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ARTIFICIAL LOADING FOR ROTATING ELECTRIC MACHINES

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ABSTRACT: The paper presents many methods to produce synthetic loading of rotating electric machines (induction, synchronous and DC) without load to the shaft using power converter. The required equipment is simple. Setting-up time is considerably reduced because it is not required to connect an external load to the machine's shaft. The range of r.m.s. current control is large beginning from no-load current to overload at rated speed and temperature, that the total losses in the machine can be identified by taking the average of the measured power over one cycle of synthetic loading of the machine.
KEYWORDS: Ytterberg's method, DC machine, induction machine, synchronous machine, synthetic loading

❖ INTRODUCTION

The machine temperature at full load represents an essential parameter of rotating electric machine. The conventional method is to produce the shaft's load using another electric machine. The cost of test equipment and setting-up procedure for mechanical coupling make the conventional method prohibitively expensive, especially for large machine or for high speed machine. Thermal test of vertical mounted machines is quite impossible due difficulties to fit the vertical load [1].

Hence, currently there is no cost-effective method of assessing the state of a machine on-site and whether or not it would be economically and environmentally beneficial to replace it. However, the regulations are not retrospective and so many poor performing machines will remain in service for many years to come. A method of evaluating the efficiency of machines currently in service to ascertain whether or not it should be replaced needs to be developed [2], [3], [4].

The dual frequency method was proposed in 1921 by Ytterberg [5] in order to produce synthetic loading of induction machine.

Now, using power converters several methods have been developed. Dynamic thermal loading [6], [7], [8], constant speed method [9], sweep frequency method [10] and also the dual frequency method [10], [11], [12], [13], [14], can be implemented using power converters.

❖ THEORETICAL STUDY

The essence of the dual frequency method is to produce a supply voltage containing two distinct frequencies. This way, two magnetic fields are produced, rotating at different speeds. The shaft speed can not change quickly, so the machine is oscillating between motoring and regenerating. This way, the r.m.s. motor current is increased compared to the no-load current [1].

In Ytterberg's method the loading machine is supplied from two series three-phased symmetrical systems having different frequencies. One of the sources has a fixed frequency f_1 (frequency of the network's power supply) and is called "base source" and the other one has a variable frequency f_2, usually less than f_1, and it is called "auxiliary source". The emf's supply by the two sources can be written as:

$$u_1 = \sqrt{2} \cdot U_1 \cdot \sin \omega_1 t \ , \tag{1}$$

$$u_2 = \sqrt{2} \cdot U_2 \cdot \sin \omega_2 t \ . \tag{2}$$

Consequently, the resulting wave has amplitude modulated by a frequency equal to the difference between f_1 and f_2. In the rotating rotor winding is induced a voltage with the frequency equal to the difference between the frequencies f_1 and f_2. The interaction between rotoric current and the rotating magnetic field in the core creates an electromagnetic torque which in a semi-period acts as an accelerating torque, while in the next semi-period acts as a generating torque, reducing the rotating speed of the rotor. In other words, in the first semi-period the machine absorbs active power from the source, while in the next semi-period it releases active power to the source. The resulting voltage has the following expression [15], [16]:

$$u(t) = \sqrt{2} \cdot U_1 \cdot \sin \omega_1 t + \sqrt{2} \cdot U_2 \cdot \sin \omega_2 t \ , \tag{3}$$

$$u(t) = \sqrt{2} \cdot (U_1 - U_2) \cdot \sin \omega_1 t + \sqrt{2} \cdot U_2 \cdot (\sin \omega_1 t + \sin \omega_2 t). \tag{4}$$

In figure 1 is presented the current in the machine's windings

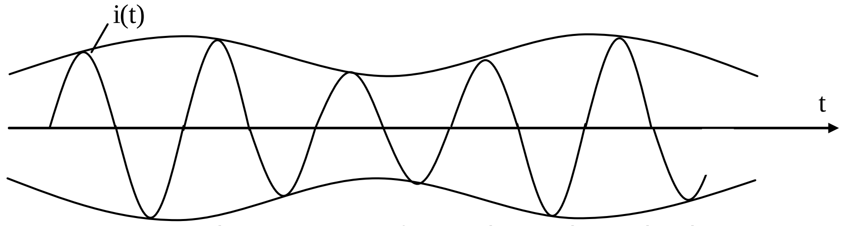

Fig. 1 The current i(t) for synthetic charge loading

Further, we introduce the following notation:

$$\alpha = \omega_1 - \omega_2 \ , \tag{5}$$

$$\beta = \frac{\omega_1 + \omega_2}{\omega_1 - \omega_2} \ , \tag{6}$$

$$\beta \cdot \alpha = \omega_1 + \omega_2 \ . \tag{7}$$

By combining equations (5) and (6) results:

$$(\beta + 1) \cdot \alpha = 2\omega_1 \ . \tag{8}$$

Thus equation (4) becomes:

$$u(t) = \sqrt{2} \cdot \left[(U_1 - U_2) + U_2 \cdot \cos \frac{\alpha t}{2} \right] \cdot \sin \frac{\alpha \beta}{2} \cdot t \ . \tag{9}$$

We can observe that this voltage varies periodically with the frequency ω_1 and is modulated with the frequency $\frac{\alpha}{2}$.

In dynamic thermal loading, the rotor's inertia moment will produce the electromechanical load during the acceleration and brake cycle. The induction machine will be repeatedly motor and generator. The average value of electromagnetic torque is close to zero, but not zero, in order to compensate the ventilation and mechanical losses. This method can be implemented as torque control or speed control.

In torque control implementation the reference will be a rectangle wave with a small positive offset. The amplitude of reference torque controls the stator and rotor load current. The offset value of reference torque controls the average value of speed. The average reference speed will be the rated speed in order to keep the same cooling conditions and mechanical loss as in conventional loading [1].

The internal air-gap voltage of an unloaded induction machine is very close in magnitude and phase angle to the applied armature voltage and no load current is small. As the machine becomes loaded, the load angle increases and a larger armature current is produced. The principle of equivalent loading is to increase the internal load angle without connecting any mechanical load onto the shaft. The inertia of the rotor acts as an energy storing device [17].

The constant speed method keeps the flux speed constant and changes only its amplitude. This method works in much the same way as a transformer in which the primary and secondary windings are magnetically coupled by varying flux magnitude. A small oscillating torque will be produced due to interaction of rotor current and the resultant rotating flux. The rotor speed will be close to rated speed ensuring equivalent cooling conditions. In order to produce the flux magnitude oscillating around rated flux value a higher then rated voltage is necessary in DC link circuit [1].

The other method to produce artificial loading is the sweep frequency method [1], [9]. In this method the supply voltage of induction machine is the result of standard frequency modulation. This voltage, as in the two frequency method, produces a flux wave which varies both in magnitude and angular velocity.

For synchronous machines, there are two loading methods in artificial load: by sub-excitation or over-excitation, and active loading by passing repeatedly from the motor regime in generator regime.

The reactive loading presents the advantage that it only intervenes upon excitation, so it will be adjusted small powers. The synchronous machine can be reactively loaded by sub-excitation or over-excitation, according to the excitation currents I_{min} and I_{msx}. These currents being different by the rated value, the condition to have the same losses distribution is not respected. The average heating of the excitation winding can be achieved if the machine passes periodically form a loading regime to the other.

Thus, during t_{sub} the current through excitation will have the value I_{min} and during $T-t_{sub}$ will have the value I_{max}. The period T will be chosen in such way that the duration of the transitory processes to be negligible against the duration of the stabilized process and sufficiently small compared with the thermal time constants of the machine.

The active loading is achieved by accelerating the machine in motor regime, than braking in generator regime. During loading, the machine's speed is oscillating around the rated speed. Loading is achieved by controlling the internal angle θ by means of a voltage inverter and a control system. The position of d-axis can be known either using a position transducer, or is estimated knowing the machine's parameters and the variation dynamics of currents and voltages.

The reactive loading can also be done by means of a voltage inverter that modifies the stator voltage (it increases it in the sub-excited regime and decreases it in over-excited regime in such way that the operation point at rated current to be within the stability field, respectively the excitation current to not reach to high values).

The synthetic on-load charging of the DC machines is achieved by producing an oscillating couple that has the average value approximately equal to zero and amplitude close to the rated value. This condition is met if the average couple developed in the machine equals the couple of mechanical losses produced when the machine operates at rated speed. For the DC machines with separate excitation, in derivation or with permanent magnets, the artificial load can be obtained by supplying from a 4-quadrant chopper or by connecting the machine between two branches of a three-phased inverter. Occurrence of some small errors in estimating the mechanical losses depending on speed is producing high deviations of the average speed. Is imposed the utilization of a speed regulator, and for speed's control can be used a speed transducer or a speed estimator.

At the DC machines with serial excitation is needed an additional voltage source, of reduced value and high currents, which during the test to supply separately the excitation and to have the possibility of voltage adjustment. Utilization of a single chopper for testing of some machines with much different voltages is possible by adapting the variator's supply voltage to the rated voltage of the tested machine, or only by adjusting the variator's output voltage. By using of a three-phased inverter, with the 3^{rd} branch can be achieved the source in commutation for supplying the serial excitation winding.

❖ DIAGRAMS FOR EXPERIMENTAL TESTS

A. Synthetic loading for induction machine. The first block diagram of the dual frequency method is presented in fig. 2. Autotransformer (AT) plays the role of the base source supplying the voltage with the constant frequency f_1 = 50Hz. Static frequency converter (SFC) supplies a voltage with variable amplitude and frequency f_2, and plays the role of an auxiliary source which gives the power of the machine that can be loaded. Adapting block controls the level of the signals provided by the transducers to the input of the data acquisition system, which acquires analog signals and convert them to digital. The computing system compares the data received from the transducer to the default set of the loading machine and controls the change of the voltage sources' parameters until one obtains the default value of the artificial charge. The shunts play the role of current transducers.

In fig. 3 is presented another system for synthetic loading [17]. The driver motor D_0 is on the same shaft with generators G_1 and G_2. Generator G_1 of system (1) is rated at the maximum power rating P_{max} of the test rig (highest motor rating to be tested), and feeds the motor M_1 under test. The test motor could be either a wound rotor machine or a squirrel cage machine. Both the generator G_2 and the recovery machine M_2 of the system (2) are rated at P_{max}. If the field modulation of each generator is in opposition of phase, the power generated by each system is also in opposition of phase and, therefore, when one system absorbs power, the other generates it and vice-versa. By adjusting the magnitude of the excitation swing of generator G_2, one can adjust the power exchange with system (2) to exactly match the power swing of system (1). When this equilibrium is reached, the driver motor D_0 needs to provide only the losses in all five machines. Driver D_0 is preferably a synchronous motor, but can be a DC motor or an induction motor with low slip. In the latter case, the motor would have to be slightly over rated in order to perform the test at close to synchronous speed. It's been shown that the optimal performance to reach full rated load is achieved with a 10 Hz modulation depth (55 to 65 Hz).

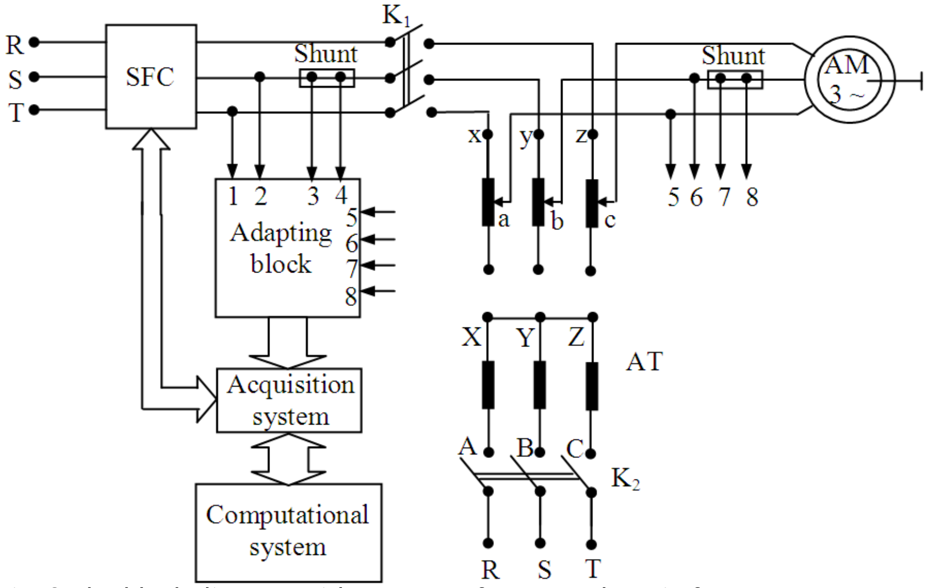

Fig. 2 The block diagram with autotransformer and static frequency converter

Fig. 4 presents the diagram of artificial loading using a single supply source. The static frequency converter (SFC) is supplied from the power system and is controlled by a computing system.

The frequency converter supplies the induction machine with the free shaft. Before the start, in the computing system are introduced the prescribed values. Depending on the rated speed $n_{N,}$ is chosen the maximum speed n_{max} and minimum speed n_{min} values. The values of voltage and current are controlled by the computer with the adapting block and transducers.

The power delivered towards the SFC in the generating period is consumed by the broke resistance in the DC link of SFC. The speed can be adjusted until the rated value is obtained.

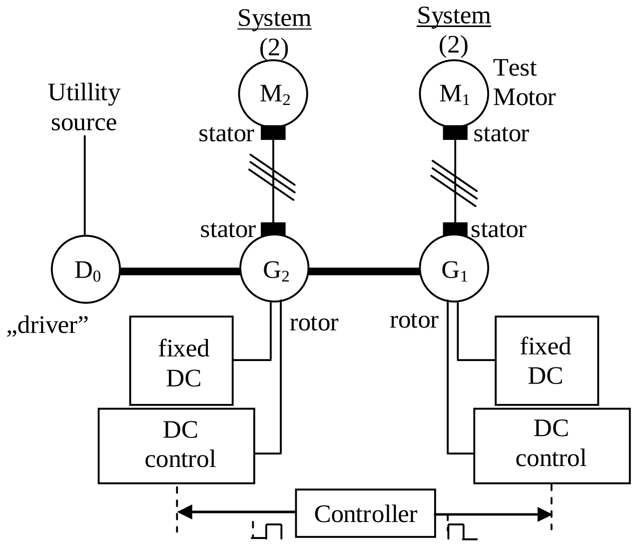

Fig.3 Diagram for large induction machines with no feedback into the power system

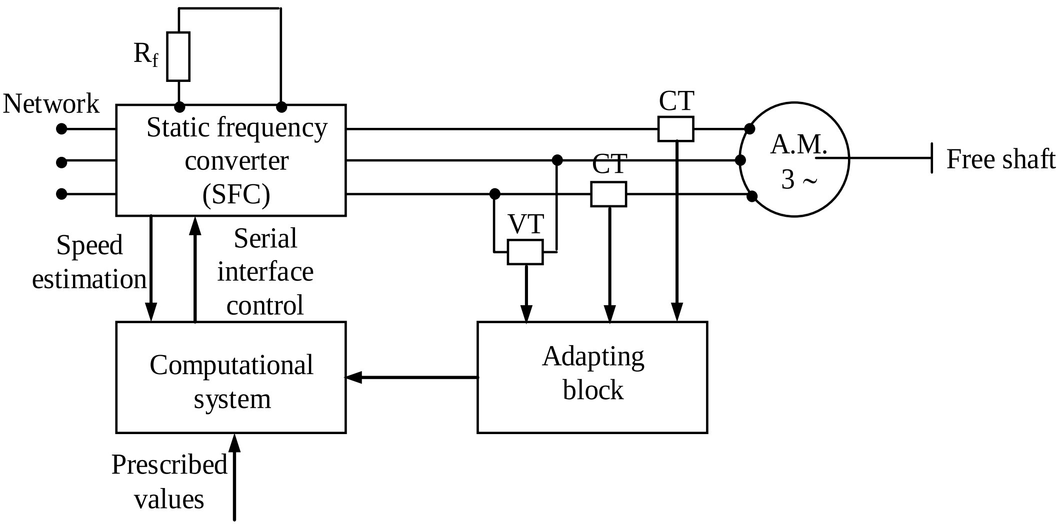

Fig. 4 Artificial loading of induction machine using a single supply source

B. Synthetic loading for synchronous machines

The diagram presented in fig. 5 allows the utilization of the synthetic charge of the synchronous machines (SM) both by using the reactive loading method and the active loading method. The AC/DC converter allows the excitation's supply both in sub-excited regime and in over-excited regime, and the static frequency converter (SFC) allows the modification of the voltage and stator frequency. The rotor position is obtained by means of a position transducer.

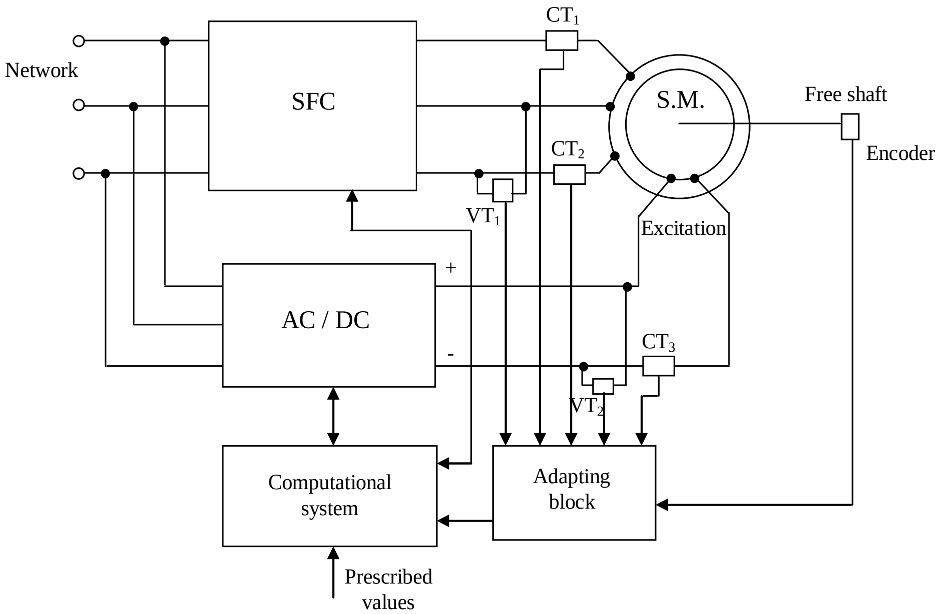

Fig.5 Reactive and active artificial loading for synchronous machines

C. Synthetic loading for DC machines

A synthetic on-load charging diagram of the DC machine using a 4-quadrant chopper is presented in fig. 6.

For a DC machine perfectly compensated, the induced voltage is directly proportional with speed. The proportionality factor between voltage and current is the flux produced by excitation which can be read from a table depending on the measured current.

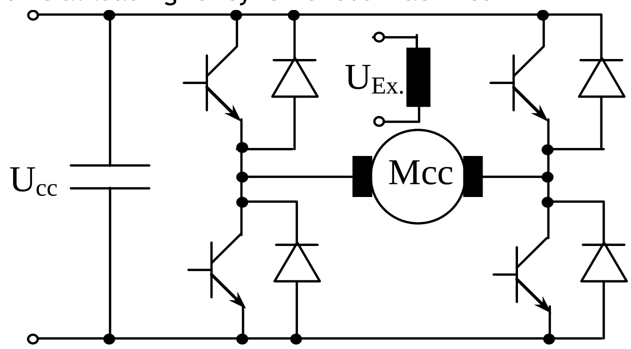

Fig.6 Artificial loading with DC machine by using 4Q chopper

❖ EXPERIMENTAL RESULTS

The test machine was an induction motor with the following rated values: shaft power P_N = 2,2 kW, voltage U_N = 380 V, speed n_N = 1420 rpm, current I_N = 4,7 A, stator winding resistance R_1 = 2,75 Ω, rotor winding R_2 = 2,1 Ω at 20^0C and R_1 = 3,7 Ω, R_2 = 2,85 Ω at 90^0C. The temperature of the stator winding was measured using electrical sounders.

In table I we present the variation of the loading current, average speed, voltage and efficiency as a function of the source's frequency.

Table I

Frequency [Hz]	Average speed [rpm]	Voltage U[V]	Loading current I[A]	Efficiency [%]
45	1445	377,6	4,75	84,9
46	1450	378,2	4,73	85,2
47	1447	378,6	4,77	85,4
48	1453	379,1	4,8	85,6
49	1441	379,5	4,66	85,9
50	1420	380	4,68	86,2
51	1418	379,9	4,72	86,15
52	1425	380,2	4,71	86,0
53	1433	380,1	4,73	85,9
54	1435	380,3	4,74	85,7
55	1438	380	4,725	85,1

The final over-temperature on artificial loading was higher than for shaft loading and sinus supply by about 5^0C (10 %) for windings and about 6^0C (12 %) for core. The voltage supply from inverter source contains high harmonics which are increasing the core losses and copper losses.

The main problem indentified during the experimental port was the need for a closed-loop control to maintain the constant ratings on the test motor and the matching power exchanged with the recovery system.

Further this, the variation of efficiency with auxiliary frequency is only small, namely 1% as shown in Table I. The friction and winding losses will only be marginally higher since the average speed during synthetic loading is near to the rated speed.

❖ CONCLUSION

The artificial on-load testing of the rotating electric machines is a modern solution for the simple verification, low-cost, of parameters and characteristics. In the specialty literature is insisted more on testing the induction machines, but of great interest becomes the testing of the synchronous machines and DC machines, including the ones where the inductor field is produced with permanent magnets.

Synthetic loading, the two frequency method, dynamic thermal loading and the constant speed methods of evaluating the efficiency of electric machines has been confirmed, using computer modeling and simulation techniques, as accurate, and able to indentify the total losses in the machine under test. Experimental results agree with the modeled synthetic loading and measured steady-state efficiencies.

❖ REFERENCES

[1.] I. Boldea, L. Tutelea and Klumpner C., "Artificial loading of induction machines: a review", Workshop on Electrical Machine's Parameters, Technical University of Cluj-Napoca, 26th of May, 2001, pp. 9-14.

[2.] D.J. McKinnon and C. Grantham, "Experimental Confirmation of On-Site Efficiency Evaluation of Three-Phase Induction Motors using Synthetic Loading Techniques", Australasian Universities Power Engineering Conference AUPEC 2004, 26-29 September 2004, Brisbane, Australia, pp. 78-83.

[3.] D. McKinnon, D. Seyoum and C. Grantham, "Novel dynamic model for a three-phase induction motor with iron loss and variable rotor parameter considerations", Journal of Electrical & Electronics Engineering, Australia, Vol. 22, No. 3, The Engineers Australia College of Electrical Engineers, 2003, pp. 219 - 225.

[4.] D.J. McKinnon, D. Seyoum and C. Grantham, "Investigation of parameter characteristics for induction machine analysis and control", Conf. Proc. Of the Second International Conference on Power Electronics, Machines and Drives, (PEMD 2004), Universityof Edinburgh, UK, 31 Mar. – 2 Apr. 2004, pp. 320-325.

[5.] A. Ytterberg, "Ny method for fullbelasstning av electrisca maschiner utan drivmotor eler avlastningsmaskin", s.k. skakprov, Teknisktidskrift, 1921, S42-44.

[6.] P. Templin, M. Alacula, M. Gertmar, "Dynamic Thermal Loading of an inverter fed Induction Machine", IEEE /KTH Stocckhlom Power Tech. Conference, 1995, pp. 241-244.

[7.] P. Lesage, M. Alacula, L. Gertmar, "The dynamic thermal loading of an induction machine", Record ENE'97 vol.2 pp. 520-525.

[8.] C. Klumpner, I. Boldea, F. Blaabjerg, "Artificial loading of the induction motors using a matrix converter", Proceedings of PEMD London 2000, pp. 40-45.

[9.] C. Grantham and M. Sheng, "The synthetic loading of three-phase induction motors using microprocessor controlled power electronics", Record IEEE Catalogue No. 95TH8025/1995, pp. 471-476.

[10.] D.J. McKinnon and C. Grantham, "Modeling of synthetic loading for efficiency evaluation of three-phase induction motors", Proc. AUPEC 2003, Christchurch, New Zeeland, 28 Sept. – 1 Oct. 2003.

[11.] C. Grantham, "Full load testing of three phase induction motors without the use of a dynamometer" ICEMA, 14-16 September 1993 Adelaide Australia, pp. 147-152.

[12.] S. Garvey, I. Kolak and M.T. Wright, "Aspect of mixed frequency testing for induction machines", Record of ICEM-1994, D14, Paris, France.

[13.] I. Boldea, L. Tutelea and N. Muntean, "A new approach to inverter-fed mixed frequency testing of induction machines", Proc. Electromotion'97, Cluj-Napoca, Romania, pp. 82-87.

[14.] L. Tutelea, I. Boldea, E. Ritchie, P. Sandholdt and F. Blaabjerg, "Thermal testing for inverter-fed induction machines using mixed frequency method", Proceedings of ICEM'98 Istanbul, vol.1, pp.248-253.

[15.] M. Biriescu, "Testing elements of electric machines", Politechnica Publishing House, Timisoara, Romania, 1994 (in Romanian).

[16.] S.I. Deaconu, G.N. Popa and L. Gherman, "Diagram for artificial charge loading of asynchronous machine and the study of the influence of the frequency change on the charge loading", Buletin of Politechnic Institute of Iasi, Tom XLVIII, Fasc. 5, 2002, pp. 127-130.

[17.] J. Soltani, B. Szabados, and Gerry Hoolboom, "A New Synthetic Loading for Large Induction Machines With No Feedback Into the Power System" IEEE Transactions on Energy Conversion, Vol. 17, No. 3, September, 2002, pp. 1-7.

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