Comparison of Two Methods for Full Load In-Situ Induction Motor Efficiency Estimation from Field Testing in the Presence of Over/Under Voltages and Unbalanced Supplies

Arbi Gharakhani Siraki, *Student Member, IEEE,* Pragasen Pillay, *Fellow, IEEE*

***Abstract*— Numerous techniques with different level of intrusion and accuracy have been proposed for in-situ efficiency estimation. Among them, optimization based techniques and the air-gap torque method show promise when unbalanced supply conditions exist. In this paper, an optimization based algorithm is proposed for in-situ efficiency estimation of induction machines operating with over/under voltage and unbalanced supplies. In addition, a comprehensive study is done on the functionality and accuracy of the non intrusive air gap torque (NAGT) method which is claimed to be one the most promising methods in literature. It is shown that the efficiency calculated by this method under field conditions cannot be used in the decision making process on replacement of the existing machines as well as the relevant calculations regarding the payback period. The research is supported by experimental results on two different induction machines.**

***Index Terms*—Evolutionary algorithm, induction motor, in-situ efficiency estimation, over/under voltage condition, unbalanced supply, non intrusive air gap torque method**

I. Introduction

ELECTRICAL machines and more specifically induction motors utilize a significant portion of the generated power in industrialized and developing countries. Generally, the real working efficiency of these motors is significantly different from their rated efficiencies. This is due to the fact that these motors operate at 60% or less of their rated load conditions mainly because of oversized installations [1]. The efficiency of a motor also changes due to aging, over/under voltage conditions, unbalanced supplies and operating conditions. In-situ efficiency monitoring of the installed motors provides the opportunity to detect the motors with poor efficiencies and take the appropriate action. Replacement of an existing motor with a new efficient one is a solution which can lead to a significant energy savings. The efficiency of the existing machines should be measured with lowest intrusion level and highest accuracy under real operating conditions. This is generally different from the standard condition in terms of supply voltage magnitude, supply voltage unbalance and the loading condition. Since the efficiency of new machines is only available for standard test conditions, the comparison, energy savings and payback period calculations will be meaningful only if the efficiency of the existing machine in the plant can also be estimated for standard test conditions. However the operating conditions rarely meet the standard test conditions, so it is necessary to translate measurements in the field to standard test conditions. This is a very critical issue which is often neglected in literature.

Numerous methods are proposed in the literature for in-situ efficiency estimation of induction machines. These methods are as follows:

- Slip method
- Current method
- Simplified equivalent circuit method (such as the Oak Ridge National Laboratory method which is known as ORMEL96 [2]).
- Simplified loss segregation method (such as the method of Ontario Hydro [3]).
- Non intrusive air gap torque method [1]
- Optimization based methods[4]-[14]

Based on the NEMA MG1 standard, induction motors can operate with up to 5% unbalance voltages [15]. In addition, up to ±10% over/under voltage supply conditions are commonly seen in industrial facilities.

In real industrial conditions and specifically in weak power systems, the voltage unbalance factor or the over/under voltage rate can be even more severe. An unbalanced power supply occurring with a combination of over/under voltage conditions can significantly affect the machine's efficiency [15, 16]. Thus a method which is compatible with these conditions should be employed to have a reliable estimation of the efficiency under real industrial situations.

Only the last two methods are applicable in the real industrial conditions where some level of unbalanced and over/under voltage conditions exist. Unbalanced supplies can be present due to many reasons such as incomplete transposition of transmission lines, open delta transformers,

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A. Gharakhani Siraki is with the Electrical and Computer Engineering Department of Concordia University, Montreal, QC H3G 1M8, Canada (e-mail: arbi@ieee.org).

P. Pillay is with the Electrical and Computer Engineering Department of Concordia University, Montreal, , QC H3G 1M8, Canada and also an Adjunct Professor with the University of Cape Town, Cape Town, South Africa (e-mail: pillay@encs.concordia.ca).

blown fuses on three phase capacitor banks, unequal distribution of single phase loads, or defective transformers in power systems [15, 16].

In the non-intrusive air gap torque method [1], the air gap torque is calculated based on the voltage and current signals as well as the magnitude of the stator's resistance at the operating temperature. In this method the effect of the unbalanced voltages is considered on the net produced torque. However, the accuracy of this method is degraded due to the fixed assumption of the no load losses as well as stray load loss at different loading and supply voltage conditions.

Optimization based methods are another alternative for the efficiency estimation under real industrial conditions. In these methods the efficiency of the machine is calculated based on estimation of the parameters of the equivalent circuit of the machine with help of an optimization based search algorithm (such as Genetic Algorithm [4]-[12], bacterial foraging algorithm [13], multi-objective optimization [14]).

Based on a literature review, [4]-[10] present the optimization based techniques for efficiency estimation under balanced supply conditions. In [11] the equivalent circuit method is combined with the Genetic Algorithm (GA) to deal with the efficiency estimation problem under unbalanced supply conditions. In [12] the authors of this paper reported a new evolutionary based efficiency estimation algorithm which works with balanced and unbalanced supplies. In this paper, an extended version of the algorithm of [12] is proposed which is designed for efficiency estimation under real industrial conditions where machines work under some level of over/under voltage and unbalanced supplies.

The paper is organized as follows: the proposed evolutionary based efficiency estimation algorithm is presented in section II. Fundamentals of the air gap torque method are discussed briefly in section III. In the same section, the non-intrusive air gap torque (NAGT) method is discussed in detail and a comprehensive study has been presented on its functionality and accuracy. In section IV, the proposed evolutionary based efficiency estimation algorithm is used to estimate the efficiency of a 3 hp squirrel cage induction machine under unbalanced rated, unbalanced over-voltage and unbalanced under-voltage conditions. Unbalanced rated voltage and under voltage tests have been repeated in section V with an energy efficient 7.5 hp induction machine to verify the generality of the proposed method. The experimental results of the efficiency estimation with the non-intrusive air gap torque method (NAGT) and its modified version (MNAGT) under the same conditions are presented in the section VI and they are compared with results of the proposed evolutionary based method and the direct measured efficiencies from installed torque/speed sensor. The effect of assuming an empirical value for no load losses in the NAGT method is also investigated in this section. The summary and the conclusions are presented in section VII.

II. Fundamentals of the Proposed Algorithm

In this section, the fundamentals of the proposed evolutionary based efficiency estimation algorithm are discussed in detail. This algorithm is designed for efficiency estimation under real industrial conditions where machines work with over/under voltage and unbalanced supplies. Operation of a machine under an over-voltage or under-voltage condition alters the saturation level of the motor and thus changes the magnitude of the no load magnetizing current as shown in Fig. 1 for a 3hp induction motor with a nameplate data as shown in Table I.

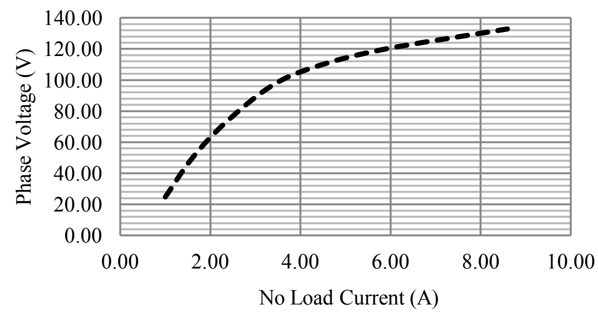

Fig. 1. No load phase voltage vs. no load current curve of the 3hp machine

TABLE I
NAMEPLATE DATA OF 3 HP INDUCTION MACHINE

f	60Hz	Design class	B
V_{LL}	208	Insulation class	B
I	10.3	Nominal speed	1740
Connection	Y	Poles	4

The change in magnetizing current is due to the change in the core losses and the mutual reactance as shown in Fig. 2 for the tested 3 hp machine. In this figure, V_m is the voltage across the magnetizing branch.

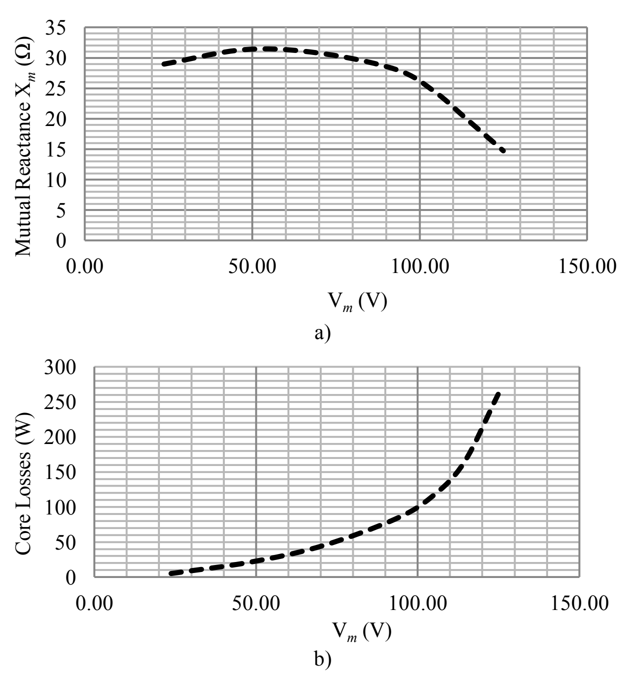

Fig. 2. a) Mutual reactance b) core losses vs. V_m for the 3 hp machine

In the presence of an unbalanced supply condition, unbalanced currents are produced in the machine. The unbalanced currents generate the positive sequence and negative sequence fluxes that lead to the positive and negative sequence torque components which act against each other.

The performance of an induction machine working under different magnitudes of source voltage and with some level of voltage unbalance can be presented by the positive and negative sequence equivalent circuits as shown in Fig. 3.

As can be seen in Fig. 3, the mutual reactance is considered as a variable component. More specifically, this component is considered as a function of "V_m" which is the voltage across the magnetizing branch. This is to model the change in core saturation level due to over/under-voltage conditions.

If all the parameters of the positive and negative sequence equivalent circuits are known, the efficiency of the machine can be estimated simply by solving the circuit and calculating the converted power at the known slip. To consider the effects of the voltage variation on the efficiency estimation process the change of the mutual reactance (X_m) with voltage shall be known. Based on IEEE 112 standard [17], the accuracy of this value is critical for accurate estimation of the efficiency.

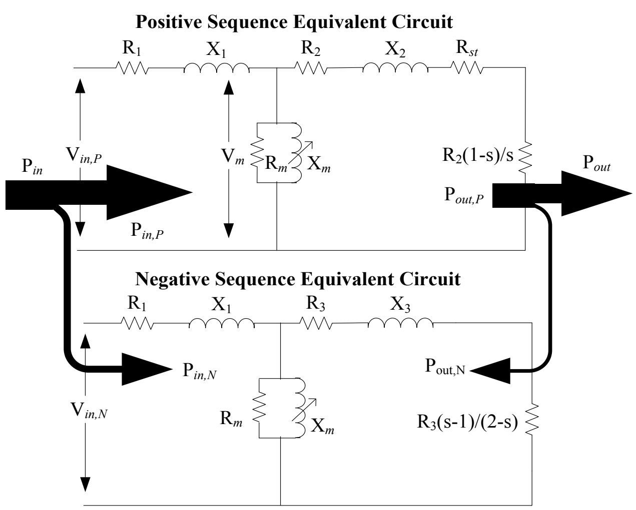

Fig. 3. Positive and negative sequence equivalent circuits of an induction machine .

Where

R_1: is the stator resistance.

X_1: is the stator leakage reactance.

R_2: is the rotor positive sequence resistance.

X_2: is the rotor positive sequence leakage reactance.

R_3: is the rotor negative sequence resistance.

X_3: is rotor negative sequence leakage reactance.

X_m: is mutual reactance of the machine which is a function of V_m.

R_m: is representative of the core loss which is a function of V_m.

R_{st}: is representative of the stray load loss defined based on IEEE 112 standard.

s: is the slip of the induction motor.

Normally, at most ±10% voltage variation is expected in an industrial facility. As shown in Fig. 4 for the case of a 3 hp motor, the mutual reactance changes almost linearly with voltage in that limited range. Considering the trend of change of the mutual reactance with voltage, it seems reasonable to assume a linear relationship for this limited range of voltage variation.

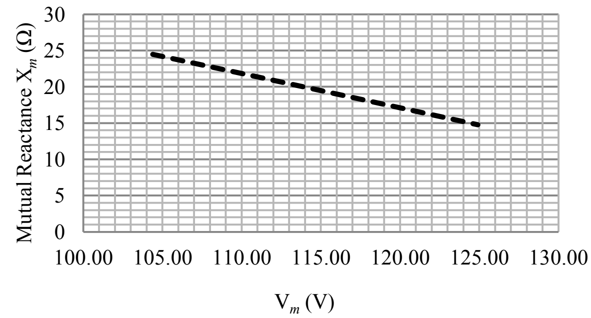

Fig. 4. Mutual reactance vs. V_m for the 3 hp machine

Thus the mutual reactance is represented as a linear function of the voltage as shown in (1).

$$X_m = a.V_m + b \quad (1)$$

The proposed evolutionary based search algorithm can be used to estimate these unknown parameters (a and b) and to define this relationship, using the measured current and voltage signals at multiple operating points without the requirement for the no-load test at different voltage levels.

The core losses can be assumed based on a simple representation as sum of hysteresis (P_h) and eddy current (P_e) components:

$$P_c = P_h + P_e = K_h.\beta\ f + K_e.\beta\ f^2 \quad (2)$$

Where

f : is the frequency

β : is the flux density

K_h : is constant coefficient of the hysteresis losses

K_e : is constant coefficient of the eddy current losses

n: is the constant changing in range of 1.6 to 2.0

For the fixed frequency operation and by accepting the error caused by assuming n=2, it is possible to simplify the above equation as (3).

$$P_c \approx K_1.\beta \quad (3)$$

Since flux density is directly proportional to the voltage of the magnetization branch (V_m), the core losses change with the square of this voltage and therefore R_m is independent of the voltage variation as shown in (4).

$$P_c \approx K_2.V_m^2 = \frac{V_m^2}{R_m} \Rightarrow R_m = \frac{1}{K_2}. \quad (4)$$

Therefore core losses can be estimated with a parallel resistor "R_m", as shown in the equivalent circuit of the machine. In this case, core losses will be changed with the square of the voltage. Based on experiments, it was observed that using a more complex model would not necessarily improve the core loss estimation since the losses should be estimated only based on the measured voltage and current signals under the loaded condition.

An evolutionary based search algorithm is used to find the parameters of the equivalent circuits of the machine and the unknown coefficients "a, b" which define the relation between "X_m" and the magnetizing voltage "V_m". This should be done with help of the limited electrical data, non-intrusively. For the purpose of this paper non-intrusiveness refers to electrical measurements at the terminals only with no mechanical measurements, not even the speed. Therefore no- load and locked rotor tests are not permitted.

The available data is the magnitude of the positive sequence input current ($I_{in,P}$), negative sequence input current ($I_{in,N}$), positive sequence input active power ($P_{in,P}$) as well as negative sequence input active power ($P_{in,N}$). The slip information is obtained non-intrusively with a current signature analysis based technique that extracts the slip information from the speed dependent current harmonics.

The data of multiple operating points is used to increase the available data and to help the search algorithm to converge to a unique set of solution. It is reasonable to assume that the machine works for a time at a particular loading condition which allows steady state measurements to be made. Therefore the temperature of the machine is stabilized at this loading condition and it remains the same during the short term load variations. Hence, it is possible to have a set of data with different electrical loading points for the same thermal condition.

As proposed in [12] by the authors of this paper, the positive sequence parameters of the machine can be estimated with help of an evolutionary based search algorithm. Knowing the negative sequence input active power ($P_{in,N}$), the negative sequence voltage magnitude ($V_{in,N}$) and the negative sequence input current magnitude ($I_{in,N}$), the negative sequence equivalent circuit can be used to calculate the negative sequence rotor components at each operating point.

To reduce the number of unknown parameters the following assumptions are made:

1) It is assumed that the value of the cold stator resistance at the ambient temperature is known based on the preliminary measurements.
2) The ratio of X_1/X_2 is known based on the design class of the machine (known from the nameplate) and the recommendation of IEEE 112 standard. As shown in [12] the final efficiency estimation is not really affected by this ratio.

In order to make the proposed algorithm of [12] compatible with over/under voltage unbalanced conditions, each individual is modified as shown in Fig. 5.

X_2	R_2	R_m	K_{th}	a	b

Fig. 5. One individual of the population.

K_{th} is the thermal coefficient of the machine and it will be chosen along with the other parameters using the proposed evolutionary search algorithm with the goal of having the least square errors from measured currents, powers and the rated temperature based on insulation class of the machine, as shown in (5) [12].

The specification of the used evolutionary algorithm is as follows:

- Population number: 250 individuals
- Initial population: Randomly selected in a predefined period as shown below:
  - X_2 : [0:50]
  - R_2 : [0:50]
  - R_m: [0:5000]
  - K_{th}: [0:1]
  - a: [-1:0]
  - b: [0:500]
- Recombination: Single arithmetic recombination $P_c = 0.8$.
- Mutation: Non uniform mutation with a fixed distribution $P_m = 0.2$.
- Reproduction: Tournament based selection combined with elitism (2 fittest old individuals).

A fitness (goal) function inspired from a non linear least square optimization technique is used to find a unique set of solutions (parameters) which has the least square error at all of the operating points as shown in (5).

$$F = \frac{1}{1 + E_1^2 + \sum_{i=1}^{N}\left(E_{2,i}^2 + E_{3,i}^2\right)} \quad (5)$$

N is the number of the operating points used in the algorithm and E_1, is the percentage of the error between estimated full load temperature ($T_{Rated,Est}$) (using estimated motor parameters as well as nominal voltage and speed values) and the real full load temperature (T_{Rated}) which is known based on the rated temperature rise indicated on the nameplate or the insulation class of the machine as shown in (6).

$$E_1 = \frac{\left(T_{Rated} - T_{Rated,Est}\right)}{T_{Rated}} \times 100 \quad (6)$$

$E_{2,i}$ is the percentage of the positive sequence input current estimation error at operating point "i" as defined in (7).

$$E_{2,i} = \frac{\left(I_{in,P,i} - I_{in,P,i,Est}\right)}{I_{in,P,i}} \times 100 \quad (7)$$

$E_{3,i}$ is the percentage of the positive sequence input active power estimation error at operating point "i" as presented in (8).

$$E_{3,i} = \frac{\left(P_{in,P,i} - P_{in,P,i,Est}\right)}{P_{in,P,i}} \times 100 \quad (8)$$

The temperature of the machine is estimated based on the same non linear temperature estimation technique developed in [12] by the authors.

Knowing the parameters of the machine and the unknown coefficients, the efficiency of the machine can be calculated for the measured field condition or any other condition of interest. This means the efficiency of the machine under standard conditions can be estimated even when the in-situ measurements have been done under field conditions. This is the main advantage of this method.

The flowchart of the method is shown in Fig. 6.

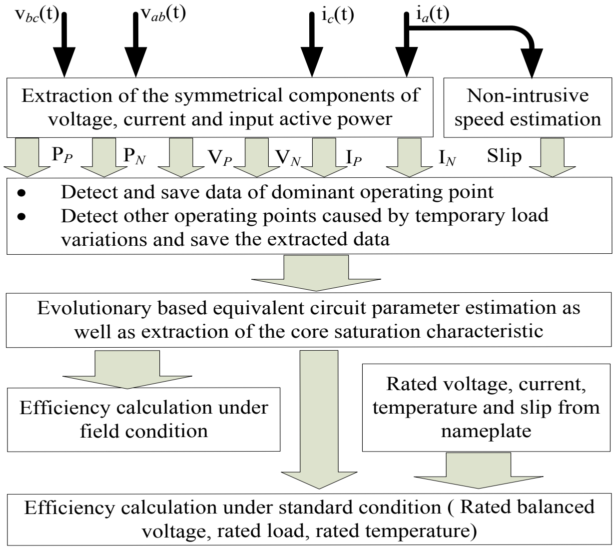

Fig. 6. Flow chart of the proposed efficiency estimation technique

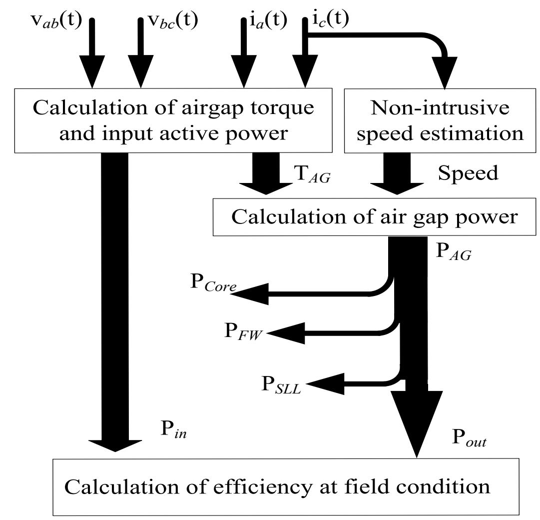

Fig. 7. Illustration of the air gap torque efficiency estimation technique

III. Non Intrusive Air Gap Torque (NAGT) Method

The air gap torque (AGT) method was proposed for the first time in [18] for in situ efficiency estimation. Later in [19] the same authors improved their method with considering the core losses in the efficiency estimation process. In this method the air gap torque is calculated based on (9) with use of the voltage and current signals as well as the magnitude of stator's resistance at the operating temperature. The air gap torque calculation includes the effects of the unbalanced supplies which is one of the advantages of this method.

$$T_{AG} = \frac{P.\sqrt{3}}{6}\left\{ \begin{array}{l} (i_a + i_c).\int [v_{ca} - R_s (i_c - i_a)]dt \\ -(i_c - i_a).\int [v_{ab} - R_s (i_a + i_c)]dt \end{array} \right\} \tag{9}$$

Where

P: the number of poles
i_a, i_c: the line currents
v_{ab}, v_{ca}: the line voltages
R_s: the stator resistance in the operating temperature

The efficiency (η) can be calculated based on (10).

$$\eta = \frac{T_{AG}.\omega_{m} - P_{core} - P_{FW} - P_{SLL}}{P_{in}} \tag{10}$$

Where

T_{AG} : is the air gap torque defined by (9)
ω_{m} : is the motor's speed in radians/second
P_{core}: is the core loss
P_{FW}: is the friction and windage losses
P_{SLL}: is the stray load loss
P_{in}: is the input power

The illustration of the method is shown in Fig. 7.

In [19], it is suggested that the core loss as well as friction and windage losses can be calculated with the air gap torque calculation while motor is working in no-load condition. The stray load loss at rated load is assumed as a fixed percentage of the rated output power based on recommendations of the IEEE 112 standard.

As it can be seen from (10), the efficiency calculation with this method requires the no load test that imposes a high level of intrusion. Besides the resistance of the machine shall be measured at the operating point which requires shut down of the motor. Despite these facts, this method can lead to a very accurate estimation of the motor's efficiency as shown in [19] and in the section VI of this paper.

In [1], it is suggested that empirical values can be used for core loss as well as friction and windage losses to avoid the intrusive no-load test. Besides a DC injection circuit is used for calculation of the stator's resistance. This method is called the non intrusive air gap torque method (NAGT).

Some practical concerns are highlighted regarding this method.

1) Is adding a circuit for online measurement of the stator resistance, less intrusive than measuring the resistance itself?
2) Is considering a fixed value (3.5% of the output power) for the sum of core losses and friction and windage losses accurate for machines with different sizes?
3) In real life some level of under voltage or over voltage exists in industry. What will happen in this case?
4) Is considering a fixed value for stray load loss acceptable for partial loaded conditions?
5) What is the meaning of the calculated efficiency at the field condition? Is the calculated value useful for comparison purposes or for calculation of the payback period in order to justify the replacement of an existing motor with a new one?

These are some important concerns that are addressed in this section. Adding a DC injection circuit requires an unpowered machine and this imposes an additional intrusion level beyond direct resistance measurement from the terminals of an unpowered machine.

The answer to the second concern is reported in [20] where the no load tests were performed with three different machines with different sizes. There, it is concluded that the assumption of the 3.5% of the rated output power for combination of the core and friction and windage losses in the rated condition is not accurate for different machines. A similar conclusion has been made in the section VI of this paper.

Moreover, as is stated in the third concern, the core loss is dependent on the magnitude of the input voltage of the machine. Assumption of a fixed value may lead to a significant error in estimated efficiencies where under/over voltage problem exist. The significant change in core loss due to change in the magnitude of the voltage level is evident in Fig. 2.

As suggested in [19], the stray load loss can be assumed based on recommendations of IEEE 112 standard. In this standard it is also mentioned that the stray load loss shall be corrected for different loading conditions using (11) based on the rotor's current which can be estimated with (12) if the no load current of the machine is known [17].

$$P_{SLL}' = P_{SLL}\left(\frac{I_r'}{I_r}\right)^2 \qquad (11)$$

$$I'_r = \sqrt{I_{in}'^2 - I_0^2} \qquad (12)$$

Where
P_{SLL}: is the stray load loss at rated load
P_{SLL}': is the stray load loss at partial load
I_r: is the rotor current at rated load
I_r': is the rotor current at partial load
I_{in}': is the input current at partial load
I_0: is the no load current

In the NAGT method neither the no-load current nor the rotor's current is known at different loading condition as the no load test is basically avoided. In [1], the value of the stray load loss at different loading conditions is simply considered equal to the rated condition. In the same work, it is mentioned that on average motors are working at no more than 60% of their rated load due to oversized installation or under loaded conditions. Considering the rated stray loss equal to 1.8% of the rated output, the stray load loss for a machine that works with a rotor current equal to 60% of the rated current will be as in (13).

$$P_{SLL}' = P_{SLL}\left(\frac{0.6 I_r}{I_r}\right)^2 = 0.36 P_{SLL} = 0.36 \times 1.8\% \times P_{out} \qquad (13)$$

As can be seen the assumption of stray load loss equal to the rated value will lead to overestimation of the losses by around (1-0.36) x 1.8% = 1.15% of the rated output power. Considering roughly a linear relationship between output power and rotor current for simplicity, the relative error in efficiency can be calculated as shown in (14).

$$\varepsilon_\eta = \frac{\Delta}{\eta} = \frac{\dfrac{1.15\% \times \dfrac{P'_{out}}{0.6}}{P'_{in}}}{\dfrac{P'_{out}}{P'_{in}}} = 1.92\% \qquad (14)$$

In [20], a linear regression method is proposed for improvement of the stray load loss estimation in partial loaded conditions. The stray load loss is considered as a function of the square of the torque for each load. Therefore a straight line, passing through the origin and the assumed value of the stray load loss at rated condition, is used to calculate the improved value of the stray load loss in partial loaded condition. The effect of this modification is shown in section VI.

With the NAGT method, there is no way to come up with the efficiency at standard conditions (balanced rated voltage and rated load) when the measurements are done in the field condition. Therefore comparison of the estimated efficiency with the efficiency of other machines will be meaningless. This is the main weakness of the NAGT method.

As discussed in the previous section, in contrast to the NAGT method, the optimization based method is capable of estimating the efficiency under standard condition even when the in-situ measurement has been done under field conditions. This is due to the fact that the parameters of the machine are extracted and therefore the equivalent circuits can be used for efficiency estimation at any condition. This is the main advantage of this method over the NAGT method.

IV. Experimental Results of the Proposed Algorithm with a 3hp Machine

In this section the proposed evolutionary based efficiency estimation method is used to estimate the efficiency of a 3 hp squirrel cage induction motor with the nameplate data as shown in the Table I.

An experimental setup with the schematic as shown in Fig. 8 was used for this test.

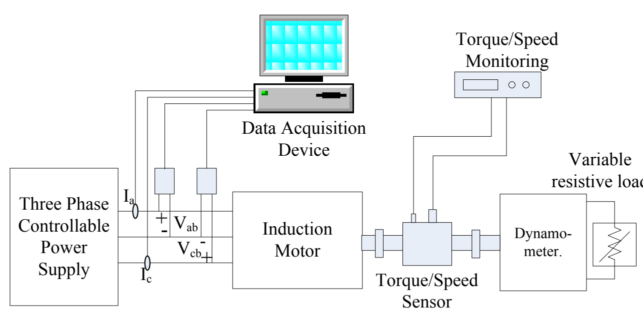

Fig. 8. Schematic of the test setup used for this experiment.

A combination of 4 variacs and 3 transformers has been used to create a controllable power supply which is capable of providing the desired unbalanced voltage set with a desired positive sequence level up to 240 V in order to have desired unbalanced and over/under voltage conditions.

The stator phase resistance at the ambient temperature was found equal to 0.67 Ω through measurements from the terminals of the machine. The ratio of X_1/X_2 is assumed equal to 0.67 based on the design class of the machine and the recommendation of IEEE 112 standard.

A dynamometer was used to impose different torque levels on the shaft of the tested induction motor. A torque/speed sensor has been used to measure the accurate speed and torque values at each operating point. The measured values of efficiencies are calculated based on these measurements and they are used as a reference in comparison to estimated efficiencies with the proposed method or the NAGT method. Fig. 9 shows the overall view of the designed experimental setup in the laboratory.

The proposed evolutionary based efficiency estimation algorithm is used to estimate the efficiency of the tested 3 hp induction machine under three different cases:

1) Rated voltage unbalanced operation (RVU): the positive sequence component of the voltage was equal to rated value (208 V) and the VUF was around 5%.
2) Under voltage unbalanced operation (UVU): the positive sequence component of the voltage was around 90% of the rated value and the VUF was around 5%.
3) Over voltage unbalanced operation (OVU): the positive sequence component of the voltage was around 105% of the rated value and the VUF was around 5%.

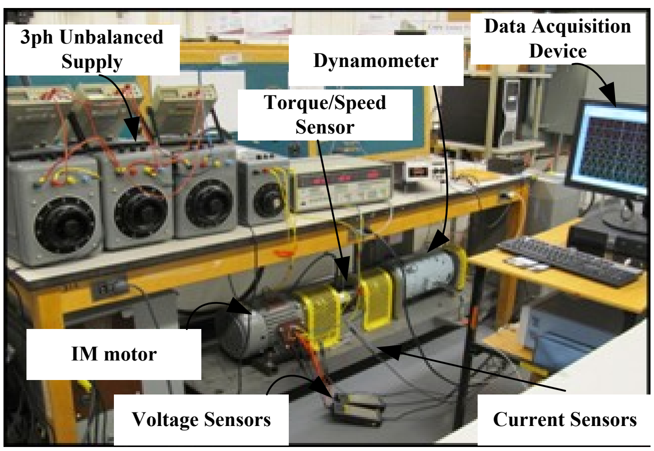

Fig. 9. The test setup of induction machine

In all three cases, the induction machine worked at 75 % of the rated load until the thermal steady state operating point was achieved. Then short term load fluctuations (e.g. with 1 minute duration) where applied to the motor in order to obtain the additional load points for the efficiency estimation process. In this case, the temperature of all short term operating points is considered equal to the temperature of the main operating point. The extracted data after measurements are shown in Table II, Table III and Table IV for the case of unbalanced rated, under and over voltage conditions respectively.

As an instance, from the measured data of Table III, and for the case of 75% of the rated load it can be shown that:

$$\frac{V_P}{V_{Rated}} = \frac{108.05}{120.00} \times 100 = 90\% \quad (15)$$

$$\frac{V_N}{V_P} = \frac{5.79}{108.05} \times 100 = 5.3\% \quad (16)$$

So it is assured that the machine was working with 10% under voltage and around 5% voltage unbalanced factor (VUF).

TABLE II
DIFFERENT OPERATING POINTS WITH AROUND 5% VUF AND RATED VOLTAGE FOR 3HP MACHINE (RVU)

% of rated load	25	50	75	85	100
$V_{in,P}$	120.30	119.82	119.25	118.58	118.53
$V_{in,N}$	7.47	7.39	7.24	7.32	7.25
$I_{in,P}$	6.26	7.00	8.21	8.81	9.85
$I_{in,N}$	3.41	3.43	3.43	3.47	3.46
$P_{in,P}$	872.94	1468.32	2087.04	2359.50	2765.63
$P_{in,N}$	47.47	48.90	49.48	51.63	51.86
Speed	1786.0	1773.1	1760.0	1751.9	1742.3

TABLE III
DIFFERENT OPERATING POINTS WITH AROUND 5% VUF AND 10% UNDER VOLTAGE FOR 3HP MACHINE (UVU)

% of rated load	25	50	75	85	100
$V_{in,P}$	109.32	108.71	108.05	107.39	106.84
$V_{in,N}$	6.02	5.92	5.80	5.79	5.66
$I_{in,P}$	4.93	6.15	7.91	8.77	10.09
$I_{in,N}$	2.64	2.78	2.86	2.85	2.83
$P_{in,P}$	790.75	1400.44	2051.87	2342.17	2755.39
$P_{in,N}$	25.89	30.23	32.45	33.32	33.18
Speed	1784.3	1768.1	1750.3	1740.1	1727.2

TABLE IV
DIFFERENT OPERATING POINTS WITH AROUND 5% VUF AND 5% OVER VOLTAGE FOR 3HP MACHINE (OVU)

% of rated load	25	50	75	85	100
$V_{in,P}$	126.76	126.06	125.67	125.36	125.17
$V_{in,N}$	7.24	7.14	7.12	7.06	7.01
$I_{in,P}$	7.38	7.84	8.81	9.27	10.12
$I_{in,N}$	3.49	3.45	3.49	3.46	3.45
$P_{in,P}$	950.26	1527.34	2145.46	2400.06	2797.06
$P_{in,N}$	49.87	49.57	51.04	51.03	51.25
Speed	1787.1	1775.8	1762.9	1756.6	1748.6

The estimated efficiencies after convergence of the algorithm are compared with the measured values as shown in Table V to Table VII for RVU, UVU and OVU cases respectively. It should be emphasized that the estimated efficiencies in these cases are efficiencies at the field condition.

TABLE V
ESTIMATED EFFICIENCIES VS. MEASURED EFFICIENCIES FOR 3 HP MACHINE WITH RATED VOLTAGE AND 5% VUF (RVU)

% of rated load	**25**	**50**	**75**	**85**	**100**
Measured efficiencies	59.17	72.57	77.43	77.64	78.23
Estimated efficiencies	64.87	75.92	79.30	79.76	79.79
Error (%)	5.70	3.35	1.87	2.12	1.56

TABLE VI
ESTIMATED EFFICIENCIES VS. MEASURED EFFICIENCIES FOR 3 HP MACHINE WITH 10% UNDER VOLTAGE AND 5% VUF (UVU)

% of rated load	**25**	**50**	**75**	**85**	**100**
Measured efficiencies	67.85	77.58	79.59	79.71	78.67
Estimated efficiencies	70.86	79.35	80.92	80.61	79.83
Error (%)	3.01	1.77	1.33	0.90	1.16

TABLE VII
ESTIMATED EFFICIENCIES VS. MEASURED EFFICIENCIES FOR 3 HP MACHINE WITH 5% OVER VOLTAGE AND 5% VUF (OVU)

% of rated load	**25**	**50**	**75**	**85**	**100**
Measured efficiencies	55.55	70.25	75.75	76.78	77.85
Estimated efficiencies	61.88	74.02	78.09	78.90	79.35
Error (%)	6.33	3.77	2.34	2.12	1.50

As can be seen from the results, the proposed algorithm is capable of estimating the efficiency of the tested machine in-situ with an acceptable error under unbalanced over/under voltage conditions. However what is important is to be able to estimate the efficiency of the machine under standard condition (balanced rated supply and rated load) even when the in-situ measurement has been done under the field condition (unbalanced supply, under/over voltage condition, partial loaded machine). To verify this capability the data of the under voltage unbalanced condition (UVU) has been used to estimate the efficiency of the machine under rated condition. The results are compared with the measured values of the efficiency under standard condition as shown in Fig. 10.

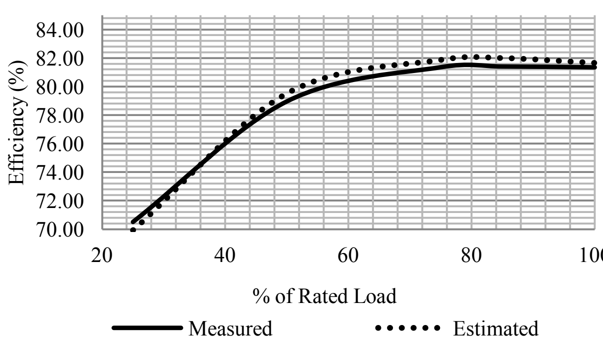

Fig. 10. Estimated efficiencies for standard condition from the UVU measurements vs. measured efficiencies at standard condition

V. TESTING GENERALITY OF THE PROPOSED ALGORITHM WITH A 7.5HP MACHINE

The efficiency of a 7.5 hp energy efficient motor by TECO-Westinghouse (Cat. No. PDH7/504TE2N) [21] has been estimated with the proposed algorithm to verify the generality of the method. The nameplate data is shown in Table VIII. The stator phase resistance at the ambient temperature was found equal to 0.71 Ω through measurements from the terminals of the machine. The ratio of X_1/X_2 is assumed equal to 0.43 based on the design class of the machine and the recommendation of IEEE 112 standard.

TABLE VIII
NAMEPLATE DATA OF 7.5 HP INDUCTION MACHINE

f	60Hz	Design class	C
V_{LL}	230/460	Insulation class	F
I	17.7/8.85	Nominal speed	1755
Connection	Δ	Poles	4

The test was performed under two different cases:

1) Rated voltage unbalanced operation (RVU): the positive sequence component of the voltage was equal to rated value (230 V) and the VUF was around 6%.
2) Under voltage unbalanced operation (UVU): the positive sequence component of the voltage was around 90% of the rated value and the VUF was around 6%.

In both cases the induction machine worked at 65 % of the rated load until the thermal steady state operating point was achieved. Then short term load fluctuations (e.g. with 1 minute duration) where applied to the motor in order to achieve the extra load points for efficiency estimation process. The extracted data after measurements are shown in Table IX and Table X for case of unbalanced rated and under voltage conditions respectively.

TABLE IX
DIFFERENT OPERATING POINTS WITH AROUND 6% VUF AND RATED VOLTAGE FOR 7.5HP MACHINE (RVU)

% of rated load	**25**	**50**	**65**	**85**	**100**
$V_{in,P}$	234.16	231.98	230.69	229.81	228.43
$V_{in,N}$	14.24	13.72	13.46	13.21	13.07
$I_{in,P}$	4.19	5.86	7.03	8.67	10.10
$I_{in,N}$	3.17	3.66	3.89	4.09	4.21
$P_{in,P}$	1613.87	3118.62	3987.63	5125.57	6064.13
$P_{in,N}$	44.60	56.23	62.65	68.35	71.77
Speed	1790.7	1780.6	1775.1	1766.9	1759.5

TABLE X
DIFFERENT OPERATING POINTS WITH AROUND 6% VUF AND 10% UNDER VOLTAGE FOR 7.5HP MACHINE (UVU)

% of rated load	**25**	**50**	**65**	**85**	**100**
$V_{in,P}$	210.47	208.54	206.09	205.13	203.83
$V_{in,N}$	12.79	12.13	12.01	11.93	11.83
$I_{in,P}$	3.97	6.08	7.53	9.58	11.22
$I_{in,N}$	2.74	3.36	3.57	3.77	3.85
$P_{in,P}$	1598.26	3114.83	4002.21	5208.29	6117.94
$P_{in,N}$	33.66	47.39	53.11	58.45	61.02
Speed	1788.0	1775.4	1767.4	1756.2	1746.0

The estimated efficiencies under measurement conditions are compared with the measured values as shown in Table XI and XII.

TABLE XI
ESTIMATED EFFICIENCIES VS. MEASURED EFFICIENCIES FOR 7.5 HP MACHINE WITH RATED VOLTAGE AND 6% VUF (RVU)

% of rated load	25	50	65	85	100
Measured efficiencies	83.43	88.31	88.57	88.70	88.32
Estimated efficiencies	85.94	89.78	89.89	89.45	88.73
Error (%)	2.51	1.47	1.32	0.76	0.41

TABLE XII
ESTIMATED EFFICIENCIES VS. MEASURED EFFICIENCIES FOR 7.5 HP MACHINE WITH 10% UNDER VOLTAGE AND 6% VUF (UVU)

% of rated load	25	50	65	85	100
Measured efficiencies	86.25	88.64	88.53	87.86	86.97
Estimated efficiencies	84.48	88.15	88.13	87.35	86.25
Error (%)	-1.77	-0.49	-0.40	-0.50	-0.73

The data of the under voltage unbalanced condition (UVU) has been used to estimate the efficiency of the machine under standard conditions. The results are compared with the available values of the efficiencies provided by the manufacturer as shown in Fig. 11 [21].

The experimental results verify the generality and effectiveness of the proposed efficiency estimation algorithm.

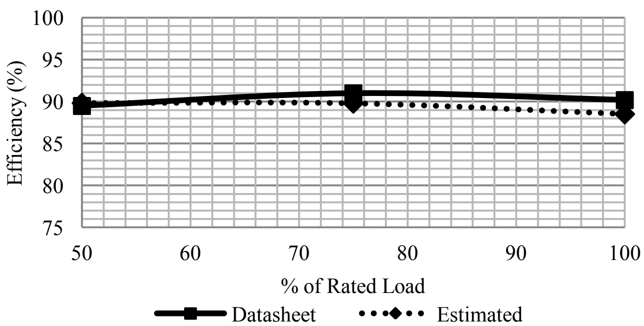

Fig. 11. Estimated efficiencies for standard condition from the UVU measurements vs. efficiencies from data sheet [21]

VI. EXPERIMENTAL RESULTS OF THE NAGT METHOD

The non intrusive air gap torque method (NAGT) of [1] and its modified version (MNAGT) [20] have been used to estimate the efficiency of the same machines at the same conditions. In fact the same recorded data has been used with these methods. The efficiency estimation results are shown in Fig.12 to Fig. 14 for the 3 hp machine and Fig. 15 to Fig 16 for the 7.5 hp machine.

In these figures, the results of NAGT, MNAGT and the proposed evolutionary based (EVB) efficiency estimation methods are compared with the direct measured efficiencies (using the torque/speed sensor).

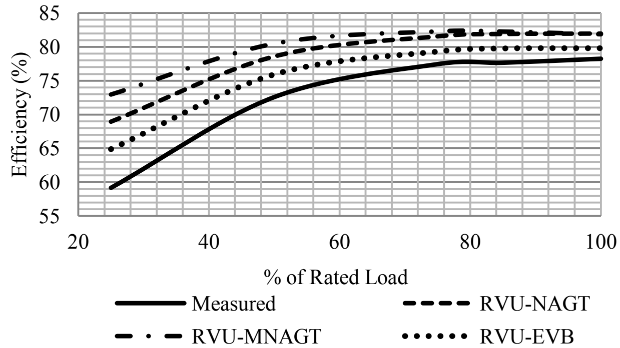

Fig. 12. Estimated efficiencies vs. measured ones for the 3 hp machine at rated voltage unbalanced supply condition (RVU)

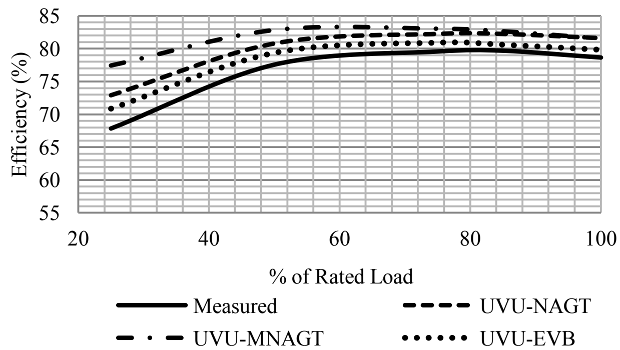

Fig. 13. Estimated efficiencies vs. measured ones for the 3 hp machine at under voltage unbalanced supply condition (UVU)

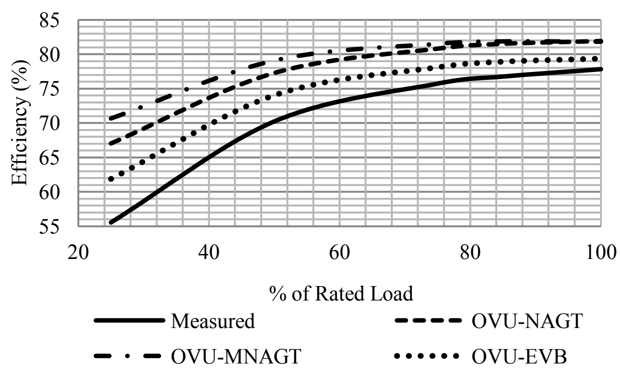

Fig. 14. Estimated efficiencies vs. measured ones for the 3 hp machine at over voltage unbalanced supply condition (OVU)

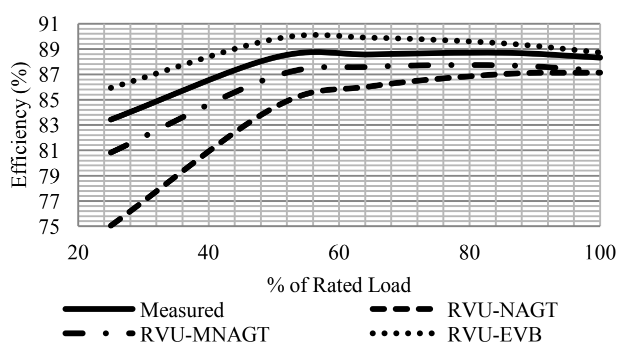

Fig. 15. Estimated efficiencies vs. measured ones for the 7.5 hp machine at rated voltage unbalanced supply condition (RVU)

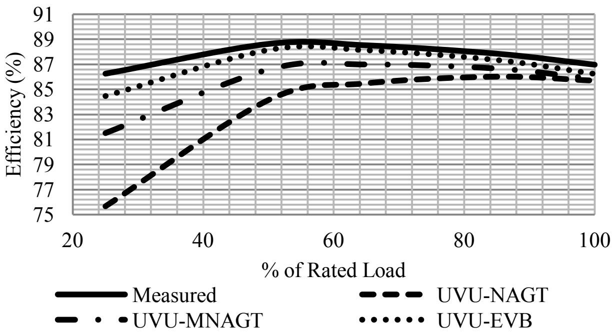

Fig. 16. Estimated efficiencies vs. measured ones for the 7.5 hp machine at under voltage unbalanced supply condition (UVU)

As can be seen the error of efficiency estimation with the NAGT method is higher specifically for partial loaded conditions. Besides in case of the 3 hp machine, the modified method (MNAGT) which should have better estimation in partial loaded conditions leads to higher errors.

Based on the performed no load tests, the total no load losses minus the copper losses at the rated condition were found around 196W and 125W for the 3 hp and 7.5 hp machines respectively.

As assumed in the NAGT method [1], the total no load losses minus the stator copper losses is 3.5% of the output power. This will be around 78W for the 3hp machine and 195W for the 7.5hp machine. The difference between assumed and real values leads to an over estimation of the efficiency in case of 3hp machine and an under estimation in case of 7.5 hp motor.

The results of the air gap torque method (AGT) which uses the real values of the no load losses are shown in Fig. 17 and 18 for of the 3hp and 7.5hp machines under the rated unbalanced condition. As it can be seen, the efficiency estimation is improved dramatically in comparison to Fig. 12 and 15. Besides, the modified method provided more accurate estimation.

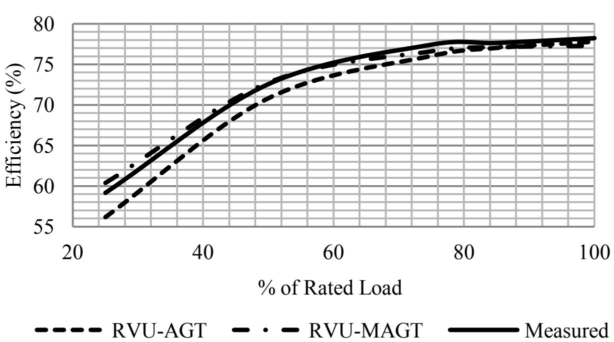

Fig. 17. Estimated efficiencies with real no load values vs. measured ones for the 3 hp machine at rated voltage unbalanced supply condition (RVU)

Based on the results, it can be concluded that although the air gap torque method (AGT) is very accurate the NAGT method which is the non-intrusive version of AGT method lacks the accuracy due to the fixed assumption of the no load losses.

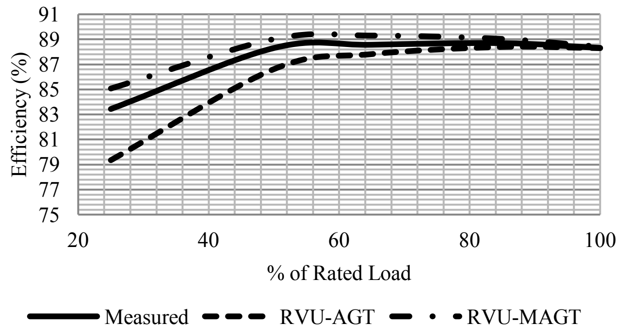

Fig. 18. Estimated efficiencies with real no load values vs. measured ones for the 7.5 hp machine at rated voltage unbalanced supply condition (RVU)

Even assuming an accurate estimation for NAGT method, there is no way to come up with the efficiency of a machine at standard condition when the measurements are done in the field conditions. This may lead to a significant error when calculating the benefits of replacing the existing motor with a new one.

VII. Conclusions

In this paper, an optimization based algorithm is proposed for in-situ efficiency estimation of induction machines operating with over/under voltage and unbalanced supplies. The results are compared with the non- intrusive air gap torque (NAGT) method and it is shown that the efficiency calculated by the NAGT method under the field conditions cannot be used in the decision making process on replacement of the existing machines as well as the relevant calculations regarding the payback period. The proposed method is capable of estimating the efficiency of the machine under standard condition even when the in-situ measurement has been done under the field conditions.

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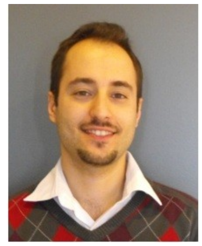

Arbi Gharakhani Siraki (S'07) received the B.S. degree in electrical engineering from Azad University, Tehran, Iran, in 2004 and the M.Sc. degree in electrical engineering from K.N.T University of Technology, Tehran, Iran, in 2007.

He is currently working toward the Ph.D. degree, in the Power Electronics and Energy Research Group, Department of Electrical and Computer Engineering of Concordia University, Montreal, Canada.

Pragasen Pillay (F'05) received the Bachelor's degree from the University of Kwa-Zulu Natal, Durban, South Africa, in 1981, the Master's degree from the University of Kwa-Zulu, Natal, Durban, South Africa, in 1983, and the Ph.D. degree from Virginia Polytechnic Institute and State University, Blacksburg, in 1987.

Currently, he is a Professor in the Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada, where he holds the NSERC/Hydro Quebec Industrial Research Chair.