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Field computation of efficiency of induction machine working on unbalanced conditions using modified non-intrusive air-gap method

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Various techniques have been suggested for efficiency estimation of Induction Machines (IMs) with different levels of intrusion and accuracy. Traditional methods depicted in IEEE Standard 112 can't be employed for industrial environment where continuous industrial processes are in occurrence. This paper put forth an approach for non-intrusive air gap torque evaluation for efficiency estimation of IM by utilizing IM terminal quantities like input voltages and input currents. Base difference between Method-E and air-gap torque method is discussed. In vector control system, the speed estimation of IM is done based on Model-Reference Adaptive System (MRAS) by utilizing input electrical quantities and instantaneous reactive power. Algorithm used does not need intrusive no load testing. Experimental validation is carried out to verify the effectiveness of the proposed structure.

Keywords: *Air-gap torque method, efficiency estimation, induction machine, non-intrusive techniques*

1.0 INTRODUCTION

Electric drives consume bulk portion of electric power in industrial processes. In Indian scenario, majority of the industrial premises have oversized installation of IMs. Most of the IMs are operating near half of their rated values. This reduces their efficiency and results in electric power wastage. Low cost techniques are the need of hour for condition monitoring and energy auditing of the small and medium segment IMs. This will result in substantial savings in electric power [1]. Equivalent circuit approach seems favourable for assessing IM efficiency at different slips by means of simple calculations and empirical formulas. Tracking of parameters in field conditions is an uphill task. In actual operation, with varying voltages, IM parameters deviate from the values specified by the manufacturer. Equivalent circuit approach becomes more complex. Many times, it has been observed that power supply is polluted with unbalance voltages and some harmonic content. This further lowers the IM efficiency of in-service IM [2]. For data collection, current and potential transformers already exist in industry to monitor the input electrical quantities like terminal voltages and line currents of IM. So, no extra investment is needed for data collection. Traditional methods require sensors or transducers to monitor the shaft speed and torque to estimate output power [3]. Lot of expenditure would be done on transducers and intrusion level would be high. In continuous industrial processes, IEEE Standard 112 methods would not be applicable [4].Air-gap torque method needs line voltages, phase currents, stator resistance, rotor speed, core loss and friction-windage loss. So, no load test on in-service IM is needed. This makes this approach highly unfavourable for in-service IMs since it increases intrusion level drastically. A non-intrusive air-gap method is developed by doing modifications to original air-gap torque method

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based on air-gap torque equations employing line voltages and two phase currents with sufficient accuracy and least intrusion level.

This paper proposes a technique being experimentally validated for efficiency estimation of IM for the unbalanced industrial real scenario utilizing reduced level of intrusion and higher accuracy as per IEC Standard 60034-2-1 2007. The speed of rotor of IM is measured by optical tachometer wirelessly. It is compared with the speed obtained in SIMULINK™ platform using sensor-less Model Reference Adaptive System (MRAS) technique utilizing instantaneous reactive power due to its performance and straight forward stability approach. MRAS technique is highly reliable when the IM parameters are poorly known or have wider variation in their values. This scheme utilizes error vector as feedback for rotor speed estimation. Output error is tuned by using PI controller for yielding requisite rotor speed. Quantities like stator resistance, stator reactance and rotor time constant are needed for rotor flux based MRAS speed estimation. Tuning signal fed to adaptation mechanism for rotor flux MRAS is rotor flux error vector. Variation of stray load loss with load is considered since additional load losses vary as the square of primary current minus the square of no load current. Core losses will be evaluated using measurements from voltage and current signals rather than using empirical data. In the proposed approach, it is possible to obtain efficiency of IM at any loading condition. Experimental validation of the IM efficiency evaluation would be done. Finally, modification to air gap method would be achieved to showcase the results obtained by non intrusive air gap method to be in accordance with the results obtained by the experimental set up.

DC resistance of stator winding of IM is measured directly by utilizing fluke multi-meter. The accuracy in direct resistance measurement is high. This value can be seen at ambient temperature when motor is in shut down mode. Two case studies have been made to analyze the results. Case 1 will provide efficiency as per IEEE Standard 112 while case 2 will give efficiency based on Indian Standard Rotating Electrical Machines Part 2/ Section 1 which is identical with IEC 60034-2-1 : 2007 issued by the International Electro technical Commission (IEC) [5]. For case 1, full load stray loss is considered as 1.8% of rated output power. This loss is in addition to rotor circuit. It may change with loading condition. Also, for same case, friction and windage loss is assumed to be 1.2% of rated power. For case 2, full load stray loss is given below:

$$Stray\ load\ loss = Input\ power[0.025 - 0.005log_{10}\frac{Rated\ output\ power}{1000}] \quad ....(1)$$

This equation is in accordance with load losses variation as the square of the stator current minus the square of the no-load current. Friction and windage loss is considered as 3.5% of the rated input power. There is no way of non-intrusiveness to obtain friction and windage losses of IM. So, an empirical value is chosen for in-service IMs. Efficiencies are calculated for both the cases and comparison of results has been analyzed.

2.0 SPEED ESTIMATION OF IM ROTOR

Speed transducer or optical tachometer is needed to be installed for direct measurement of IM rotor speed. This raises the input investment. In industrial conditions, sometimes installing a speed sensor on IM shaft is a daunting task. So, sensor-less control is posing a challenging task to researchers. Since few years, various researchers have proposed numerous rotor speed estimation techniques. In this research paper, rotor flux based Model Reference Adaptive System (MRAS) is adopted which is based on instantaneous reactive power. The reactive power in terms of d and q axes provides a tuning signal to adaptation mechanism. This technique is less complicated and the error is less on comparing measured and estimated values. This approach seems stable since it is utilizing the forward stability approach. This work is realized using Landau concept on adaptation mechanism [6]. Speed estimation comprises of reference and adaptive models in addition to tuning mechanism.

In d-q axes synchronous frame of reference, IM equations are expressed as:

$$V_{ds} = R_s I_{ds} + \sigma L_s I_{ds} + \frac{L_m}{L_r}\varphi_{dr} - \sigma L_s \omega_e I_{qs} - w_e \frac{L_m}{L_r}\varphi_{qr} \quad ....(2)$$

$$V_{qs} = R_s I_{qs} + \sigma L_s I_{qs} + \frac{L_m}{L_r}\varphi_{qr} + \sigma L_s \omega_e I_{ds} + w_e \frac{L_m}{L_r}\varphi_{dr} \quad ....(3)$$

Here, R_s & L_s is rotor resistance and inductance

And $\sigma = \frac{L_s L_r - L_m^2}{L_s L_r}$ ....(4)

Multiply (2) by I_{qs} and (3) by I_{ds} to eliminate R_s .

Instantaneous reactive power is given as

$$Q = V_{qs} I_{ds} - V_{ds} I_{qs} = \frac{(V_a I_c - V_c I_a)}{\sqrt{3}} \quad ....(5)$$

It is observed that reactive power can be obtained easily without needing transformations. Speed of rotor can be attained from reactive power. In MRAS, it is ensured that estimated values converge to required values as per landau synthesis method [7]. MRAS is using the following equations given below for equations.

$$Q = V_{qs} I_{ds} - V_{ds} I_{qs} = \frac{(V_a I_c - V_c I_a)}{\sqrt{3}} \quad ....(6)$$

$$\varphi_{qr} = \frac{L_r}{L_m}\{\int (V_{qs} - R_s I_{qs})\, dt - \sigma L_s I_{qs}\} \quad ....(7)$$

$$\frac{d\varphi_{dr}}{dt} = -\frac{1}{T_r}\varphi_{dr} + \frac{L_m}{T_r} I_{ds} - \omega_r \varphi_{qr} \quad ....(8)$$

$$\frac{d\varphi_{qr}}{dt} = -\frac{1}{T_r}\varphi_{qr} + \frac{L_m}{T_r} I_{qs} + \omega_r \varphi_{dr} \quad ....(9)$$

Structure of MRAS is depicted in Figure 1:

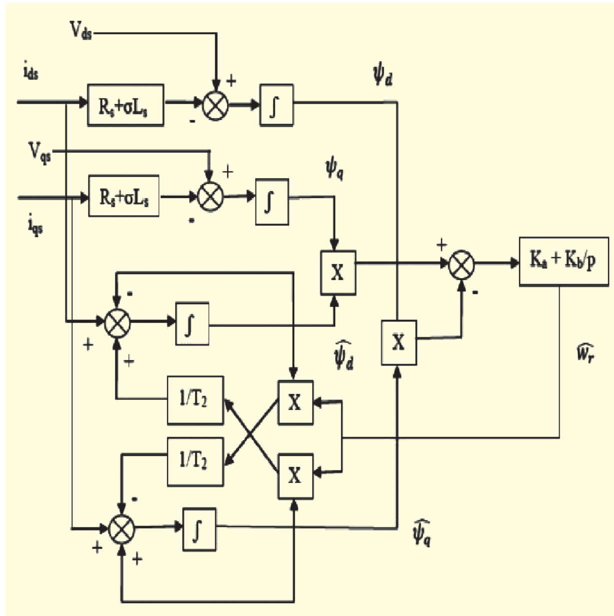

FIG. 1 MRAS STRUCTURE FOR SPEED ESTIMATION

Tuning is achieved by rotor flux error vector to make system stable. The speed of IM rotor is given as:

$$\omega = \left(K_p + \frac{K_i}{p}\right)(\varphi_q \widehat{\varphi_d} - \varphi_d \widehat{\varphi_q}) \quad ....(10)$$

3.0 DISPARITY BETWEEN IEEE METHOD-E AND AIR-GAP TORQUE METHOD

Input electrical power to three phases of IM is written as:

$$Input\ Power = \frac{\int_0^{time} (v_A i_A + v_B i_B + v_C i_C) dt}{Time\ interval} \quad ....(11)$$

Air-gap torque is given as

$$Torque = \frac{P}{2.\sqrt{3}}\left[(i_A - i_B).\int[v_{CA} - R(i_C - i_A)]dt - (i_C - i_A).\int[v_{AB} - R(i_A - i_B)]dt\right] \quad ....(12)$$

Where P is number of poles, R is the half of line to line resistance, I_A, I_B, I_C are line currents of three phases A,B,C respectively.

Method-E suggests that under any given load on IM, negative fields developed on account of unbalanced supply voltages produces loss are considered included in no load losses. At full load or no load, negative sequence fields remain unaltered due to which difference in speed between no load and full load is negligibly small. So, slip is constant and negative sequence currents remain unaffected. In this way, unbalancing and harmonic content is wrapped in Method-E. In practical field conditions, with changes in load, terminal voltages across three phases of IM vary. On application of unbalanced supply, there is rise in negative sequence voltage. Negative sequence impedance does not remain constant. When negative sequence current rises, positive sequence voltage falls. This behaviour is witnessed due to non-saturated rotor tips. Negative sequence current is small at no load and in greater proportion on full load. This explains that on various loads, negative sequence losses are not shielded in no-load losses.

In IEEE Standard 112, Method-E output power is higher. Output power is obtained by subtracting no load loss, friction-windage loss, and stray load loss from electrical input power. Input electrical power is higher because negative sequences losses are not covered in no-load losses. As per IEC 60034-2-1: 2007 [5],air-gap torque method employs air-gap power. For every load point, losses due to negative sequence currents are evaluated. Shaft torque is written as:

$$Shaft\ torque = T_{ag} - \frac{F\&W}{\frac{2\pi N}{60}} - \frac{SLL}{\frac{2\pi N}{60}} \quad ....(13)$$

Where T_{ag} is shaft torque, N is speed in rpm, $F\&W$ is friction and windage loss and SLL is stray load loss respectively.

Finally, shaft output power is obtained from shaft speed and shaft torque. Efficiency can be determined as ratio of output to input power.

4.0 NON-INTRUSIVE AIR GAP TORQUE METHOD (NIAGT)

For in-service IMs, NIAGT method seems promising since it is employing only measurable electrical input quantities like line voltages and phase currents to evaluate IM efficiency. In industrial set up, many times it's hard to reach IM terminals [8]. Line to line voltages can be measurable by electrical instruments. Consider a three phase Y-connected standard induction motor giving below expressions

$$V_{ab} + V_{bc} + V_{ca} = 0$$
$$I_a + I_b + I_c = 0$$

Where V_{ab}, V_{bc}, V_{ca} are phase voltages and I_a, I_b, I_c are phase currents.

We are assuming zero sequence components in voltages and currents of three phase induction motor being very small. So, they can be neglected. Two stator voltages V_{ab} and V_{ca} are needed which can be measured using potential transformers in industrial set up. Two current transformers are needed to get phase currents I_a and I_b. The proposed strategy needs only IM terminal data. It does not need the use of torque sensor for measurement of torque and speed measurements are avoided. All the required information can be gathered at control unit center in industrial premises. Gathering terminal quantities at control centre are easy as compared to obtaining data from IM because at some places where IM is in drive application, assessing IM terminals is very tedious.

By applying Park's transformation of Kron primitive machine on three phase IM and transforming a-b-c axes into d-q axes, the air-gap torque is obtained as

$$T_{air-gap} = \frac{\sqrt{3}P}{6}[(I_a - I_b)\int\{V_{ca} + R_s(2I_a + I_b)\}dt + (2I_a + I_b)\int\{V_{ab} - R_s(I_a - I_b)]dt] \quad ....(14)$$

The input to IM is

$$P_{in} = V_a I_a + V_b I_b + V_c I_c$$

Substituting $I_c = -(I_a + I_b)$ in above equation

$$P_{in} = I_a[V_a - V_c] + I_b[V_b - V_c]$$

$$P_{in} = -V_{ca}[I_a + I_b] - V_{ab}I_b \quad ....(15)$$

Shaft power output is the multiplication of speed of IM rotor and shaft torque.

Efficiency estimation of IM is done using two case studies.

Case-1: In reference to IEEE Standard 112, the friction and windage losses are assumed as 1.2% of rated output power of IM and stray load losses is taken as 1.8% of rated output power.

Efficiency of IM = P_{out} / P_{in}

$\eta = T_{Shaft} \times W_{rotor} / Pin$ ....(16)

Case-2: In reference to Indian Standard (Part 2/ Sec 1) adopted by Bureau of Indian Standards which is identical to IEC 60034-2-1: 2007 issued by International Electro technical Commission (IEC), the friction & windage loss in combination to core loss is assumed as 3.5% of rated input power and stray load loss for IMs in range of 1kW to 10,000 kW is obtained by the following equation

$$S_{LL} = P_{in} \times \{0.025 - 0.005log_{10}\left(\frac{P_{out}}{1000}\right)\} \quad ....(17)$$

This proposed approach contributes to efficiency estimation of IM by taking only IM terminal quantities and nameplate data. This certifies the non-intrusive nature of proposed approach. Also, the need of expensive dynamometer or torque sensor as well as speed transducers for torque and speed measurement is eliminated. Here, air-gap torque is obtained by utilizing two line voltages and two phase currents. Phasor computations are not required here.

5.0 RESULTS

The proposed approach has been worked on MATLAB/SIMULINK™ platform and MRAS speed estimation of IM rotor speed has been done. IM nameplate is depicted in Table 1 as shown.

TABLE 1

INDUCTION MACHINE NAMEPLATE RATING

Voltage	415 V	Power factor	0.81
Rating	1.1 kW	Connection	Y
Ampere	2.45 A	Insulation	F
Efficiency	77 %	Speed	1400
Frame	RC 90 SL	Duty	S1

By performing open circuit and short circuit tests on IM in laboratory, IM parameters are attained. These parameters are in Table 2 and are used in MATLAB™ simulation.

TABLE 2	
IM PARAMETERS	
Stator resistance (Ω)	2.175
Stator reactance (Ω)	1.2091
Rotor resistance (Ω)	11.7139
Rotor reactance (Ω)	12.4579
Mutual Inductance(Ω)	146.3761

The rotor speed provided by MRAS is 1370 rpm whereas speed obtained by using optical tachometer is 1394 rpm.

Figure 2 show that MRAS provided speed tracks the actual speed of IM rotor in close range at high speeds.

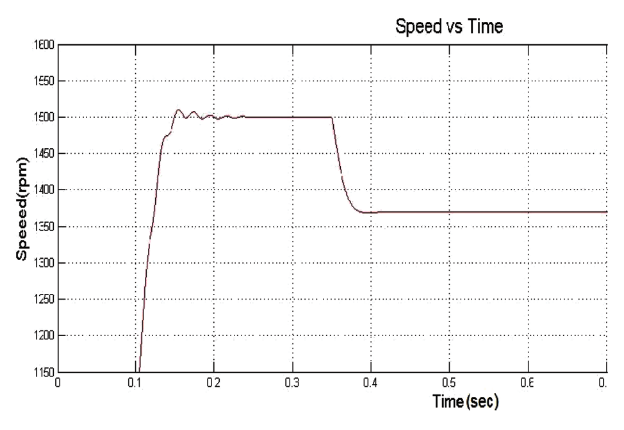

FIG. 2 SPEED TRACKING OF IM USING MRAS

6.0 LAB VALIDATION OF EFFICIENCY ESTIMATION USING PROPOSED TECHNIQUE

The proposed approach has been analyzed on MATLAB/SIMULINK™ platform for balanced and unbalanced field conditions. Experimental lab set-up is made for efficiency estimation test as shown in Figure 3. The data acquisition system operating at 2 kHz sampling frequency is installed for three phase electrical parameter measurement. This acquisition system has an accuracy of ± 1% and comprises of three AC voltage channels, 3 AC current channels, speed and torque measurement being done wirelessly. It includes all the signal processing required to do voltage, current, frequency, active power, reactive power and power factor measurements. In first case, balanced supply voltages are provided to IM. In second case, unbalanced power supplies are given to IM. Using three single phase rheostats, unbalanced supply voltages are created to provide field conditions. 5% unbalanced voltages i.e. V_{ab}= 408 volts, V_{bc}= 380 volts and V_{ca}= 400 volts respectively are provided as input to IM. Air-gap torque can be found using two input phase voltages and two phase currents in equation (13). Input power to IM is obtained using equation (14). IM's Shaft torque is calculated from equation (12).For two case studies, $F\&W$ and SLL are considered as per IEEE Std. 112 and IEC 60034-2-1: 2007. Finally, efficiency of IM is obtained using equation (15) for both cases under study.

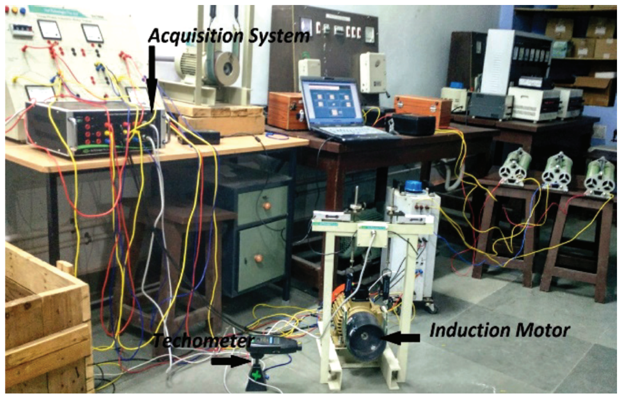

FIG. 3 EXPERIMENTAL SET-UP FOR EFFICIENCY ESTIMATION OF IM

Efficiency estimation for balanced conditions depicting the comparison of IEEE Standard 112 with IEC 60034-2-1 is shown in Table 3.

TABLE 3					
BALANCED CONDITIONS ANALYSIS					
% Load	**Speed (rpm)**	**IEEE Standard 112 Method (Case-1)**		**BIS identical to IEC 60034 -2-1: 2007 (Case-2)**	
		Efficiency	**Torque**	**Efficiency**	**Torque**
67.2	1394	63.92	4.192	60.73	3.98
79.45	1370	77.26	5.2196	73.67	4.97
96.1	1328	81.53	7.843	75.58	7.27

Table 4 provides comparison of efficiency and torque in Newton-metre of IM under unbalanced industrial conditions where supply is polluted with 5 % unbalancing and some harmonic content.

TABLE 4					
UNBALANCED CONDITIONS ANALYSIS					
% Load	**Speed (rpm)**	**IEEE Standard 112 Method (Case-1)**		**BIS identical to IEC 60034 -2-1: 2007 (Case-2)**	
		Efficiency	**Torque**	**Efficiency**	**Torque**
45.8	1489	71.59	3.1492	65.10	2.867
55.78	1383	66.54	2.645	58.32	2.318

7.0 DISCUSSIONS

It has been observed that efficiency near full load is accurate using case 2 than case 1 since case 1 is showing exaggerated value. Results obtained in Table 3 and Table 4 indicates that the efficiencies obtained by using IEC Std. 60034-2-1: 2007 are more accurate in comparison to IEEE Std. 112. IEC Std. 60034-2-1utilizes additional load losses as a percentage of input power at rated load. It means that slip changes with load is incorporated in IEC std. Std. 60034-2-1 which helps in getting the realistic values of efficiencies. In Table 4, for 45.8% loading, IEEE std. 112 gives erroneous results since it is not in accordance with the fact that efficiency starts declining steeply with increase in load on unbalancing in input powers. For finding core loss and copper loss, no- load and block rotor tests are mandatory. Using air-gap torque method, there is no need to evaluate core loss and copper loss since they are already into consideration and air-gap torque can be measured while IM is in operation. Using the proposed technique of NIAGT, continuous online measurement is quite possible.

The merits of the proposed technique are listed as under:

- Torque sensor is eliminated.
- No load test is not needed.
- Relies only on input electrical quantities and IM nameplate data.
- No obvious errors for inaccuracies in IM nameplate values.
- Intrusion level is the least.
- Reduces downtown of IM.

8.0 CONCLUSIONS

This research paper put forward a non-intrusive technique to find efficiency of in-service IMs. Technique relies only on input electrical quantities and nameplate data. This is a low cost approach for industrial conditions. There is no need to decouple the IM from the drive. The effectiveness of the proposed technique has been experimentally validated in real field conditions. Error is within limits between estimated efficiency and measured efficiency. This could be a significant highly non-intrusive approach for efficiency estimation of IM. Finally, it can be concluded that using non-intrusive air-gap method efficiency of IM can be found with least measurements and least intrusion level.

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