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Energy-efficient operation of induction motors and power quality standards

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ABSTRACT

Induction motors are usually considerably oversized and consequently often work inefficiently because of various factors such as the relatively poor voltage quality that is allowed in public and industrial networks. A possible solution is the amendment of power quality rules. This paper presents a preliminary proposal to modify the power quality standards: EN 50160 *Voltage characteristics of electricity supplied by public distribution network* and EN-ICE 61000-2-4 *Electromagnetic compatibility (EMC) – Part 2–4: Environment – Compatibility levels in industrial plants for low-frequency conducted disturbances*. The proposal consists of a complete set of power quality indices with *simplified temperature coefficient of power quality*, the value of which corresponds to the windings temperature rise of induction machines with decreased supply voltage quality. The recommended limit values for the coefficient are determined according to an analysis of various cases of induction machine heating. Additionally, the results of the factor monitoring in actual power systems are presented.

1. Introduction

Induction motors usually work with loads much lower than their maximum rating. According to various surveys [1,2], the average load factor is 57–68% of the rating, and the machines often operate with a much lower load [1–5] of even 3–16% [4]. The U.S. Department of Energy notes that 44% of machines in the industrial sector work with loads less than or equal to 40% of their rated value [5]. However, induction motors are usually considered to have the highest efficiency at 75% load. In practice, the efficiency peak significantly depends on the rated power [5–7], manufacturer [1], and machine properties. Modern premium-efficiency medium-power motors can be expected to have an efficiency peak at approximately 50–70% of the rated power (based on [1]); consequently, they can work effectively for a wide range of loads. In contrast, for low-power machines, the highest efficiency typically appears for a comparatively high load, which may even be close to the rated one [5–7]. To make the matter worse, in the industrial sector, small machines tend to work with slightly smaller load factors than the medium-power ones (based on [2]). As a result, their oversizing leads to the waste of enormous amounts of electric energy and consequently obvious economical and environmental costs.

The main causes of induction machine oversizing is weak motor system design, overestimation power on shaft [2], and necessity of motor protection against overheating, which is related to the low quality of the supply voltage. It should be stressed that oversizing is a commonly used solution to prevent machine overheating. Another solution is the application of higher classes of insulation than those that correspond to the windings temperature rise under nominal work conditions (for short, this approach is called "over-insulation" in this paper), which is often combined with oversizing.

An important factor to consider for the assessment of the necessary oversizing and/or choice of over-insulation as a method of overheating prevention is the quality of the supply voltage. In many cases, the only information on the voltage quality is the existing standards. Unfortunately, their analysis leads to virtually nothing and only reveals discrepancy in permissible levels of power quality disturbances, typical intensity, and inconsistency in the standard system.

2. Power quality standard framework and related oversizing of induction motors

To protect various components of power systems against harmful effects of power quality disturbances, appropriate standards have been introduced. It is assumed that their provisions sufficiently protect induction motors against overheating because of the decreased voltage quality. However, significant inconsistency

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in these standards is worthy of note. Refs. [8–10] provide completely different power quality requirements regarding public or industrial networks and voltage-supplying rotating machines.

According to the *IEC Std. 60034-1 Rotating electrical machines. Part 1: Rating and performance* [10], “three-phase a.c. motors shall be suitable for operation on a three-phase voltage system having a negative-sequence component not exceeding 1% of the positive-sequence component over a long period”, and a.c. motors should be capable of working with its rated load for ±5% voltage deviation. It should be stressed that both power quality disturbances (voltage unbalance and voltage deviation) are separately considered. Thus, an induction machine is not required to work properly under 1% voltage unbalance with 5% voltage deviation. In contrast, the standard *EN 50160 Voltage characteristics of electricity supplied by public distribution network* [8] admits ±10% voltage deviation and warns that in some systems, the voltage variation exceeds +10% and −15%. The permitted voltage unbalance (defined as a ratio of positive- and negative-sequence voltage components – VUF [11–13]) is 2%; nevertheless, 3% unbalance is tolerated in some areas. Additionally, the standard [8] permits significant voltage waveform distortions; the acceptable THD factor is 8% and values of the 5th, 7th, 11th and 13th voltage harmonics can be equal to 6%, 5%, 3.5, and 3% of the fundamental component U_1, respectively. The values of the 2nd and 4th harmonics can reach 2% U_1 and 1% U_1, respectively (in some power systems, even harmonics may appear [14]). It is worth mentioning that in many European countries, the recommendations in [8] are incorporated into formal rules that govern the power quality in public networks.

Furthermore, the compatibility levels in industrial networks are provided in EN-ICE 61000-2-4 Electromagnetic compatibility (EMC) – Part 2–4: Environment – Compatibility levels in industrial plants for low-frequency conducted disturbances [9]. The standard defines three classes of industrial environments. Class 1 relates to supplying notably sensitive devices such as some computers, laboratory instrumentations, and automation equipment. Class 2 corresponds to a common industry environment, and the compatibility levels are the same as in public systems. Class 3 matches industrial networks with disturbing loads [9]. The compatibility levels for this class are as follows: the continuous voltage deviation is ±10%, the voltage unbalance is 3%, THD of 10%, and the 2nd, 4th, 5th, 7th, 11th, and 13th voltage harmonics (in relation to U_1) are 3%, 1.5%, 8%, 7%, 5%, and 4.5%, respectively. For some industrial networks with large non-linear loads, the harmonic content can be increased by 20%.

It is worth adding that in the U.S. the voltage parameters are characterized in *ANSI C84.1 American National Standard for Electric Power Systems and Equipment – Voltage Ratings (60 Hertz)* [15]. Ref. [15] defines two ranges of service voltage (where the user and operator systems are connected) and utilization voltage (voltage at the line terminal of the equipment), which are denoted as *Range A* and *Range B* for both cases. Generally, the voltage variation should not exceed the limits for *Range A*. For various low-voltage systems, the maximal permitted deviation of the utilization voltage is usually approximately −6%, +9.6% for *Range A*, and −9.6%, +10.4% for *Range B*. Voltage unbalance is recommended to be restricted to 3% and partly connected with voltage deviation (each phase voltage should be within the limits for *Range A* or *Range B*). Whereas, according to the standard *NEMA MG 1 Motors and Generators* [7], induction motors should be able to operate with the rated load for 1% unbalance or ±10 voltage deviation. However, [7] warns that log-lasting work under such over- or undervoltage may accelerate the deterioration of the insulation.

Supplying with decreased-quality voltage results in additional power losses in machines [16–18] and consequently the waste of electric energy. Moreover, the power losses cause an increase in windings temperature. It should be noted that increments in windings temperature by 8–11 K usually accelerate the rate of thermal aging by a factor of two. In the considered power systems, voltage deviation and voltage unbalance cause the highest windings temperature rise [11–13]. Their effect on machine heating is well recognized in [11–13] for the case of a purely sinusoidal voltage. The results of experimental and simulation investigations show [11–13] that even one of these disturbances may lead to machine overheating, whereas voltage deviation with voltage unbalance may cause extraordinary increase in windings temperature. It should be stressed that even over-insulation does not always protect a machine against overheating [12]. Generally, under significant power quality disturbances, an induction machine cannot work at its rated load and requires derating [7,11,13,16,19–22].

The effect of the necessary derating on machine oversizing may be illustrated with the following example. Let us assume that the estimated shaft power is 1.6 kW, the supply voltage deviation is 10%, and the negative-sequence voltage component is 3% U_{rat} (i.e., approximately 2.7% U_1, which is less than the value for class 3 according to [9]). For the considered supply conditions and an exemplary induction motor TSg 100L-4B type, the derating factor is 0.67 [20]. Let us assume that this derating factor also applies for other motors. Considering the motor types for a representative manufacturer (1.5 kW, 2.2 kW and 3.0 kW), the best choice is a machine of the rated power of 3 kW. However, the machine will work with a load of approximately 50% of its full power, if the required mechanical power is correctly assessed. In fact, as previously mentioned, the shaft power is often significantly overestimated [2], and the machine may work with a much lower load factor, which causes enormous decrease in efficiency.

In summary, for power quality disturbances that are permitted by the related standards, induction machines should be derated. Moreover, the standards do not provide useful information on voltage quality in new or modernized plants. In practice, assumption of the worst possible combination of power quality disturbances may result in unjustified oversizing. Therefore, the standards should be amended to better cover cases of voltage quality disturbances that simultaneously appear.

3. Power quality assessment based on the temperature coefficient of power quality c_{pqs}

The power quality assessment in the present standards [8,9] is based on limiting each disturbance separately. It should be stressed that their permissible levels are not interrelated. For example, according to [8], the permissible voltage deviation is identical for full voltage balance and 2% voltage unbalance. This approach does not consider that various power quality disturbances have a cumulative effect on the induction machine heating [12,13,22,23]. Consequently, the present approach can be considered inadequate, and a reliable method of power quality assessment should be introduced into the standards.

An appropriate method was elaborated in a preceding study [24]. It is based on the *temperature coefficient of power quality* – c_{pq} (formerly *temperature factor of power quality*), the value of which is a measure of windings temperature rise of low-power induction motors that are particularly sensitive to various power quality disturbances [24]. It is equal to a ratio of the maximal winding temperature rise of induction motors that are supplied with lowered-quality voltage and its value under nominal work (including the case of machines with over-insulation). It should be noted that c_{pq} corresponds to the worst case (i.e., causing the highest winding temperature rise for given sets of power disturbances) of the following cases: an induction machine with a weakly or strongly saturated magnetic circuit [22] that works with a load of constant torque or a fan-type load. The coefficient is derived