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A Simple, Robust and Non-Intrusive Technique of Efficiency Determination of In-Service Induction Motors

Abstract: - *In-situ* induction machine (IM) efficiency estimation is an essential tool for improved performance and better distribution management. IN industrial scenario, working efficiency of IM is affected by operation of IM at loads much less than rated loads and the impact of rewound or repair. In this paper, a simple, robust and non-intrusive technique of efficiency determination of in-service IMs utilizing non-intrusive air-gap torque method is proposed which considers stray-load and friction-windage loss as per IEC 60034-2-1:2007 Standard. This approach eliminates the need of speed sensor as well as torque sensor. The proposed method is simulated using MATLAB/SIMULINK and supported with experimental results.

Keywords: Efficiency, estimator, level of intrusion, speed sensor.

I. INTRODUCTION

The electric motors are most convenient means for electromechanical power conversion in the industry and approximately 55%-70% of the total industrial electric power is consumed by induction machines (IMs) [1]. Electrical motors and more specifically induction motors are the main loads in the electrical power system of industrialized countries. The efficiency of an induction motor can be affected by many factors such as ageing, over or under voltage conditions, the effects of rewinding and repair of the motor, or simply due to over or under loading conditions. In industry, these motors operate below 60% of their rated load. The oversized installations or under loaded conditions results in reduced efficiency which implies to wastage in power. Therefore, effective and affordable methods are needed to monitor the motor energy usage and health conditions for medium and small size motors [2]. Energy saving calculations and the relevant decisions, such as replacement of an existing motor with an energy efficient motor, are strongly dependent on the knowledge of the motor's efficiency [3]. The majority of standard techniques that are documented in the IEEE 112 Standard are not applicable for *in situ* efficiency measurement due to their highly intrusive nature [4]. The speed and torque transducers are very costly and their installations are highly intrusive. In most cases, it is even not possible to install these equipment's because the motors may be buried inside a machine or there is no space to attach such transducers between the motor and the load. A possible approach of evaluating efficiency is to use non-intrusive methods, which only rely on terminal voltages and currents while a motor is running, have to be developed for these applications. These methods use pre-measured motor characteristic efficiencies under representative load conditions during motor development to estimate the actual *in situ* efficiency measurement. In industrial plants, the motor terminal voltages and currents are readily available from the motor control room. The terminal parameters measurements bring no additional costs in terms of data collection. Clearly, this approach is nonintrusive in nature. However, some limitation are provided that the characteristic efficiencies under representative load conditions are not always available from motor data sheets and the characteristic efficiencies are generic data which could differ greatly from actual efficiencies for a specific motor due to many factors, such as improper nameplate information and other working environments effects the parameter [5].

Sensors are used for measuring the rotor speed in industry. Speed and torque sensors are quite costly [6]. Their installation in efficiency evaluation of IM increases the level of intrusion. Sometimes, IM is buried deep into the drive where rotor shaft is inaccessible for the installation of speed or torque sensors. Therefore, research got focused on to the non-intrusive techniques which rely only on supply voltages, currents and IM nameplate information.

This paper proposes a simple, robust and non-intrusive air-gap torque method for in-service motor efficiency estimation using only IM terminal quantities and information from IM's nameplate with special considerations of motor condition monitoring requirements.

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II. METHODOLOGY

The non-intrusive air gap torque (NAGT) method is to obtain the efficiency of IMs non-intrusively, while the motor is operating in service as shown in Figure 1. In this method, only motor terminal quantities and nameplate information are needed for efficiency estimation.

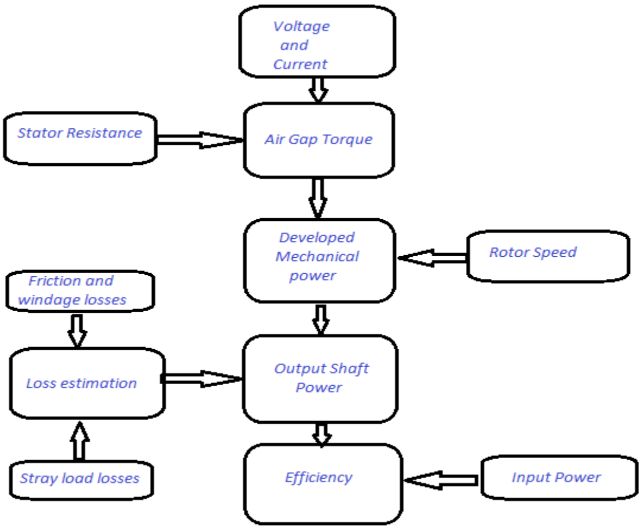

Fig. 1. NAGT procedure for efficiency estimation

III. A SIMPLE AND ROBUST TECNIQUE OF EFFICIENCY ESTIMATION OF INSERVICE IMS

This paper presents a simple and robust 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 [7]. This approach is feasible where it is quite hard to access the rotor shaft for speed measurement. The speed of rotor of IM in simulation is obtained using model reference adaptive system (MRAS) and compared with optically measured speed wirelessly. For speed estimation by MRAS in simulation, stator resistance, stator reactance and rotor time constant are required. MRAS uses error vector as feedback for attaining rotor speed. Core loss is achieved from voltages and currents using power harmonic analyzer. The proposed technique determines efficiency of IM at any load point.

The three-phase input supply to IM is given by

$$P_{input} = -V_{ca}(I_a + I_b) - V_{ab}I_b \tag{1}$$

Where, V_{ab} , V_{ca} are the line-to-line voltages and $I_{a,}I_b$ are the phase currents fed to IM.

By the application of Park's Transformation in electrical machine analysis, the air-gap torque can be obtained using the following equation [8].

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

Where, P represents number of poles, Rs denotes stator resistance, I_a, I_b, I_c are line currents of three phases A, B, C respectively.

The air-gap torque can be obtained using measured values of input two line-to-line voltages and two phase currents from power harmonic analyzer. This eliminates the need of torque sensor making the approach robust in nature.

Shaft torque of IM is expressed as

$$T_{shaft} = Shaft\ torque = T_{airgap} - \frac{F\&W}{\frac{2\pi N}{60}} - \frac{SLL}{\frac{2\pi N}{60}} \tag{3}$$

Where, T_{airgap} is air-gap torque, N is speed in rpm, F&W is friction and windage loss and SLL is the stray load loss. As per IEC standard [7], Friction and windage loss is 3.5% of rated input power and stray load loss is given by expression

$$S_{LL} = P_{in} \times \{0.025 - 0.005log_{10}\left(\frac{P_{out}}{1000}\right)\} \tag{4}$$

Speed is measured in a non-intrusive way by as given by MRAS structure employing IM voltages and currents in d-q axes transformations [9-10]. The figure 2 shows MRAS estimator which eliminates the need of speed sensor for speed measurement. MRAS speed estimator can be rotor flux based or back emf based. In this paper, rotor flux based estimator is utilized for rotor speed measurement. IN rotor flux based speed estimator, three quantities of IM namely stator resistance, stator inductance and rotor time constant are required. In the estimator, φ_{ds} and φ_{qs} are the d-axis and q-axis fluxes.V_{ds} , V_{qs} are the d-axis and q-axis voltages, R_s, L_s being the stator resistance and stator inductance and $T_2$is the rotor time constant. The rotor speed is denoted by ω_r.

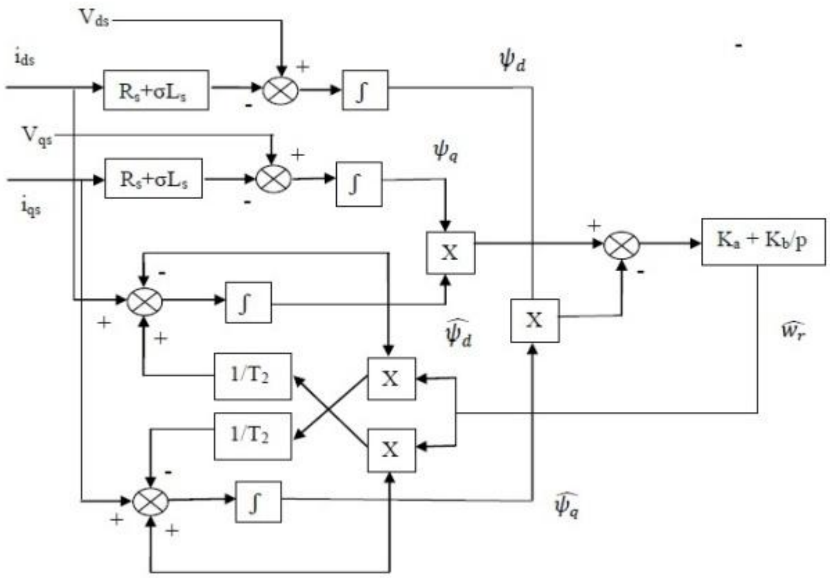

Fig. 2. MRAS for estimation of rotor speed

Efficiency of IM is given by

$$\eta = \frac{P_{output}}{P_{input}} = \frac{T_{shaft}.\omega_r}{P_{input}} = \frac{T_{airgap}.\omega_r - W_{fw} - W_{LLr}}{P_{input}} \tag{5}$$

IV. RESULTS OF THE PROPOSED TEXCHNIQUE

The proposed technique has been simulated on MATLAB/SIMULINK. Table 1 presents nameplate of IM under consideration. Parameters of IM are obtained by performing no-load and block-rotor tests. Then, these parameters are utilized in simulation and are depicted in Table 2.

TABLE 1. IM Nameplate

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

TABLE 2. IM Parameters

Stator resistance (Ω)	2.1
Stator reactance (Ω)	1.20
Rotor resistance (Ω)	11.71
Rotor reactance (Ω)	12.45
Mutual Inductance (Ω)	146.3

The figure 3 shows the experimental set-up for efficiency estimation of IM. For balanced case, three-phase supply of 410 volts is provided.

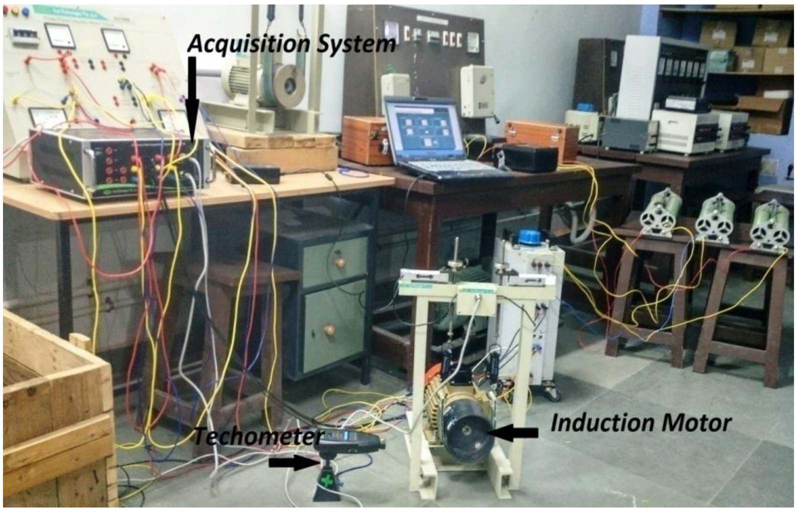

Fig. 3. Estimation of rotor speed using MRAS

The figure 4 shows rotor speed of 1372 rpm provided by MRAS estimator in simulation whereas optical tachometer shows 1394 rpm.

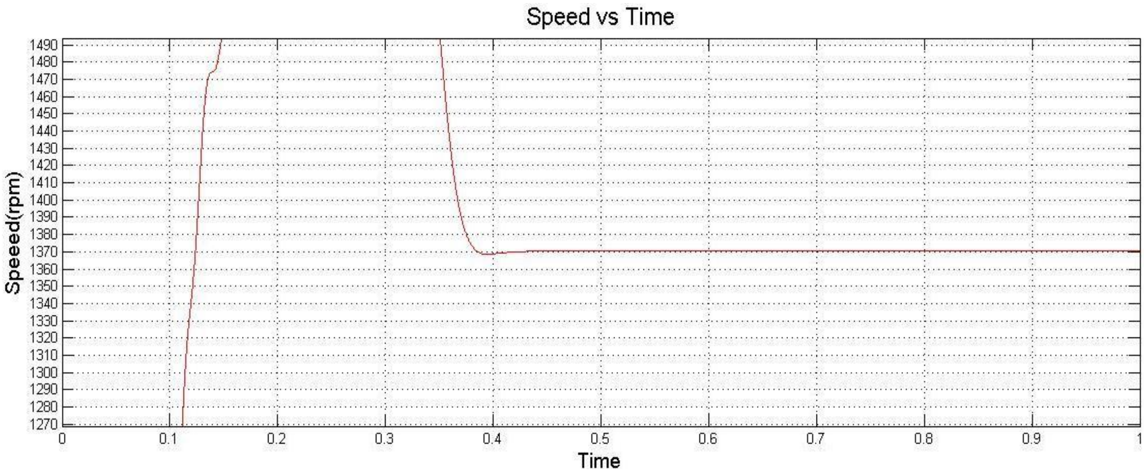

Fig. 4. MRAS speed in MATLAB simulation

The proposed technique is analyzed in balanced as well as unbalanced scenario. For unbalanced conditions in laboratory, 5% unbalancing among phases is created using rheostats. By using equations (1) to (5), efficiency of IM is obtained for both balanced as well as unbalanced cases. Table 3 gives torque and efficiency for balanced case.

TABLE 3. Torque and efficiency of IM in balanced case

% Load	Speed (rpm)	Efficiency		Torque	
		Estimated	Measured	Estimated	Measured
67.2	1394	60.7	59.2	3.9	3.63
79.0	1372	64.8	66.5	4.8	4.7

Table 4 provides efficiency and torque in Newton-metre of IM under unbalanced case where supply has 5% unbalanced voltages and harmonic content as well.

TABLE 4. Torque and efficiency of IM in unbalanced case

%Load	Speed (rpm)	Efficiency	Torque
45.8	1488	65.1	2.8
55.7	1382	58.3	2.3

It can be observed that the using proposed technique, there is no need to evaluate core loss and copper loss is not required. Core loss and copper loss are already considered in the air-gap torque.

V. CONCLUSION

This paper presents a simple, robust and non-intrusive air-gap torque method for efficiency estimation of in-service induction machines in which loss estimation is achieved using IEC 60034-2-1 Standard. The proposed technique is experimentally validated for balanced as well as unbalanced power supply case. The proposed technique avoids the use of torque and speed sensors for measurement purposes in efficiency determination of in-service induction machines. The major advantage of this technique is that it is based on IM terminal voltages and currents along with nameplate data of IM.

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