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Thermal loss of life and load-carrying capacity of marine induction motors

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ABSTRACT

This work deals with the effect of a lowered voltage quality on the thermal loss of life and load-carrying capacity of marine induction cage machines. Results of experimental investigations and computer calculations are presented for two low power induction motors with different properties. One of them has a comparatively strongly-saturated magnetic circuit and is especially exposed to the risk of overheating under overvoltage. The other machine has a comparatively weakly-saturated magnetic circuit, and is especially sensitive to undervoltage. The induction motor lifetime expectancy is also estimated on the basis of the *temperature coefficient of power quality*, whose value is proportional to the windings temperature rise in induction motors especially sensitive to various power quality disturbances. The dependence of the *temperature coefficient of power quality* and permissible loads for induction motors supplied with voltages of lowered quality is proposed.

1. Introduction

Induction cage machines are in common use in ship and land applications. Among the great number of various appliances driven by induction motors, some are of particular significance. Potential failure of their prime movers might lead to significant material losses, or even cause a threat to human life and the natural environment. For example, damage of an important auxiliary motor in a ship's propulsion subsystem (e.g. a motor driving a lubrication oil pump) may result in a loss in vessel maneuverability with untold consequences.

Induction cage machines characterize high reliability and durability, provided that they are operated under appropriate working conditions. One of the agents that considerably influences their reliability and durability is the quality of the supply voltage. The presence of any power quality disturbances in the supply network, like frequency and RMS voltage value deviations, voltage unbalance and voltage waveform distortions, leads to additional power losses occurring in the machine [1–24], and consequently to an increase in the windings temperature [5–20,25,26]. A higher windings temperature means faster aging of the insulation system [19], and as a result – a reduction in the machine's operational life [9,12,18,19].

Power quality stands are a particularly important problem in autonomous power systems, such as ship power systems. Their features are considerably different from land systems. One of the characteristics of a ship power system is the presence of single energy receivers of power comparable with the generator's power, like thrusters. Their rated power is usually within the range 300–2000 kW [11]. Consequently a single receiver is able to disturb the whole power system. Another feature is the presence of large number of non-linear loads. It should be stressed that in some cases they reach powers of many MW, for example power converters for electric propulsion. A ship's power system is also characterized by comparatively short feeder lengths. As a result power quality disturbances caused by a single receiver are not of local character, but they spread throughout the whole system. A constructional solution applied in some ship power systems are shaft generators – synchronous generators driven directly by the main engine. It should be noted that its rotational speed is not constant – it depends among the other things on the state of the sea. In order to decouple the main engine's rotational speed and voltage frequency in the grid, the voltage produced by the shaft generator is often (but not always) rectified and converted to AC by PWM or thyristor inverters. Another characteristic of a ship power system is the low number of voltage sources. During sailing only one generator usually works, of comparatively low short-circuit power. To sum up, the technical solutions applied in ship power systems result in a deterioration in power quality in some vessels [10,13].

In order to protect the electric energy receivers against being supplied with a voltage of lowered quality, ship classification societies introduced appropriate regulations [13,15,16,27,28]. It should be stressed that they consider each disturbance separately, neglecting the cumulative impact of various power quality disturbances appearing simultaneously. For example, the permissible

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frequency deviation is usually ±5%, and in some cases – even ±5.5% [27]. The voltage deviation produced by a generator is usually ±2.5% (in any steady-state operation [28] or "for all loads between zero and the rated load at rated power factor" [27]), and the permissible voltage drop along a feeder – 6% [27,28]. At the same time, the rules [27,28] specify the frequency deviation assumed for the purpose of electrical equipment design as equal to ±5%, and voltage deviation −10%, +6%. Inconsequently, thermal tests of electrical machines are to be carried out only in the nominal work conditions [16,27,28]. Further, the regulations allow significant levels of voltage waveform distortion – the permissible THD factor is usually equal to 5% or 10%, but in some cases a THD of any level can be accepted [27,28].

Ship classification societies usually do not specify the maximal level of voltage unbalance. It is also worth mentioning that the permissible levels of each power quality disturbance are not interconnected with each other. Consequently, the rules of ship classification societies do not satisfactorily protect marine induction motors against overheating due to being supplied with a voltage of lowered quality. The author's investigations show that the cumulative effect of various power quality disturbances appearing simultaneously may lead to extremely high windings temperatures [12,13,16]. For example, for $f = 105\%\ f_{rat}$, $U = 106\%\ U_{rat}$ and a fan-type load, the measured windings temperature rise (above the ambient temperature) in an exemplary induction cage machine of Sg132-S4 type was about 56 K higher than under the nominal working conditions [16]. This example highlights the necessity to modify the regulations of ship classification societies.

A proposal for new power quality regulations for ship classification societies was submitted by the author and co-workers [11,16], yet it requires further development. Additional investigations are required regarding problems with the thermal loss of life and load-carrying capacity of marine induction motors under lowered voltage quality.

2. State of the art

The problems of thermal loads and derating of an induction machine fed with a voltage of lowered quality have been analyzed in several works [5–26,29,30]. The publications generally concern machines supplied from a land power system or PWM inverter. The results of the investigations cannot be directly extrapolated to marine induction motors. It should be stressed that in land power systems the voltage frequency is practically constant, whereas in a ship frequency deviations occur [13] which considerably influence the U/f ratio and rotational speed of the induction motors. An increase in rotational speed causes an increment in the rotational torque for machines working with a fan-type load, and consequently leads to additional machine heating.

The effect of power quality disturbances typical in ship power systems on machine heating was examined by the author and co-workers [11,13,16]. Only the work [11] (D.Sc. thesis) contains preliminary research on thermal loss of life and load-carrying capacity of an induction machine under power quality disturbances expected in ship power systems. To sum up, the problems of the thermal loss of life and reduced load-carrying capacity of marine induction motors have still not been satisfactorily explained.

Synthetic factors and neural network systems to the assessment of power quality disturbances on induction machine heating were discussed in [5,11,13–16,20,31,32]. Duarte, Kuznetsov and co-workers [20,32] described synthetic power quality factors dedicated for the assessment of the quality of voltage supplying induction machines. The factors only take into account voltage unbalance, voltage harmonics and cannot be adopted for power quality assessment in ship systems. Also the neural network system presented in [31] does not take into account specific power quality disturbances occurring in ship power networks. Cummings et al. [5] presented an *unbalance voltage factor*, and proposed its permissible levels for the purpose of the thermal protection of induction machines under an unbalanced supply. The concept is based on overly simplified machine models, and cannot be adopted for the purposes under consideration.

A preliminary version of synthetic power quality coefficients appropriate for the assessment of voltage quality in ship power systems – *temperature coefficient of power quality* – c_{pq} and *simplified temperature coefficient of power quality* – c_{pqs} (formerly *temperature factor of power quality* – f_{pq} and *simplified temperature factor of power quality* – f_{pqs}), were elaborated by the author and co-workers [13,14]. In a subsequent paper [15], the author presented and experimentally verified a modified variant, based on a much more exact machine model. It should be noted that the *simplified temperature coefficient of power quality* was implemented in the universal power quality estimator–analyzer [33] elaborated at the Gdynia Maritime University for commercial purposes, and certified by the Polish Register of Shipping. More detailed information concerning the coefficients are given in Appendix A and [15].

On the grounds of the *simplified temperature coefficient of power quality* a proposal for a new power quality regulation for ship classification societies was developed [11,16] – the maximal permissible and recommended levels c_{pqs} coefficient were proposed. According to [11,16], the higher levels of c_{pqs} than the maximal permissible one, can be accepted for the following specific cases:

- Ships with induction motors of higher insulation class than resulting from temperature rises.
- Ships with induction motors working with less load than the rated one.
- Ships with induction motors certified for the real supply conditions.

Ref. [11,16] do not provide any recommendations for these specific cases, but only announce them as "the subject of future investigations". In this research, preliminary recommendations were elaborated for ships with induction motors working with less load than the rated one. Additionally, the thermal loss of life and load-carrying capacity of an induction machine are analyzed for the power quality disturbances expected in a ship's power system. This paper's scope has been limited to the low-power induction machines, connected directly to AC network under steady-state operation.

3. Thermal model

For the purpose of thermal calculations a method of equivalent thermal network [9,12] was employed. In this method the whole machine is divided into basic elements, like the stator core, rotor core, end windings, slot windings, etc. Each basic element corresponds to a node in a thermal network. Thermal resistances and capacitances in a real machine are modeled with those in the network, while heat flow and temperature corresponds to currents and voltage.

The applied thermal network is presented in Fig. 1. The node 1 models the rotor, the nodes 2, 10, 13 – slot windings in each phase, the nodes 3, 9, 12 – the average temperature of endwindings in each phase (power losses occurring in endwindings are assumed to depend on the average temperature of endwindings), the node 4 – stator iron, the node 5 – endcap air, the node 6 – casing, the nodes 7, 8, 11– maximal temperature of endwindings. The parameters of the network were identified on the basis of calculations (by