Comparative Study of Three-phase, Two-phase and One-phase Impedance Tests for Induction Machines

Milan Radić[1], Milica Rašić[2] and Zoran Stajić[3]

Abstract – **This paper presents experimental results obtained using different types of impedance tests, performed on three-phase induction machines. Four different induction machines, with rated power of 0.18 kW, 1.5 kW, 3.7 kW and 7.5 kW were tested. The first type of applied tests was the standard three-phase impedance test, based on utilization of symmetrical three-phase power supply. Two other types of tests can be considered as modifications of standard test method, and they are based on utilization of single-phase power supply. With that type of power supply, two phases of stator winding were energized (two-phase impedance test), or just one phase was energized (one-phase impedance test). Obtained results have shown that the equivalent circuit parameters, calculated using measurements from three-phase and two-phase impedance test, are in excellent agreement for all tested machines. On the other side, parameters calculated using data from one-phase impedance test have always been substantially lower.**

Keywords – **Induction machine, Impedance test**

I. INTRODUCTION

Identification of three-phase induction machine equivalent circuit parameters is of crucial importance for any type of performance analysis, or for implementation of some control system. The IEEE standard 112 defines exact experimental procedures and calculations that should be performed in order to obtain accurate parameters of the machine's equivalent circuit. Mentioned procedures require combined usage of results recorded during no-load test and impedance test ([1]). Detailed analysis of formulae given in [1] suggests that, no matter which one of four standardized impedance test methods has been exploited, precise calculation of parameters in the stator and the rotor branch of the equivalent circuit should include the influence of the magnetizing branch. On the other hand, in majority of relevant textbooks, some simplified calculation approaches are given ([2-4]). Most authors suggest that the influence of the magnetizing branch can be neglected during the analysis of data obtained from the locked rotor test (which is „impedance test", if terminology from [1] is being used). Regardless of the actual calculation method, default premise is that a three-phase induction machine is powered from a balanced, three-phase variable voltage source. Such situation requires that rotor of the machine has to be mechanically blocked, because the starting torque developed due to the three-phase supply tends to cause rotation.

In order to avoid rotation during the impedance test, some authors propose utilization of single-phase power supply, using the term „single-phase test". No starting torque is then produced, while the electric behavior of the machine is expected to be the same as in the case of three-phase excitation ([5, 6]). However, careful analysis of mentioned references reveals that different authors have different consideration of single-phase excitation. In [5], single-phase test means that single-phase supply is applied on two phase windings connected in series, while in [6] only one phase winding is energized.

The goal of the work presented in this paper was to investigate the influence that specific configuration of energized windings could have to obtained numerical results. For this purpose, single-phase supplying of two stator windings connected in series has been regarded as the „two-phase" impedance test, while single-phase supplying of the single stator winding has been regarded as the „one-phase" impedance test. Obtained results have been compared with results originating from the standard three-phase impedance test at the rated frequency, and conclusions are given.

II. MATERIALS AND METHODS

A. Machines used for experimental work

Three-phase, two-phase and one-phase impedance test were performed on each of four induction machines, whose nameplate data are given in this subsection:

Machine A:

$P_n = 0.18\,kW$, $U_n = 380\,V$, $f_n = 50\,Hz$, $I_n = 0.65\,A$,

$n_n = 885\,\mathrm{min}^{-1}$, $\cos\varphi_n = 0.75$, stator Y, cage rotor.

Machine B:

$P_n = 1.5\,kW$, $U_n = 380\,V$, $f_n = 50\,Hz$, $I_n = 3.2\,A$,

$n_n = 2860\,\mathrm{min}^{-1}$, $\cos\varphi_n = 0.86$, stator Y, cage rotor.

Machine C:

$P_n = 3.7\,kW$, $U_n = 380\,V$, $f_n = 50\,Hz$, $I_n = 8.4\,A$,

$n_n = 1400\,\mathrm{min}^{-1}$, $\cos\varphi_n = 0.79$, stator Y, wound rotor.

Machine D:

$P_n = 7.5\,kW$, $U_n = 380\,V$, $f_n = 50\,Hz$, $I_n = 15\,A$,

$n_n = 1460\,\mathrm{min}^{-1}$, $\cos\varphi_n = 0.87$, stator Y, cage rotor.

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[1] Milan Radić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: milan.radic@elfak.ni.ac.rs

[2] Milica Rašić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: milicarasa@gmail.com

[3] Zoran Stajić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: zoran.stajic@elfak.ni.ac.rs

B. Connection diagrams

During all experiments, tested machines were supplied with a voltage U, lower than the rated value U_n, using regulated three-phase autotransformer. Frequency of the applied voltage was equal to the frequency in the electric network, $f = 50\,Hz$. Voltages, currents, active and reactive power were measured using three-phase digital laboratory network analyzer. Used measuring device also enables direct reading of the actual power factor value.

Connection diagram for the three-phase impedance test is given in Fig. 1.

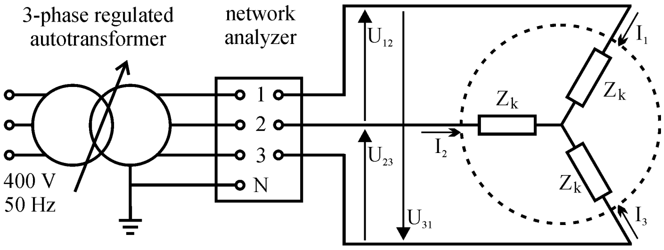

Fig. 1. Connection diagram for the 3-phase impedance test

For the two phase impedance test, connection diagram is given in Fig. 2. Note that two phase windings are connected in series and they are supplied using just one phase of the regulated autotransformer.

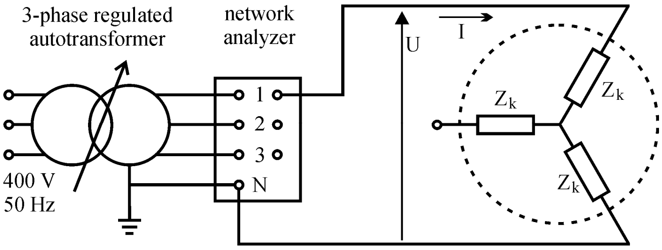

Fig. 2. Connection diagram for the 2-phase impedance test

Finally, connection diagram for the one-phase impedance test is shown in Fig. 3. In this case, current flows only through one phase winding, while other two windings are not energized. Since all tested machines have Y connected stator, neutral point of the regulated autotransformer has been directly connected to induction machine's neutral point.

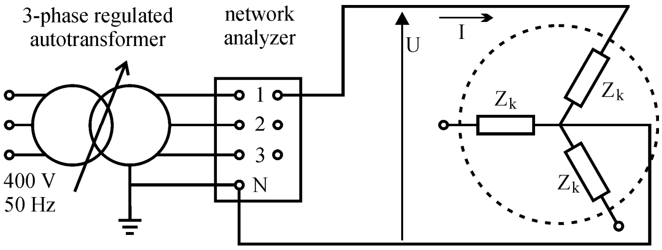

Fig. 3. Connection diagram for the 1-phase impedance test

C. Calculation of parameters Z_k, R_k and X_k

If the standard 3-phase impedance test is performed, while the rotor is mechanically blocked (see Fig. 1), total impedance per phase can be calculated as

$$Z_k = U / \sqrt{3} I \qquad (1)$$

where U is the average value of voltages between phases, calculated as

$$U = (U_{12} + U_{23} + U_{31}) / 3 \qquad (2).$$

and I is the average value of measured currents,

$$I = (I_1 + I_2 + I_3) / 3 \qquad (3)$$

Note that all four tested machines have Y connected stator, which means that the current calculated using Eq. (3) is also the average value of actual currents flowing through the stator windings.

If the 2-phase impedance test is exploited, according to the connection diagram shown in Fig. 2, total impedance per phase is calculated as

$$Z_k = U / 2I \qquad (4)$$

where U represents effective value of the applied single-phase voltage, while I is effective current flowing through the series connection of two stator phase windings.

Finally, for the case of the 1-phase impedance test, from Fig. 3, it is clear that the total impedance per phase is given by

$$Z_k = U / I \qquad (5)$$

Regardless of the exploited type of impedance test, total resistance per phase R_k, and total reactance per phase X_k have been calculated using simple formulae

$$R_k = Z_k \cdot \cos\varphi_k \qquad (6)$$

$$X_k = Z_k \cdot \sqrt{1 - \cos^2 \varphi_k} \qquad (7)$$

where $\cos\varphi_k$ is the actual value of power factor, measured by laboratory network analyzer.

III. EXPERIMENTAL RESULTS

Measured electrical quantities are presented in Tables I, II, III and IV, along with calculated values of total impedance per phase Z_k, total resistance per phase R_k and total reactance per phase X_k. Distinct segregation of R_k and X_k on stator and rotor parameters was not performed, since such action was not necessary at this stage of investigation.

Calculated values were then expressed in p.u., using a relevant parameter (Z_k, R_k or X_k) obtained from the standard 3-phase impedance test of the analyzed machine, as a normalization base. Results are shown in Figs. 4, 5 and 6.

Table I
Machine A: 0.18 kW, cage rotor

parameters		3-phase test	2-phase test	1-phase test
measured	U [V]	123.55	141.38	60.79
	I [A]	0.653	0.645	0.649
	$\cos\varphi_k$	0.763	0.764	0.78
calculated	Z_k [Ω]	109.24	109.54	93.67
	R_k [Ω]	83.32	83.71	73.11
	X_k [Ω]	70.65	70.66	58.56

Table II
Machine B: 1.5 kW, cage rotor

parameters		3-phase test	2-phase test	1-phase test
measured	U [V]	53.51	63.06	25.41
	I [A]	3.206	3.245	3.146
	$\cos\varphi_k$	0.642	0.638	0.699
calculated	Z_k [Ω]	9.64	9.72	8.07
	R_k [Ω]	6.19	6.20	5.65
	X_k [Ω]	7.39	7.48	5.77

Table III
Machine C: 3.7 kW, wound rotor

parameters		3-phase test	2-phase test	1-phase test
measured	U [V]	81.06	93.59	39.23
	I [A]	8.436	8.449	8.429
	$\cos\varphi_k$	0.463	0.469	0.468
calculated	Z_k [Ω]	5.55	5.54	4.65
	R_k [Ω]	2.57	2.6	2.18
	X_k [Ω]	4.92	4.89	4.11

Table IV
Machine D: 7.5 kW, cage rotor

parameters		3-phase test	2-phase test	1-phase test
measured	U [V]	82.35	93.57	37.43
	I [A]	14.278	13.967	14.21
	$\cos\varphi_k$	0.337	0.341	0.383
calculated	Z_k [Ω]	3.33	3.35	2.63
	R_k [Ω]	1.12	1.14	1.01
	X_k [Ω]	3.14	3.15	2.43

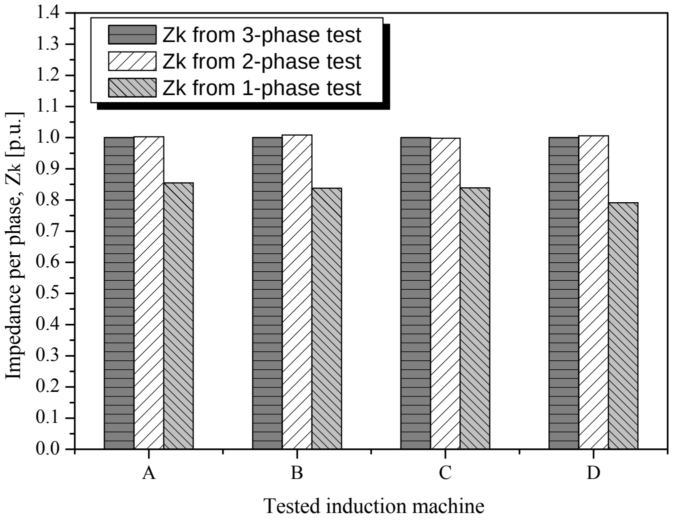

Fig. 4. Relative values of total impedances

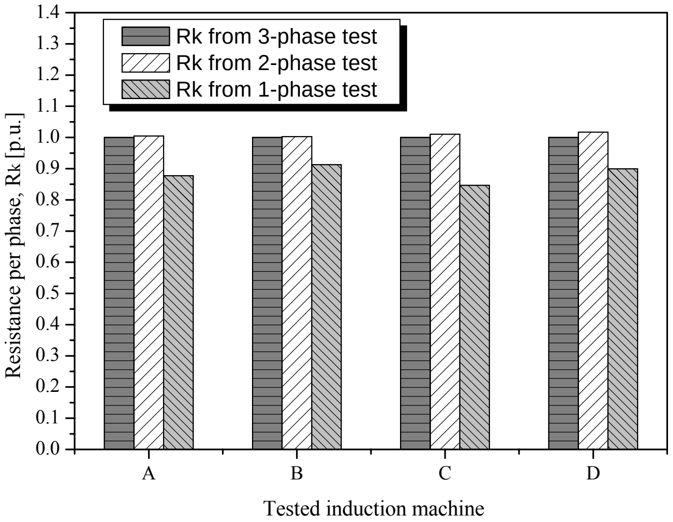

Fig. 5. Relative values of total resistances

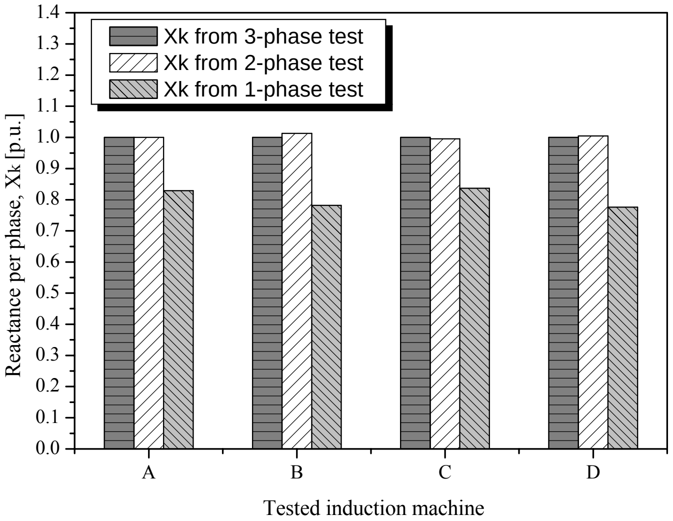

Fig. 6. Relative values of total reactances

IV. DISCUSSION

Observing relative values of total impedances per phase shown in Fig. 4, one can conclude that results obtained from the standard 3-phase test and from the 2-phase test are in excellent agreement. For two of tested machines (A with cage rotor, and C with wound rotor), it is almost impossible to notice any difference. For two other machines (B and D, both with cage rotor), a slight disagreement between total impedances obtained from 3-phase and 2-phase test can be seen. However, it is not higher than 1%, and can be neglected. On the contrary, results for total impedance per phase obtained from 1-phase test have always been significantly lower compared to those from 3-phase and 2-phase test. As it can be seen in Fig. 4, for machines A, B and C deviation is about 15%, while for the machine D it reaches almost 20%.

Considering values of total resistances per phase, shown in Fig. 5, similar conclusions can be made. The standard 3-phase test and the 2-phase test have given almost identical results. The highest deviation has been noticed for the machine D, but it is still less than 2%. Results for total resistance obtained using data measured during the 1-phase test have been notably lower, with deviation greater than 10%.

Looking at Fig. 6, almost the same conclusion can be made when values of total reactance per phase are taken into consideration. All results for total reactances per phase are in a good agreement when the 3-phase test is compared to the 2-phase test, while results from the 1-phase test are significantly lower.

Presented results could be explained by the fact that space distribution of the magnetic field inside an induction machine is not identical during standard 3-phase, 2-phase and 1-phase impedance test. However, it seems that differences in the magnetic field distribution are smaller, or at least have less influence to the final results, when 3-phase and 2-phase impedance tests are being compared. For the case of the 1-phase impedance test, space distribution is significantly different (only one third of the complete stator winding is energized), thus leading to notable deviation in obtained results.

These results are valid for the rated value of frequency applied to the stator of the machine. Knowing that frequency can affect values for rotor winding resistance obtained during an impedance test (due to deep-bar effect), it will be of interest to investigate if the value of the applied frequency has some significant influence when 3-phase, 2-phase and 1-phase impedance tests are compared.

V. CONCLUSION

According to results presented in this paper, standard 3-phase impedance test (which demands mechanical blocking of machine’s rotor), can be substituted by the modified, 2-phase test, without any important data being lost. It has been shown that results obtained using 3-phase and 2-phase impedance tests are in excellent agreement. For the case of the 1-phase impedance test, where only one phase of the stator winding is being energized, measured data do not give accurate results after calculations, and this type of the test should be avoided.

In the future work, it could be investigated if 3-phase and 2-phase impedance tests, performed at a frequency of the applied voltage different than the rated frequency, will still have similar output, or obtained results will be in an unacceptable disagreement.

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