Comparison of Superposition Equivalent Loading Methods for Induction Machine Temperature Tests

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***Abstract*— The superposition equivalent loading method proposed by international standards for testing induction machines allows to conduct temperature tests at reduced different conditions than rated and extrapolate the results to rated values. Much as this test is suitable for large machines that test facilities lack capacity to test, the principle is also applicable to small machines. However, its applicability to small machines has not been extensively studied yet. Furthermore, the three types of the method categorized in the standard IEEE 112-2017 have not been compared to establish their equivalence or otherwise. This paper reports an extensive test campaign on different small size induction motors to determine both the applicability of the method to small machines and to compare the equivalence of the three types of approach. Multiple reduced voltage and reduced current selections have also been investigated to assess the accuracy of the methods for different test conditions. Test results show that all the three alternative loading methods proposed by the standard seems to be practically equivalent, whit a goodness of fit of the obtained results that tends to improve as the machine rating increases.**

Keywords*— *Induction machines, temperature test, load test, superposition equivalent loading method, steady state temperature

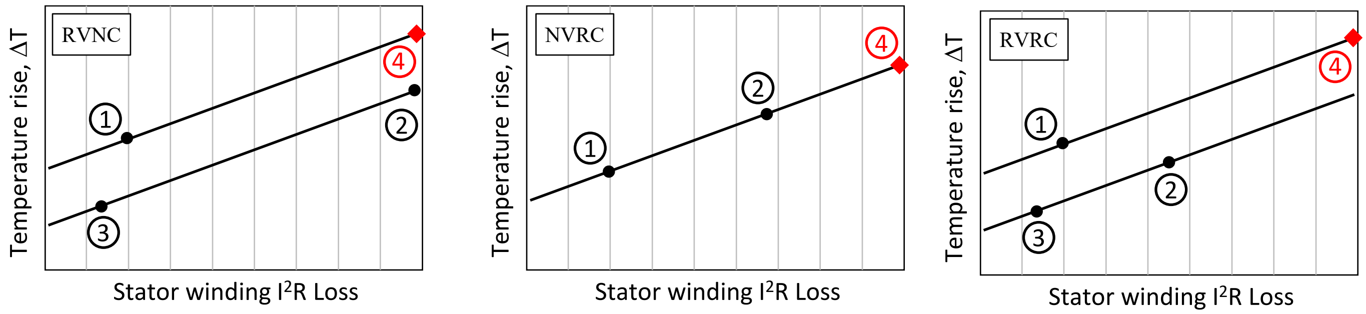
I. INTRODUCTION

Electric motor temperature tests are conducted by loading a motor at rated load until its temperature stabilizes. To load any machine, another machine of equal or larger rating must be available. Sometimes due to lack of capacity, these tests encounter challenges, especially for large machines. Because of this, methods to avoid or minimize these challenges are important [1]. The superposition equivalent loading method was developed to minimize these challenges for large machines [2]-[4]. There are several variations of this method, but the overarching goal is to conduct temperature tests at reduced capacity and extrapolate the results to rated machine conditions. The three main variations of the method include conducting the tests at reduced voltage or reduced current or at both reduced voltage and reduced current compared to the nominal quantities. The superposition method was introduced recently in a test standard and has been the subject of increasing research interest [5]-[8]. A critical assumption is that this method is suitable for large machines which intuitively makes sense. As a matter of fact, due to the number of tests involved in the superposition method, it will take a shorter time to conduct a direct loading heat run test on a small machine than a superposition equivalent load test. However, there is value in knowing that the test is equally valid for all machines. Since the method is based on linear superposition principle which should apply equally to all linear systems, it is reasonable to assume that small machines will behave in a similar way to large machines. However, the extent to which the method is applicable to small machines has not been well studied. In addition, the different variations of the superposition method have not been subjected to comparison to determine their equivalence. Indeed, past tests aimed at investigating the general applicability of the superposition equivalent loading method, resulted in much less promising results for low power machines [7]. Based on those results, the authors planned to perform an extended test campaign to comprehensively evaluate the utility of the three equivalent loading approaches for small size machines.

This paper conducts an evaluation and comparison of the superposition equivalent loading methods on three 4-pole, 50Hz Total Enclosed Fan Cooled (TEFC) Induction Motors (IMs) rated 11kW, 15kW and 18.5kW. These motors would be considered small size motors relative to the machines that the method is intended for (reasonably for machines larger than a hundreds of kW that may exceed laboratory equipment capability). All the three equivalent loading approaches identified in the IEEE 112-2017 standard have been applied to each motor, considering different reduced voltage and reduced current levels. This comprehensive test campaign allows to address the questions posed earlier as to the suitability of the method for small machines as well as to answer the question regarding the equivalence of the three methods for small IMs.

II. SUPERPOSITION EQUIVALENT LOADING METHODS

The standard considers the superposition equivalent loading approach as an alternative to the temperature test based on the actual loading method, and the obtained results have to be considered as a close approximation of the thermal conditions of the machines under rated conditions [5]. The fundamental idea of the method is to linearly extrapolate the temperature rise achieved from several separate tests conducted on the motor at reduced voltage and current conditions compared to their rated values for the machine.



(a) (b) (c)

Fig. 1: Superposition equivalent loading methods: (a) reduced voltage and nominal current – RVNC, (b) nominal voltage and reduced current – NVRC, and (c) reduced voltage and reduced current – RVRC. For each method, points 1, 2, 3 are the subtest meaasurements, point 4 is the estimated full load temperature rise [5].

TABLE I
SUBTESTS FOR THE DIFFERENT EQUIVALENT LOADING METHODS [5]

	All methods	RVNC method	NVRC method	RVRC method	RVNC & RVRC methods
	Subtest 1	Subtest 2			Subtest 3
Test conditions	No-load • Rated voltage • Rated frequency	Reduced load (such that I_L=I_{LN}) • Reduced voltage(1) • Rated frequency	Reduced load (such that $I_L \geq 0.7 I_{LN}$) (2) • Rated voltage • Rated frequency	Reduced load (such that $I_L \geq 0.7 I_{LN}$) (2) • Reduced voltage(1) • Rated frequency	No-load • Reduced voltage (as in subtest 2) • Rated frequency
Test outputs	ΔT_1 due to: • Stator I^2R at rated I_{S0} • No-load P_{iron} at rated V_S • Full f&w losses (3)	ΔT_2 due to: • Stator I^2R at rated I_S • Rotor I^2R at quasi-rated I_R • P_{iron} at reduced V_S • Full f&w losses	ΔT_2 due to: • Stator I^2R at reduced I_S • Rotor I^2R at reduced I_R • P_{iron} at nominal V_S • Full f&w losses	ΔT_2 due to: • Stator I^2R at reduced I_S • Rotor I^2R at reduced I_R • P_{iron} at reduced V_S • Full f&w losses	ΔT_3 due to: • Stator I^2R at reduced I_{S0} • No-load P_{iron} at reduced V_S • Full f&w losses

(1) The applied voltage at rated frequency shall be as high as practical using the available equipment.
(2) The absorbed stator current shall be as high as practical using the available equipment and preferably not less than70% of the rated current.
(3) f&w = friction and windage losses.

The IEEE 112-2017 standard reports three different methods for the superposition equivalent loading approach:

a) reduced voltage and rated (nominal) current (RVNC);
b) rated (nominal) voltage and reduced current (NVRC);
c) reduced voltage and reduced current approach (RVRC).

These three methods are graphically illustrated in Fig. 1 and are described in greater detail in [5]. Each method consists of a series of subtests with the machine supplied at rated frequency in no-load and load conditions until the thermal steady-state is achieved. Table I summarizes the test conditions and outputs for each subtest prescribed for the three superposition equivalent loading methods. The quantities to be measured are voltage, current, input power, and stator winding resistance and the temperature from embedded temperature detectors (if available). The machine losses and temperature rise over the ambient are determined at the test conditions and the results are extrapolated to obtain the temperature rise at rated load condition.

In the RVNC method three subtests are performed (Fig. 1a) – one load test at reduced voltage and reduced load such that the machine absorbs the rated current (point 2), and two no-load tests, one at full voltage (point 1) and the other at the same reduced voltage as the load test (point 3).

To estimate the temperature rise at the stator winding loss corresponding to the rated stator current (point 4), standard [5] reports the following formulations:

$$\Delta T_4 = \Delta T_1 + K \cdot (P_{SIR4} - P_{SIR1}) \tag{1}$$

$$K = \frac{\Delta T_2 - \Delta T_3}{P_{SIR2} - P_{SIR3}} \tag{2}$$

In (1) and (2), ΔT_n and P_{SIRn} are, respectively, the temperature rise and the stator Joule loss in the n–subtest. The stator winding loss P_{SIR1}, P_{SIR2} and P_{SIR3} can be easily calculated from the stator current and shutdown resistance measured in each subtest. On the other hand, the stator winding resistance for computing P_{SIR4} at the machine rated current I_4 depends on the temperature rise ΔT_4. Hence, the standard prescribes computing R_4 resistance by (3), where R_2 is the line-to-line resistance measured in subtest 2 and k_1 is the inferred temperature for zero resistance (k_1 = 234.5 for copper).

$$R_4 = R_2 \frac{k_1 + \Delta T_4 + 25}{k_1 + \Delta T_2 + 25} \tag{3}$$

Substituting in (1) and solving for ΔT_4 yields:

$$\Delta T_4 = \frac{\Delta T_1 + \frac{K \cdot 1.5 \cdot I_4^2 \cdot R_2}{k_1 + \Delta T_2 + 25} \cdot (k_1 + 25) - K \cdot P_{SIR1}}{1 - \frac{K \cdot 1.5 \cdot I_4^2 \cdot R_2}{k_1 + \Delta T_2 + 25}} \tag{4}$$

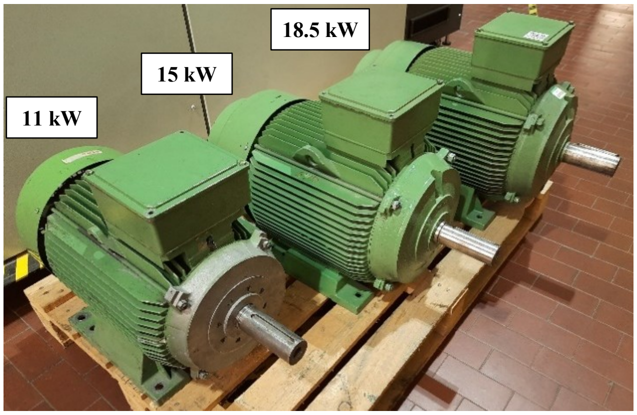


Fig. 2: The tested 4-pole, 50Hz TEFC induction motors.

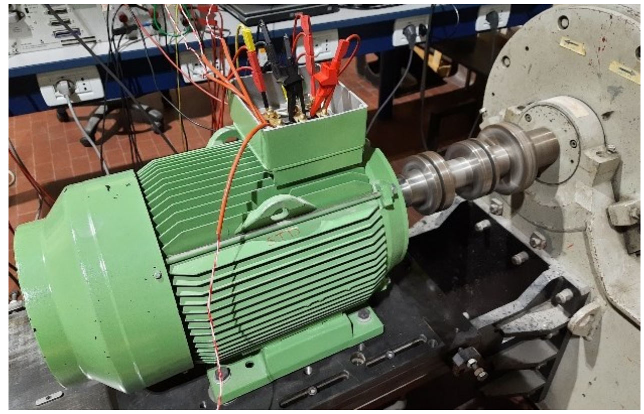


Fig. 3: The 15kW, 4-pole, 50Hz TEFC induction motor during the load test.

The selection of the reduced voltage level is loosely specified in the test standard, that suggests a voltage value as high as practical using the available equipment. Therefore, in [7] the authors extensively investigated the RVNC method, applying more than one reduced voltage point to understand the issues involved in the selection of the reduced voltage value. The results showed that the reduced voltage level has some effects on the final temperature that is achieved. It was observed that in some cases the impact was not significant and in other cases, the certain reduced voltage values tended to be too low for the machine to go through a complete temperature rise test.

In the NVRC method only two subtests are performed: (i) a no-load test at rated voltage, and (ii) a temperature test at rated voltage and reduced current that shall be higher as practical using the available equipment and preferably not less than 70% of the rated current. These two subtests can be respectively illustrated graphically as points 1 and 2 in Fig. 1b, and the temperature rise at full load condition (point 4) can be determined by linear extrapolation of the trend line through points 1–2. Hence, ΔT_4 can again be computed using (4), but in this case the value of K is given by (5).

$$K = \frac{\Delta T_2 - \Delta T_1}{P_{SIR2} - P_{SIR1}} \tag{5}$$

The RVRC method is like the RVNC method in that both comprise three subtests. However, the load test for the RVNC method is performed at the machine rated current, while for the RVRC method the load test is conducted at reduced current level. In Fig. 1c, the test points of the RVRC method are illustrated. Points 1 and 3 represent the test at no-load at rated voltage and reduced voltage, respectively. The value of reduced voltage is the same as would have been used to perform the temperature test, under load, of point 2 under the same method.

Comparing RVRC and RVNC methods, the graphical illustration for these methods would be similar and the main difference lies in the location of the load test point 2 for each of the methods. In the case of RVNC, point 2 is performed at full load current corresponding to higher Joule losses and higher temperature rise than for RVRC method. Because of the similarities between these two methods, the same analytical formulations (1)-(4) can be used also for the RVRC method.

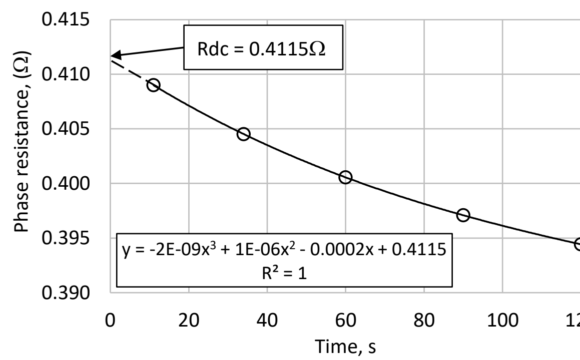


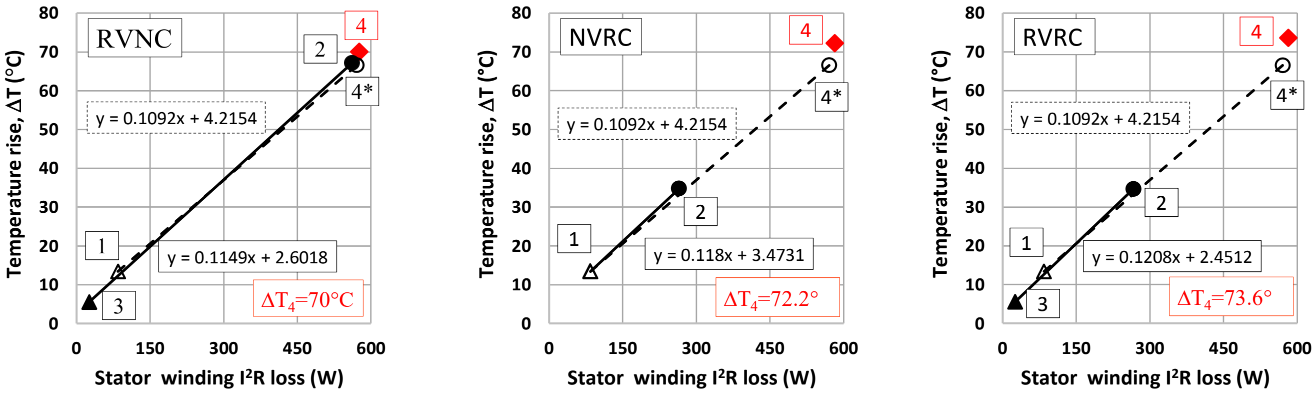
Fig. 4: Phase resistance measurement for the 11kW TEFC motor after subtest 2 for the RVNC equivalent loading test.

Substantially, the no-load test at nominal voltage (point 1) and the no-load test at reduced voltage (point 3) are the same for the three methods, while point 2 is performed at different test conditions according to the selected equivalent loading approach. In this study, all the three equivalent loading methods proposed by the standard are applied to different IMs to assess their applicability and repeatability.

III. Experimental Activity

The three alternative superposition equivalent loading methods proposed in [5] have been applied to the 4-pole, 50Hz TEFC induction motors shown in Fig. 2, rated 11kW, 15kW and 18.5kW, respectively. To perform measurements according to the different subtests, the IMs have been supplied using a sinusoidal variable voltage power source, while a brake machine controlled in torque has been used to apply different load levels, hence different absorbed stator current values for the machines under test. Figure 3 shows the 15kW motor on the test rig during the execution of a subtest in loaded condition.

All the tested IMs are also equipped with three thermocouples positioned in the end-windings, and one thermocouple positioned into the stator slot. During the conducted tests, these thermal sensors have been used only to monitor the machine temperature variation in order to determine whether the steady state thermal conditions have been achieved or not (1°C or less variation in temperature rise above the ambient temperature over a 30-minute period).



(a) (b) (c)

Fig. 5: Temperature rise for the tested 11kW IM for the three equivalent loading methods: (a) reduced voltage ($V_s = 0.7\ V_n$) and nominal current, (b) nominal voltage and reduced current ($I_s \cong 0.72\ I_n$), and (c) reduced voltage and reduced current ($V_s = 0.7\ V_n$ and $I_s \cong 0.72\ I_n$).

TABLE II

MEASUREMENTS FOR THE 11 KW – 50 HZ TEFC INDUCTION MOTOR

	Subtest 1	Subtest 2			Subtest 3	Full load test (4*)
Test condition	No-load	Load test			No-load	Load
Test method	All	RVNC	NVRC	RVRC	RVNC & RVRC	All
Supply voltage %	100%	70%	100%	70%	70%	100%
Line current %	-	100%	~72%	~72%	-	100%
Stator voltage, (V)	401.4	281.2	401.9	281.4	281.2	401.5
Line current, (A)	9.1	21.3	15.4	15.5	5.1	21.5
Input power, (W)	411	8730	7821	6291	213.5	12158
Stator winding I^2R loss, (W)	84	562	265	266.7	25.7	571
ΔT by *dc* shutdown resistance, (°C)	13.4	67.2	34.7	34.7	5.6	66.6

According to the outcomes of the research activity reported in [7], the temperature rise for the comparison of the equivalent loading methods have been evaluated by the stator winding *dc* resistance measured at shutdown. In detail, multiple readings at specified time intervals have been taken and the resistance value is extrapolated to the shutdown instant (see Fig. 4). To improve the measurement accuracy, this procedure has been used even if the first reading was within the maximum time delay prescribed by the standard for using a single measurement (30s for machines up to 50kVA) [9]. For instance, despite the first reading in Fig. 4 is within the 30s limit, the extrapolation at shutdown results in a temperature rise about 2°C higher than using the first reading only.

IV. EXPERIMENTAL RESULTS

The test campaign has been initially conducted selecting for each motor a reduced test voltage and current close to 70% of the rated values. Figure 5 shows the temperature rise versus the stator Joule losses measured for the 11kW IM according to the three superposition equivalent loading methods. In the plots point 4* is the temperature rise measured on the machine through a conventional load test at rated voltage and rated current, while point 4 (in red) is the value predicted by the corresponding equivalent loading method.

Of course, the equivalent loading method does not require measurements for point 4*, but for this research activity they have been done to evaluate the goodness of fit for the temperature rise predicted by the equivalent loading method versus the target point. Figure 5 also includes the linear trend lines that connect the subtests at rated conditions (points 1 – 4*, dashed lines) and those at reduces supply conditions (points 2 – 3, continuous lines). Table II reports the measured data for all the subtests conducted on the 11kW motor, including the full load test at rated voltage and rated stator current, for which a temperature rise equal to 66.6°C has been measured. The predicted temperature rise for each equivalent loading method has been calculated using (1)–(5) and are indicated in Fig. 5, while the corresponding stator winding loss (P_{SIR4}) have been estimated equal to 576W, 582W and 583W, respectively.

Despite all the three approaches predicted a temperature rise not far from the target point, the graphical representations in Fig. 5 clearly show that the results for the 11kW motor do not match the trends expected by the standard (see Fig. 1). In particular, for RVNC and RVRC methods a vertical shift between parallel lines that connect points 1–4 and points 2–3 was expected; subtest 2 for RVNC method resulted in a temperature rise even higher than the target value at full load. This inconsistency maybe due to the small difference in core losses when such a machine is supplied with 70% of the nominal voltage compared to rated conditions. Such a small difference may also be in the order of the measurement accuracy and slightly different results can even be obtained for multiple repetitions of the same test, as verified with the 11kW motor that has also been tested for the activities presented in [7].

Figure 6 and Table III report the results for the three equivalent loading methods conducted on the 15kW motor. The stator winding loss have been estimated equal to 556W, 557W and 564W, respectively.

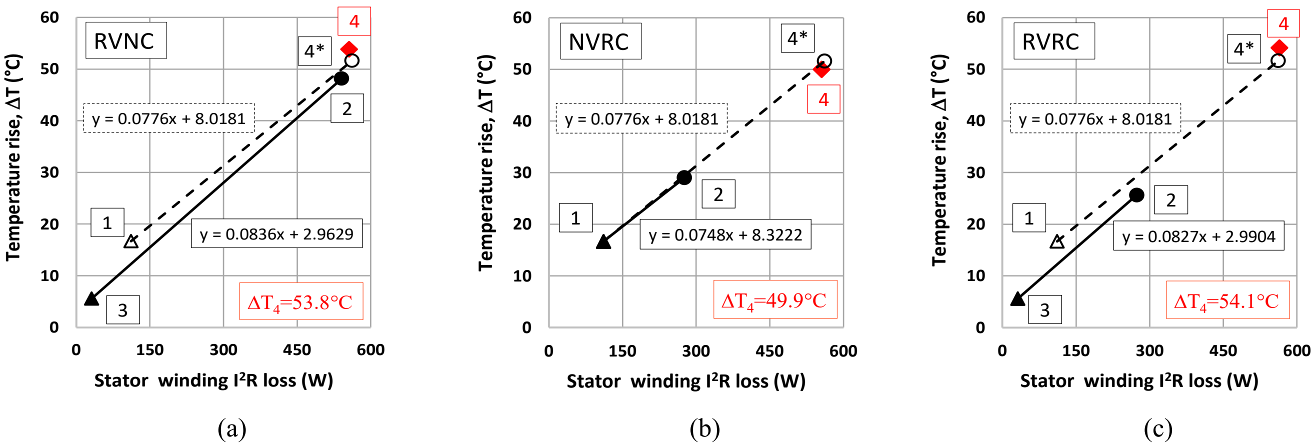


Fig. 6: Temperature rise for the tested 15kW IM for the three equivalent loading methods: (a) reduced voltage ($V_s = 0.7\ V_n$) and nominal current, (b) nominal voltage and reduced current ($I_s = 0.73\ I_n$), and (c) reduced voltage and reduced current ($V_s = 0.7\ V_n$ and $I_s = 0.73\ I_n$).

TABLE III

MEASUREMENTS FOR THE 15 KW – 50 HZ TEFC INDUCTION MOTOR

	Subtest 1	Subtest 2			Subtest 3	Full load test (4*)
Test condition	No-load	Load test			No-load	Load
Test method	All	RVNC	NVRC	RVRC	RVNC & RVRC	All
Supply voltage %	100%	70%	100%	70%	70%	100%
Line current %	-	100%	~73%	~73%	-	100%
Stator voltage, (V)	401.3	282.1	401.7	282.2	282.1	401.1
Line current, (A)	13.7	28.7	21.1	21.1	7.4	28.8
Input power, (W)	510	12377	10299	8875	222.8	16326
Stator winding I^2R loss, (W)	112	541	276	274	31.1	562
ΔT by *dc* shutdown resistance, (°C)	16.7	48.1	29.0	25.6	5.6	51.6

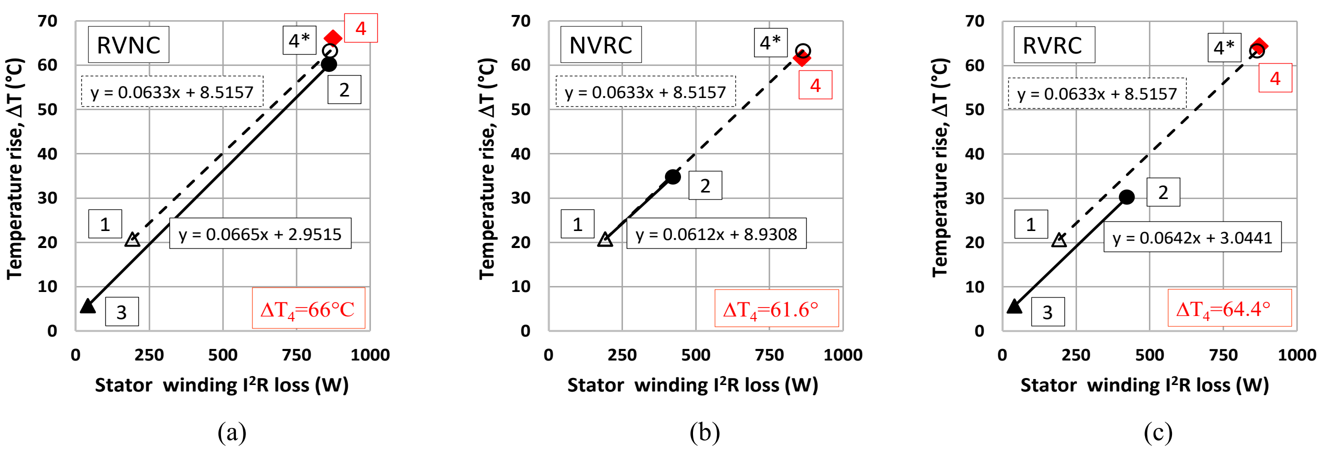


Fig. 7: Temperature rise for the tested 18.5kW IM for the three equivalent loading methods: (a) reduced voltage ($V_s = 0.7\ V_n$) and nominal current, (b) nominal voltage and reduced current ($I_s = 0.73\ I_n$), and (c) reduced voltage and reduced current ($V_s = 0.7\ V_n$ and $I_s = 0.73\ I_n$).

TABLE IV

MEASUREMENTS FOR THE 18.5 KW – 50 HZ TEFC INDUCTION MOTOR

	Subtest 1	Subtest 2			Subtest 3	Full load test (4*)
Test condition	No-load	Load test			No-load	Load
Test method	All	RVNC	NVRC	RVRC	RVNC & RVRC	All
Supply voltage %	100%	70%	100%	70%	70%	100%
Line current %	-	100%	~73%	~73%	-	100%
Stator voltage, (V)	401.5	282.1	401.0	282.1	282.3	400.7
Line current, (A)	18.8	37.1	27.1	27.3	8.9	37.0
Input power, (W)	844	16219	12973	11660	349	20991
Stator winding I^2R loss, (W)	193	861	422	423	40.9	864
ΔT by *dc* shutdown resistance, (°C)	20.7	60.2	34.8	30.2	5.7	63.3

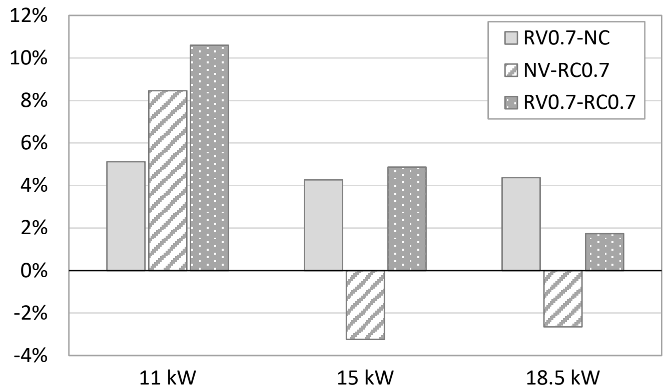


Fig. 8: Percentage errors vs. measurements for the full load temperature rise predicted by the three equivalent loading methods conducted on TEFC IMs.

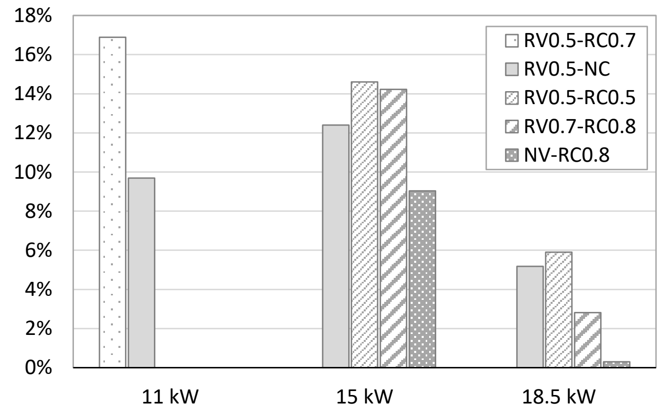


Fig. 9: Percentage errors vs. measurements for the full load temperature rise by the equivalent loading methods at different reduced voltage and current levels.

Compared to the previous case, for the 15kW motor both RVNC and RVRC approaches resulted in a better parallelism between the trend lines though points 1–4 and points 2–3; also point 2 in the NVRC well aligns with the other test points. The goodness of these results is also proven by the similar angular coefficients for the continuous and dashed trend lines in Fig. 6, confirming for this motor the validity of assuming a linear superposition to the temperature rise obtained by various combination of tests. Hence, shifting the continuous line in Fig. 6a and in Fig. 6c to pass through point 1 (conventional no-load test), a good prediction of the temperature rise in load conditions (point 4) can be obtained. Similarly, in Fig. 6b the prediction at full load is done by a linear extension of the trend line through point 1 and 2.

The results of the three equivalent loading methods well match the expectations also for the 18.5kW motor, whose measurements and predictions are summarized in Fig. 7 and Table IV. For this motor, the estimated stator winding loss resulted equal to 874W, 861W and 872W, respectively.

Comparing for the three tested IMs the predicted temperature rise with the measured values for the full load – rated conditions test, it is possible to notice that the result goodness tends to improve with the machine size. Indeed, looking at Figs. 5–7, point 4 (in red) falls closer to the target value (point 4*) for the 18.5kW and 15kW machines rather than for the 11kW motor. This trend is also highlighted by the bar diagram in Fig. 8 that reports the percentage errors of the predicted temperature rise versus measurements in full load conditions. In the figure legend, 0.7 approximates the above-mentioned reduced voltage/current levels used for these tests with respect to the rated machine values. The percentage errors resulted in the range 5–11% for the 11kW motor, while for the 15kW and 18.5kW the obtained errors are below 5%.

These outcomes show that comparable results are obtained for machines having similar rating. Therefore, it is reasonable to assert that the three equivalent loading methods can be considered practically equivalent for small-size IMs.

V. Assessment of Reduced Voltage and Reduced Current Levels

As aforementioned, the standard does not specify the reduced voltage and reduced current levels at which the different subtests have to be performed, but it only suggests values as high as practical with the available equipment. For only the NVRC method, a load level sufficient to absorb at least 70% of the machine rated current is preferred. Therefore, the test campaign on the three small-size IMs has been extended including different reduced voltage and current levels to assess their impact on the predicted temperature rise at full load.

Figure 9 reports the percentage errors of the predicted full load temperature rise versus measurements for the different combinations of voltages and currents which values are indicated in the figure legend. The bar graph shows that, regardless the current level, equivalent loading methods conducted at 50% of reduced voltage provided larger percentage errors compared to those at 70% voltage level. As discussed in [7], this may be due to a lower rotational speed of the rotor when small machines are supplied at lower voltage values, with consequent variations on the slip, the rotor Joule losses and on the friction and windage losses. Moreover, at different speeds also the cooling capabilities of TEFC motors varies. All these deviations with respect to the standard assumptions have impact on the results for small-size IMs. Tests with reduced voltage equal to 70% and reduced current equal to 80% (RV0.7–RC0.8), as well as tests with nominal voltage and 80% reduced current (NV–RC0.8) have also been conducted on the 15kW and 18.5kW motors. Figure 9 again confirms better results as the machine size increases. Note also that, compared to the results presented in Section IV, these additional tests provided higher percentage errors for the 11kW and 15kW machines, while comparable values have been obtained for the 18.5kW motor.

The experimental results obtained from this test campaign show that the superposition equivalent loading methods based on reduced voltage levels tend to provide precautionary estimations of the full load temperature rise, while by increasing the test voltage toward the rated value, the percentage errors tend to zero.

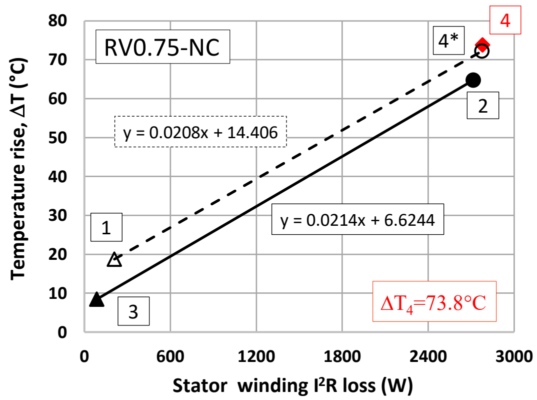


Fig. 10: Temperature rise for the 150kW ODP induction motor for the RVNC equivalent loading method at 0.75 V_n.

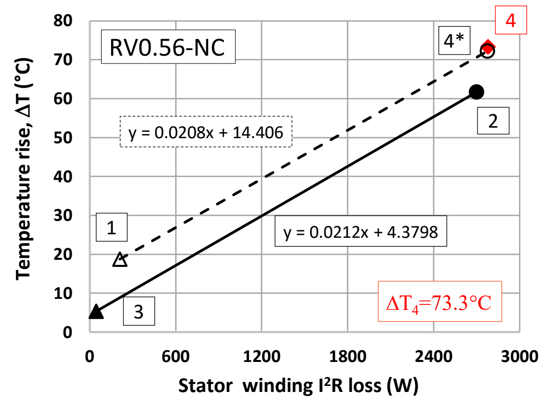


Fig. 11: Temperature rise for the 150kW ODP induction motor for the RVNC equivalent loading method with at 0.56 V_n.

VI. Test Results for a Medium-Size Induction Motor

In the frame of previous activities focused on the investigation of the RVNC equivalent loading method, a 150kW, 6-pole, 60Hz Open Drip Proof (ODP) induction motor was tested, selecting 75% and 56% as reduced voltage levels [7]. The obtained results are shown in Fig. 10 and Fig. 11, respectively and reported here for comparison. Note that, for this medium-size IM, the *dc* resistance at shutdown has been taken at a single measurement point within the time limit and not extrapolated. Both reduced voltage levels resulted in a good prediction of the full load temperature rise, with percentage errors approximately equal to 2% compared to the measured value of 72.2°C. Looking at Figs.9–10, also the estimated stator winding loss well agree with the measured value (2777W). It is interesting to observe that also for this machine the superposition equivalent loading method predicted precautionary full load temperature rise values compared to measurements. However, the percentage errors obtained for this medium size IM are roughly half than those obtained for small-size TEFC motors (see Figs. 8–9).

For the 150kW machine, the superposition equivalent loading method has also been verified using overtemperatures measured by embedded thermal sensors instead of the *dc* resistance, as permitted by the standard. Indeed, medium and large machines usually feature small stator winding resistances, and small differences in the measured values results in large variations in the estimated temperature. As reported in [7], the results obtained by embedded thermal sensors well confirm those by *dc* resistance measurements.

VII. Conclusion

The conducted test campaign revealed that the three superposition equivalent loading methods categorized in the standard IEEE 112-2017 are practically equivalent for application on small size IMs. Several tests conducted on 4-pole, 50Hz TEFC induction motors rated 11kW, 15kW and 18.5kW resulted in full-load temperature rise predictions having 4–10% percentage error compared to the measured target values. The goodness of fit for the obtained results tend to improve as the machine size increases. However, superposition equivalent loading methods conducted on medium– and large–size induction machines are expected to provide percentage errors in the range of 2%, as proven by measurements on a 150kW motor.

The conducted experimental investigation also considered multiple levels of reduced voltage and reduced current values to assess their impact on the predicted full load temperature rise. The outcomes show that for small-size IMs the superposition equivalent loading methods executed at low voltages tend to provide precautionary results compared to the measured target values; for higher voltage levels that are as close as possible to the rated value, the percentage errors between predictions and measurements tend to zero. The obtained test results show that, among the three alternative equivalent loading approaches, the RVNC method with a voltage level equal to 0.7V_n seems to be the most repetitive for machines in the range of tens of kWs, providing errors below 5%. Future activities will investigate the applicability of the superposition equivalent loading method also to inverter supplied machines. Indeed, the possibility of testing large machines at reduced voltage and current levels is particularly interesting for industry, because it can avoid the necessity of renting inverters for occasional validations on large machines. This would pave the way also for its use on testing large permanent magnets synchronous machines, synchronous reluctance and switched reluctance machines.

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