graph. During the derating tests the 4 kW squirrel cage induction motor temperature rise was kept constant at the rated value and the windings temperature was measured on-line by means of an accurate digital thermal monitoring system with nine thermocouples positioned in both stator and rotor circuits. The obtained results show that the positive sequence voltage plays an important role in the derating performance of the induction motor under unbalanced conditions, and that the unbalance voltage indices currently used do not allow for accurately measuring this influence.**

***Index Terms*-- Derating, induction motor, heating test, NEMA MG1, thermal monitoring system, voltage unbalance, positive sequence voltage.**

I. INTRODUCTION

Three-phase induction motors are widely used in industrial, commercial and residential systems, because of their ruggedness, simplicity and relatively low cost. Approximately 65% of the electricity consumed in industry is used to drive electrical motors. Therefore, the efficiency and reliability of induction motors operation is of major importance, in order to improve the energy efficiency in industry. The IEC standard [1] and the European Commission's report [2] show that induction motors in the power range from 0.75 kW to 4 kW represent a particularly attractive opportunity for electricity savings.

Unbalanced voltage is one of the most frequent disturbances in electrical systems. The major cause of voltage unbalance in power systems is the uneven distribution of single-phase loads. There are also other additional causes like unbalanced transformer banks, power systems faults, blown fuses on three-phase capacitor banks etc. [3], [4]. The American National Standards Institute's report [5] pointed out that 98% of utilities customers have less than 3% unbalance, while 66% have less than 1% (Fig.1), and that there is not a relation between unbalance and load.

The operation of three-phase induction motors under unbalanced voltages can cause serious ill effects such as overheating, drop of efficiency and reduction in output torque. In order to avoid the excessive heating in the windings the motor load has to be reduced so as to limit the temperature rise to the rated value. Therefore to maintain the operational life of the motor, the international standards [6], [7] recommend the derating of the motor.

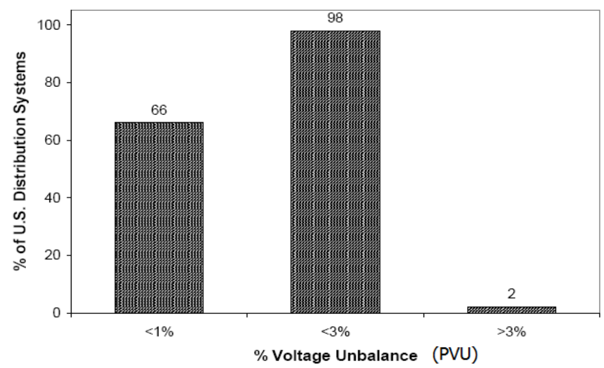

Fig. 1. Approximate "percent voltage unbalance" (PVU) in the U.S.A. Distribution System [5].

Researches about the derating of induction motors under unbalanced voltage conditions have been reported in the literature since 1959 [8-20]. The most accurate method for derating under unbalanced voltage conditions is to reduce the induction motor load so as to limit the temperature rise to the normal value. The complexity of the thermal behavior of an induction motor under unbalanced voltages makes necessary the development of experimental studies with an accurate measurement of the temperature inside the motor; however in the literature few experimental works with this methodology are reported.

This paper presents the results of an experimental study about the influence of positive sequence voltage on the derating of an induction motor and its comparison with the NEMA derating curve. The importance of positive sequence voltage in derating has been reported by several authors [19-21], however no experimental work in this field has been reported in the literature. During the heating tests the temperature rise was maintained constant at rated value, and the winding temperature was measured on-line by means of an accurate thermal monitoring system. The importance of the effect the positive sequence voltage in the motor performance is analyzed and it is also shown that the unbalance voltages indices currently used do not allow for measuring the influence of the positive sequence voltage in the performance of the induction motor.

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II. STATE OF THE ART

Studies concerning the derating of induction motors under unbalanced voltage conditions have been reported in the literature since 1959. Gafford et al. [8] stressed the importance of the negative sequence current in causing unbalanced spatial distribution of losses and heat and presented an equation to estimate the maximum temperature rise. Berndt and Schmitz [9] presented the results of a series of laboratory tests on three motors and determined theoretically and experimentally the derating factors using the symmetrical components method. Lee, in the discussion of [9], suggested a method of predicting the derating factors considering that the thermal impedance between stator windings was negligible. Rama and Jyothi [10] determined the derating factor experimentally using Berndt, Schmitz and Lee methods and compared these with two additional methods of prediction.

In 1978 the National Electrical Manufacturers Association (NEMA) [6] presented the MG1 derating graph (Fig. 2). Brighton and Ranade [11] reported that the NEMA MG1 derating curve is based on empirical results, obtained from laboratory tests, indicating that the percentage increases in the motor temperature, due to voltage unbalance is approximately equal to two times the square of percentage of voltage unbalance. The NEMA MG1 derating curve is the most used method in industry to evaluate the motor derating under unbalance voltage conditions.

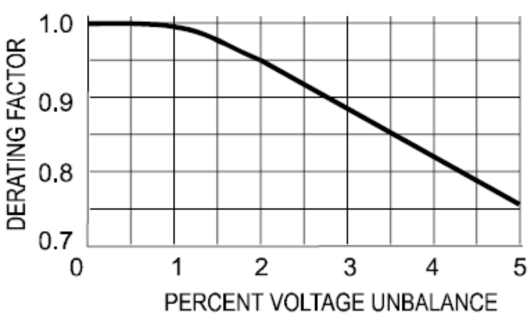

Fig. 2. Derating factor for squirrel cage induction motors due to unbalanced voltage. Standard ANSI/NEMA MG1 [6].

Since the motor derating is defined by the motor temperature rise it is necessary to develop experimental studies with an accurate measurement of the temperature inside the motor. Few experimental studies were reported in the literature in the last years. In 1996 and 1998, López-Fernández et al. [12], [13] presented the development of a thermal monitoring system to study the thermal behavior of induction motors under unbalanced supply. In 2006, Reineri et al. [14] presented an experimental study with a 1.1 kW wound-rotor induction motor under different unbalance conditions while the average value of the motor three-phase voltages was kept constant at rated value. In 2007, Farahani et al. [15] report an experimental study with a 1.1 kW squirrel cage motor using a temperature monitoring system. In 2009, several authors [16-18] have presented studies about the performance of induction motors under different voltage unbalance conditions. In [16] a 1.5 kW standard induction motor has used but without a thermal monitoring system. In [17] the load carrying capacity of two induction motors of 3 kW and 5 kW was studied under voltage unbalance combined with over- or under-voltage. In [18] an empirical verification of the NEMA MG1 derating graph was presented using temperature sensors embedded in a 5 HP motor.

The importance of positive sequence voltage in derating has been reported in [19-21]; however no experimental work has been reported in this field. This paper presents the results of an experimental study about the influence of positive sequence voltage on the derating of a 4 kW induction motor and its comparison with the NEMA derating curve. During the derating tests the temperature rise was maintained constant at rated value, and the windings temperature was measured on-line by means of an accurate thermal monitoring system with nine thermocouples positioned in both stator and rotor circuits.

III. CHARACTERIZATION OF UNBALANCED VOLTAGES

A. Standards Definition of Voltage Unbalance

There are two general definitions for measuring the voltage unbalance, given by international standards NEMA [6] and IEC [7].

NEMA defined the unbalance voltage by means of the "percent voltage unbalance" (PVU) [6]:

$$PVU = 100 \times \frac{MVD}{V_{Avg}} \quad (1)$$

where MVD is the maximum voltage deviation from the average line voltage magnitude and V_{Avg} is the average line voltage magnitude.

The IEC standard [7] adopts the "voltage unbalance factor" (VUF) as defined by the method of symmetrical components:

$$VUF = \frac{V_2}{V_1} \quad (2)$$

where V_1 and V_2 are the amplitudes of positive and negative sequence voltages, respectively.

B. Characterization of Unbalanced Voltages

The appearance of over-voltages or under-voltages at the motor terminals depends on its location and on the length of the feeder used. Additionally, the supply voltage is not always balanced, and, therefore the motor can run on the combination of over- or under-line voltages. The standards about power quality do not allow voltage deviation and unbalance levels higher than those specified in IEC standard 60034-1 and ANSI/NEMA Standard MG1-2003 [6]. The acceptable line voltage deviation is ±10% of their rated value V_n and the ratio between the negative and positive sequence voltage component should not exceed 2%.

The rated power of an induction motor is defined for motor operation at rated voltage under balanced supply, where the magnitude of positive sequence voltage is the rated voltage. But the standards definition of PVU and VUF, do not give information about the magnitude of the positive sequence voltage; they only give information about the grade of unbalance of the voltage system.

When a voltage system is unbalanced the positive sequence voltage gives information about if it is over- or under-voltage.

Then, in order to reduce uncertainty, two parameters can be used to characterize the unbalanced voltage situations: the PVU or the VUF to consider the grade of unbalance and the positive sequence voltage V_1 to consider the effects of over- or under-voltages (Table I).

TABLE I
EQUIVALENT UNBALANCE VOLTAGE

Characterization Indices	Ratio of V_1 and V_n	Type of voltage unbalance
V_1 and VUF	Greater than 1	Over-Voltage Unbalance
	Equal to 1	Rated-Voltage Unbalance
	Less than 1	Under-Voltage Unbalance

IV. EXPERIMENTAL STUDY

A. Experimental Setup

The test rig comprises a standard IEC three-phase induction motor, 4 kW, 50 Hz, 380 V, 9.2 A, 1435 rpm, mechanically coupled to a separately excited dc generator. The induction motor is totally enclosed fan cooled (TEFC), with a cast-aluminum squirrel cage and the stator winding has thermal class F insulation.

The motor output power was determined by the use of a digital torque sensor that measures static and dynamic torque and by measuring the speed with a digital tachometer. The electrical variables were measured using a digital power quality analyzer. The voltages applied to the motor under test are controlled by a three-phase autotransformer, with phase-to-neutral voltages independently controlled in the range of 0 V to 440 V. The experimental setup is shown in Fig. 3.

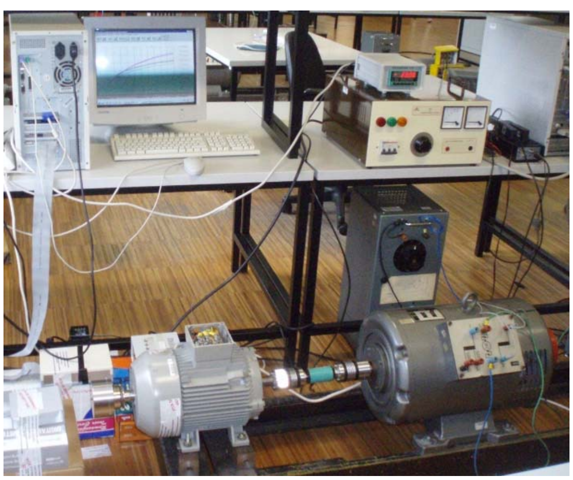

Fig. 3. Experimental setup.

The stator and rotor temperatures were measured by several thermocouples positioned inside the motor according to the schematic presented in Fig. 4.

The thermocouples T2, T3, T4 and T5 are for stator temperature measurements; T2 is placed in a stator tooth on the load side and the other three are placed in the slots of the phases U, V and W, respectively. The thermocouple T1 is used to measure the room temperature where the motor was tested.

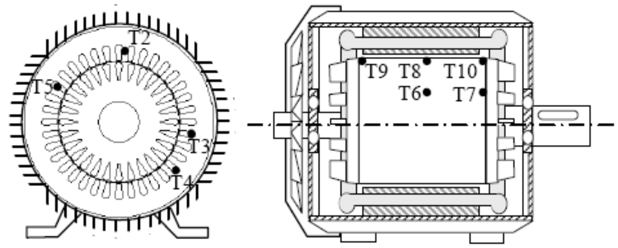

Fig. 4. Stator and rotor thermocouples location.

The thermocouples T6, T7, T8, T9 and T10 are for rotor temperature measurements. The thermocouples T8, T9 and T10 are placed at the rotor surface, while T6 and T7 are placed 5 cm deep inside the rotor. The temperature evaluation is obtained on-line by a data acquisition system through an infra-red transmission device (for the rotor) [12]. The rotor measurement system is placed on the shaft at the fan side, as can be observed in Fig. 5. Therefore, the presence of the measurement device has no influence on the induction motor performance. Each thermocouple temperature sample is acquired every 15 min.

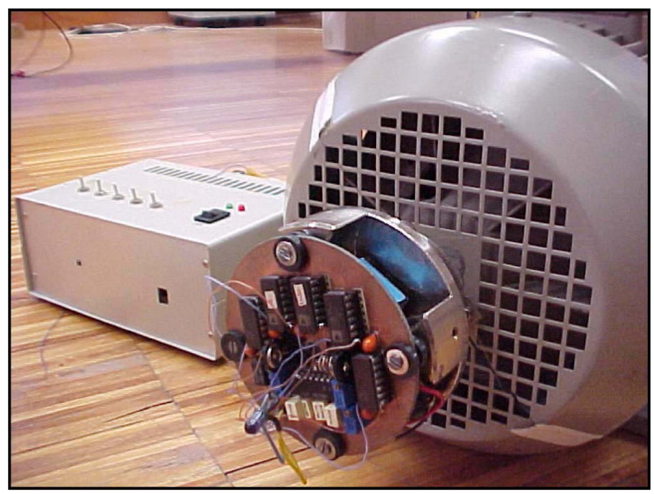

Fig. 5. Infra-red transmission system [12].

B. Experimental Methodology

In order to evaluate the rated temperature rise of the motor, it was subjected to a heating test operation under rated conditions with balance voltage. The heating test lasted four hours and the temperature rise (ΔT) was of 76°C.

In order to evaluate the influence of the positive sequence voltage in the derating, the motor was tested with three types of voltage unbalance as defined in Table I. To study the under-voltage unbalanced condition, the positive sequence voltage was fixed at 95% of the rated voltage and the heating test was performed for seven different values of PVU between 0% and 5%. To study the rated-voltage unbalanced condition, the positive sequence voltage was fixed at the rated voltage and the heating test was conducted for seven different grades of PVU from 0% to 5%. To study the over-voltage unbalanced condition, the positive sequence voltage was fixed at 105% of the rated voltage and the heating test was performed for seven different values from PVU since 0% to 5% (Table II).

TABLE II
UNBALANCE VOLTAGES USED IN THE HEATING TEST

PVU	V_1/V_n	Type of Voltage Unbalance
1% 2% 3% 4% 5%	1,05	Over-Voltage Unbalance
	1,00	Rated-Voltage Unbalance
	0,95	Under-Voltage Unbalance

During the heating tests for each unbalanced voltage condition, defined by V_1 and PVU, the motor load was reduced so as to limit the temperature rise to the rated value of 76°C. Finally, twenty two heating tests were performed under unbalanced conditions, each test having a duration of four hours, approximately. Fig. 6 shows the heating test results for a PVU of 4% and a magnitude of positive sequence voltage of 380 V. When the unbalanced voltage is lower than 5% the PVU is approximately equal to VUF.

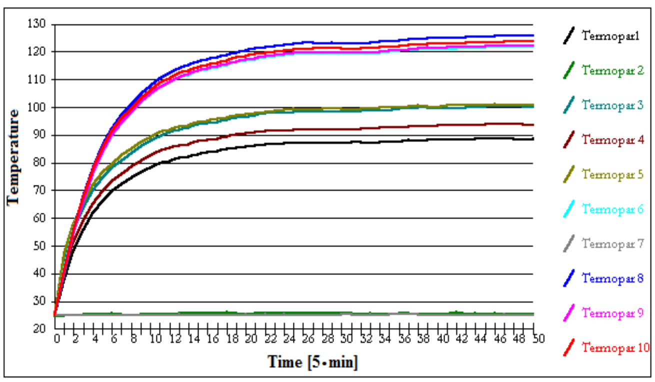

Fig. 6. The heating curves for a derating test corresponding to a PVU=4% and V1 =380 V

C. *Experimental Results*

Fig. 7 shows the results of twenty two heating tests conducted in order to evaluate the influence of the positive sequence voltage on the derating of the induction motor and its comparison with the NEMA derating curve. The magnitudes of the positive sequence voltage were 0.95, 1 and 1.05 of the rated voltage. For each of the three cases the tests were performed for seven different levels of PVU, from 0% to 5%.

If the magnitude of the positive sequence voltage is 100% and 105% of the rated voltage the experimental derating factors are equivalent to NEMA in the range of 0 to 1.5 % of unbalance, but when the PVU is larger than 1.5% the NEMA derating curve is overprotecting the motor.

If the magnitude of the positive sequence voltage is 95% of the rated voltage the experimental derating factor is less than NEMA derating factor for the range of 0 to 1.5% of PVU. This means that NEMA derating curve does not protect the induction motor in this range. However, if the unbalance is greater than 2% the NEMA derating curve is again overprotecting the motor.

From the NEMA derating curve, between 0 and 1 % of unbalance the derating factor is one but the tests have demonstrated that this is not true if the magnitude of the positive sequence voltage is 95% of rated voltage.

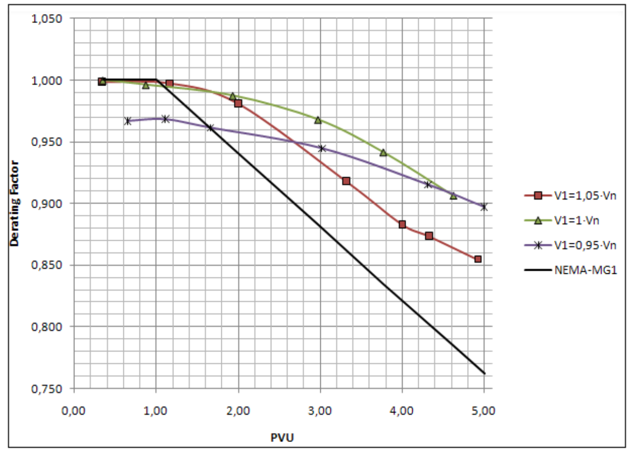

Fig. 7. Comparison of experimental Derating Factors (for three different values of positive sequence voltage) with NEMA MG1 derating curve.

V. CONCLUSIONS

This paper presents the results of an extensive series of heating tests in a 4 kW, 1435 rpm induction motor, in order to study the influence of the positive sequence voltage on the derating of an induction motor under voltage unbalance and to compare it with the NEMA derating graph. An accurate digital thermal monitoring system, with nine thermocouples positioned in both stator and rotor circuits, was used for the on-line measurement of the motor temperature.

The experimental results show that the positive sequence voltage has a strong influence in the derating performance of the induction motor. Therefore the positive sequence voltage must be considered together with the PVU index for derating purposes. If only the PVU index is taken into account, a facility user can not appropriately derate the motor.

NEMA MG1 derating graph provides fully protection for the motor only if the magnitude of the positive sequence voltage is equal or greater than the rated voltage.

The tests suggest that the standard limits for derating of induction motors operating under unbalanced voltage condition must be reconsidered in order to propose more adequate limits.

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