Efficiency Optimization of an Induction Machine using Optimal Flux Control

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***Abstract*—This paper presents the efficiency optimization of a variable speed induction machine (VSIM) using an Optimal Flux Control (OFC). To optimize the efficiency, an approach called as Maximum Torque per Ampere (MTA) algorithm was used to provide the constant optimal flux (COF) during the speed control, where the minimisation of the winding losses is considered along the operation. In this paper, the total power and total power loss during machine motoring is presented. The performance of the proposed OFC design is compared with the conventional open-loop scalar-control (OLSC) method. From the finding, it was found that the COF approach provides better performance than the OLSC in terms of settling time, steady-state error and efficiency.**

***Keywords*— optimal flux control, maximum torque per ampere, speed control, scalar-control**

I. Introduction

Constant speed constant frequencies (CSCF) of induction machines (IMs) are widely used because of their design simplicity and low cost. In many applications, at high speeds, IM runs at full speeds or at the rated torque, therefore, enabling high efficiency of machine's operation. However, at light loads, iron losses increase dramatically since power is directly proportional to the square of resistance. This loss increment reduces the machine's efficiency [1]. To improve machine efficiency, the flux must be optimized to obtain a balance between copper and iron losses [2].

Basically, the efficiency of electric-machines with loss minimization can be improved via two methods, which are loss model based and power measured based [1]. The loss model based method is simple as this method does not require additional hardware [3]. However, this method relies heavily on the accuracy of the machine parameters, is difficult to implement and also has high sensitivity to the parameter variations [4]. Meanwhile, the power measured based does not require knowledge on machine's parameters. In this method, the power consumption is measured and the optimum flux algorithm is searched for [2]. However, compared between these two, the former method is more efficient in any state-conditions [5].

This paper addresses the first method, and proposes a simple technique for efficiency optimization by optimizing the flux control over their speed ranges, by reducing the power losses. This study focuses on optimizing the performance of scalar-controlled of squirrel-cage variable speed induction machine (VSIM) of a small IM, with rated power of 1.1kW. Optimal speed control, which is based on the well-known Maximum Torque per Ampere (MTA) algorithm with the adaption of vector control that provides the optimal flux to the speed control by minimizing the machine losses, is used in this method.

This paper is organized into four sections, including the introduction. In the Methods section, the principle work of the open-loop scalar-control (OLSC) and the proposed constant optimal flux control (COFC) is explained. The simulation results of the proposed methods are discussed, which can be found in the third section, whereby the last section provides the conclusions.

II. Methods

In this section, the methods employed in this study are explained, which consisted of scalar control, adaptation of vector control approach in the squirrel-cage induction machine (SCIM) model, proposed COF method, loss minimization strategy, maximum torque per ampere (MTA) approach in minimizing the stator current, and also system parameters.

A. Scalar Control of IM

Scalar control, or known as V/f control of induction machine, functions to indicate the scheme of controlling the torque and speed by varying the voltage and supply frequency simultaneously to maintain the magnetic flux at its rated value. This variation is done to ensure that torque capability is maximized during the operation. As stated in [7], if the voltage of an IM is changed without a proper frequency modification, the machine may instead operate in saturation region or in the flux field weakening region.

This work was supported by Ministry of Higher Education (MOHE), Malaysia and Universiti Teknologi Malaysia (UTM) for the financial support provided under Research University Grant (RUG) Q.J130000.2523.05H18

The conventional scalar control, or also usually known as open-loop scalar control (OLSC), is widely used in the industry due to of its ease of use and minimal cost. The OLSC method that was applied to an IM in this study is shown in Fig. 1. OLSC allows speed control by adjusting the supply frequency. When the frequency is changing, the reference voltage, V_{ref} will be changed accordingly by maintaining the V_{ref}/ω_s^* ratio.

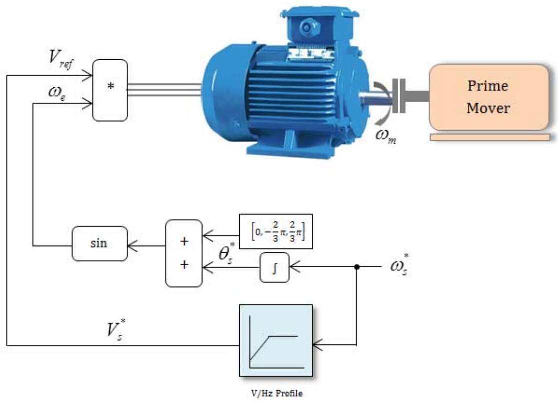


Fig. 1 Block diagram of open-loop scalar control (OLSC)

B. SCIM Dynamic Model Adapting Vector Control

A dynamic model of a SCIM is presented by the following set of equations which are derived from Kron's equations equivalent circuit model [6]. The modelling equations in this model are expressed as follows:

$$v_{qs}^e = R_s i_{qs}^e + p\varphi_{qs}^e + \omega_e \varphi_{ds}^e \tag{1}$$

$$v_{ds}^e = R_s i_{ds}^e + p\varphi_{ds}^e - \omega_e \varphi_{qs}^e \tag{2}$$

$$v_{qr}^e = R_r i_{qr}^e + p\varphi_{qr}^e + (\omega_e - \omega_r)\varphi_{dr}^e \tag{3}$$

$$v_{dr}^e = R_r i_{dr}^e + p\varphi_{dr}^e - (\omega_e - \omega_r)\varphi_{qr}^e \tag{4}$$

$$\varphi_{qs}^e = X_{ls} i_{qs}^e + X_m i_{qr}^e \tag{5}$$

$$\varphi_{qr}^e = X_{lr} i_{qr}^e + X_m i_{qs}^e \tag{6}$$

$$\varphi_{ds}^e = X_{ls} i_{ds}^e + X_m i_{dr}^e \tag{7}$$

$$\varphi_{dr}^e = X_{lr} i_{dr}^e + X_m i_{ds}^e \tag{8}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right) \tag{9}$$

$$T_e - T_L = J\left(\frac{2}{P}\right)p\omega_r \tag{10}$$

$$P_m = \omega_r T_e \tag{11}$$

where d : direct axis, q : quadrature axis, s : stator variable, r : rotor variable, v_{qs}, v_{ds} : q-axis and d-axis stator voltages, v_{qr}, v_{dr} : q-axis and d-axis rotor voltages, v, i and φ : voltages, currents, fluxes, R_s, R_r : stator and rotor resistance, X_{ls}, X_{lr}, X_m : stator, rotor leakage and mutual reactance, p : time derivative component, P : number of poles, J : moment of inertia, T_e : electrical torque, T_L : load torque, P_m : mechanical speed, ω_e : stator angular electrical frequency, ω_r : rotor angular electrical speed.

The type of SCIM, v_{qr}andv_{dr} in (3) and (4) are set to zero. The steady state equations may be expressed by integrating (5) and (7) into (3) and (4), which consequently give:

$$0 = \frac{r_r}{X_{lr}}\left(\varphi_{qr}^e - X_m i_{qs}^e\right) + \omega_{sl}\varphi_{dr}^e + p\varphi_{qr}^e \tag{12}$$

$$0 = \frac{r_r}{X_{lr}}\left(\varphi_{dr}^e - X_m i_{ds}^e\right) - \omega_{sl}\varphi_{qr}^e + p\varphi_{dr}^e \tag{13}$$

where $\omega_{sl} = \omega_e - \omega_r$. Then, vector control is adapted to the dynamic equations, $\theta_e = 0$ is preferred such that φ_{qr}^e is equal to zero. Hence, (12) and (13) become:

$$0 = -\frac{r_r}{X_{lr}}\left(X_m i_{qs}^e\right) + \omega_{sl}\varphi_{dr}^e \tag{14}$$

$$0 = -\frac{r_r}{X_{lr}}\left(\varphi_{dr}^e - X_m i_{ds}^e\right) + p\varphi_{dr}^e \tag{15}$$

Then, when i_{ds}^e is controlled to a constant value, by assuming that $p\varphi_{dr}^e = 0$, (15) can be written as

$$\varphi_{dr}^e = X_m i_{ds}^e \tag{16}$$

C. Loss Minimization Strategy

As mentioned previously, the main objective of this study is to optimize the SCIM system by minimizing the copper losses of the machine. In IM, copper losses contribute 60% to overall losses produced [8]. Meanwhile, 37% of the total losses are composed from the stator side, whereby the rest comes from the rotor side. Since these losses occur during the flow of the electric current through the stator and rotor windings, the losses can be calculated by using the information of the current flow in the wires and the conductor bars along with their resistances. For the three-phase windings of IM, the copper losses can be expressed as

$$P_{copper} = 3I_s^2 \cdot R_s + 3I_r^2 \cdot R_r \tag{17}$$

Therefore, by considering only the copper losses and neglecting other losses in order to optimize the system, it is possible to show that:

$$P_{elec} = P_{copper} + P_{mech} \tag{18}$$

For the purpose of modelling simplicity in this study, the IM losses were modelled in the steady state condition.

D. The Proposed Constant Optimal Flux (COF) Method

Fig. 2 depicts the COF model algorithm applied in an IM.

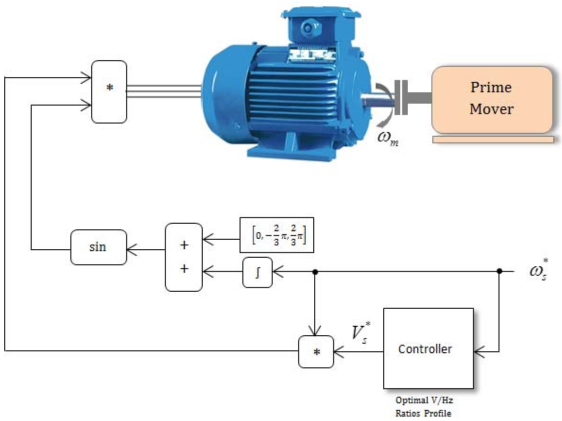


Fig. 2 The Proposed optimal speed control scheme

To obtain the COF strategy, the torque-speed curve at several operating points should be plotted. By fixing the load torque, T_{load} and the stator angular speed, ω_s^* at a certain value, the operating points where the minimum losses occurred could be identified. By considering a steady-state equivalent circuit of an IM as depicted in Fig. 3, the electromotive force E was formulated as:

$$E = V_{as} - R_s I_s \tag{19}$$

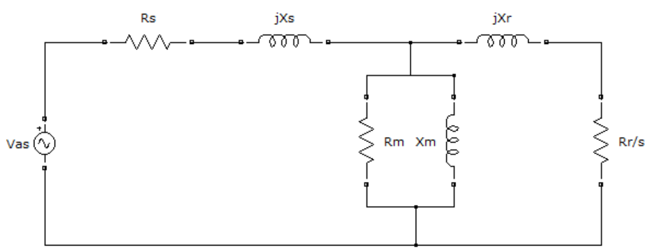


Fig. 3 Equivalent circuit of per-phase IM

When the developed simulation model using the parameter values as listed in Table 1 was tested, the values of the COF for each synchronous speed could recorded.

TABLE I. SYSTEM PARAMETER

Parameter	Value
Number of phases	3
Rated power	1.1kW
Rated voltage	230/400 V
Frequency	50 Hz
Rated speed	1400 rpm
Number of poles	4
Stator resistance	8.37 Ω
Rotor resistance	8.79 Ω
Stator/Rotor inductance	499 mH
Magnetising inductance	476 mH
Rotor inertia	0.01 kgm^2

Fig. 4 shows the comparison of total loss between conventional V/f control (constant V/f ratio) and optimal V/f ratio at ω_r = 100 rad/s and T_e = 5 Nm. Both of total power loss curves are obtained by calculating the copper losses occur at the stator and rotor windings of the machine using equations (16) to (19). It shows that the optimal condition that assures minimum losses at this operating point is $\omega_{e(opt)} = 117$ rad/s.

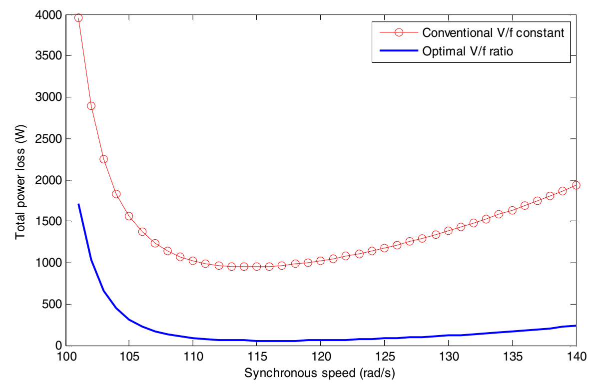


Fig. 4 Total power loss when $\omega_r = 100$ rad/s and $T_e = 5$ N.m.

E. Loss Minimization Strategy

As previously mentioned, this paper provides optimal flux to the scalar-controlled IM system based on MTA approach. Using MTA approach, the efficiency of IM can be controlled based on this (16) expression,

$$= \frac{Torque_{max}}{Amp} \tag{20}$$

Maximum Torque per Ampere (MTA) promises maximum efficiency to the system by minimizes the value of the current while ensuring the value of torque is maximized during the operation. Therefore, by substituting (16) into (14) and solving for ω_{sl},

$$\omega_{sl} = \frac{R_r}{X_{lr}} \cdot \frac{i_{qs}^e}{i_{ds}^e} \tag{21}$$

At this point, the value of optimal ω_{sl} (slip angular frequency) can be obtained by varying the components of stator current, I_s. By adapting Indirect Vector Control method to the IM, the electromagnetic torque and the slip angular frequency can be expressed as [18]:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_m}{L_r}\right)\left(\varphi_{dr} \cdot i_{qs}\right) \tag{22}$$

Then, by substituting (16) into (18),

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_m^2}{L_r}\right)\left(i_{ds} \cdot i_{qs}\right) \tag{23}$$

In order to ensure that the torque is at the maximum capability during the operation, the components of stator current should in (21) be set equal to each other so that the product of $i_{ds} \cdot i_{qs}$ is maximized. Thus, the MTA approach acts by regulating ω_{sl} which is achieved by controlling i_{ds} and i_{qs} components of stator current to be equal, by means of

$$\omega_{sl} = \frac{R_r}{X_{lr}} \tag{24}$$

According to power losses curves obtained from Fig.4, the optimal slip angular frequency $\omega_{sl(opt)}$ at $\omega_r = 100$ rad/s that provides the lowest total power loss is when $\omega_{sl(opt)} = 117$ rad/s. It is coincides with the MTA approach which is obtained from equation (24). For the different load conditions, the total power loss is calculated based on the obtained fix $\varphi_{(opt)}$ at $T_L = 5$ Nm for $\omega_r = 100$ rad/s is depicted in Fig. 5. It shows that at different load conditions (1 Nm, 3 Nm, 5 Nm and 7 Nm), the value of $\omega_{sl(opt)}$which is located at the lowest point of total power loss curves for each conditions are approximately equals to $\omega_{e(opt)} = 117$ rad/s which means that the fix $\varphi_{(opt)}$ is satisfied for all load conditions when the machine is operating at $\omega_r = 100$ rad/s. Other than that, this figure indicates that the total power loss is inversely proportional as the load torque T_{load} is increased thus it caused the efficiency of machine to be contrary with the increment of T_{load}.

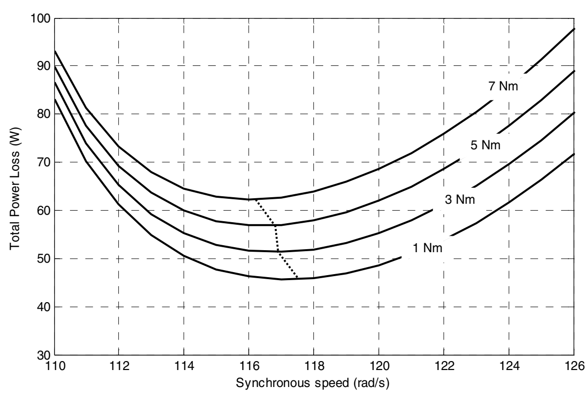


Fig.5 Total power loss as function of synchronous speed under variable load torque T_{load} at $\omega_r = 100$ rad/s.

The values of the optimal V/f ratios chosen by varying the flux values that can minimized the losses at all operating points including low speed and high speed operating points are plotted in Fig. 6.

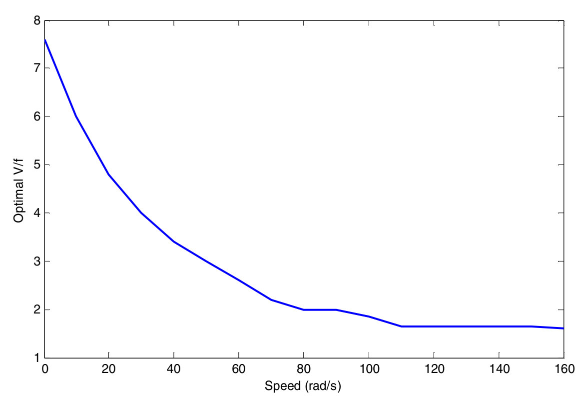


Fig. 6 Optimal V/f ratios at during all speed range

The system efficiency of IM can be calculated using equation below.

(20)

$$= \frac{P_m}{P_e}\ x\ 100\% \tag{25}$$

III. SIMULATION RESULTS

As this study was focused to the motoring mode, the machine behavior was examined when rotor speed was operating from zero to the synchronous speed ($0 \leq \omega_r \leq 157.7$) rad/s. To find the COF for each operating speed, the test was executed when the torque was set at the rated value. The rated torque of the study machine at 1.1 kW was 7 N.m.

The comparison (from calculation) of the total power loss in the conventional (constant V/f) and the optimized system under variable operating speeds, covering from 20 to 150 rad/s, with 20 rad/s interval is shown in Fig. 7. From this figure, it can be seen that the optimized system presents lower losses compared to the conventional constant V/f system. The least losses occurred at 100 rad/s. However, the most significant difference of the losses occurs when speeds are set at high speed range between 140 rad/s and 150 rad/s. Losses can be significantly reduced when COF method is used.

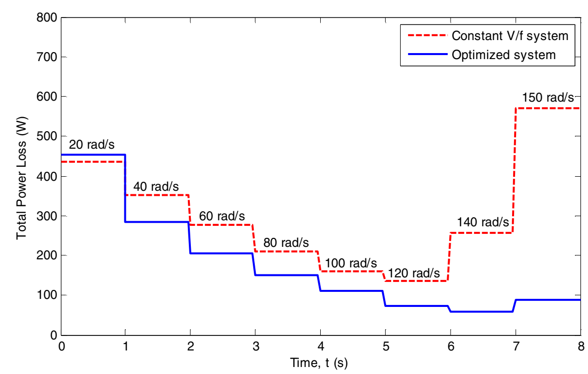
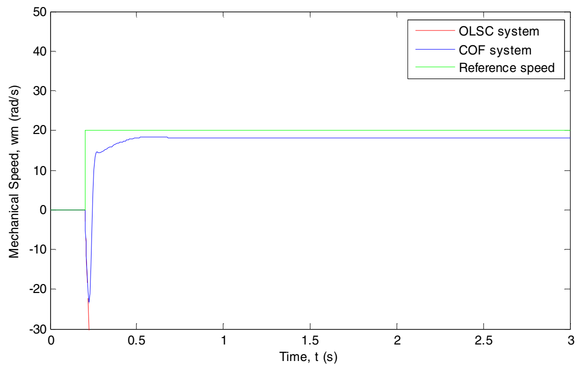


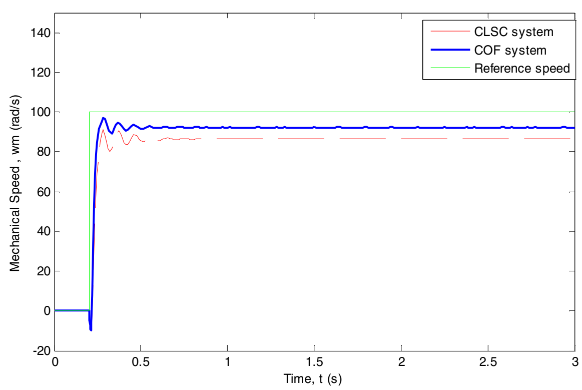
Fig. 7 Total power loss in conventional system and optimized system under variable operating speeds in producing mechanical energy at $T_L = 7Nm$

The dynamic response performances between these two methods (OLSC and COF) at different operating speed ranges are shown in Fig. 8. Fig. 8(a) to Fig. 8(c) show the mechanical speed responses when the synchronous speeds were set at 20, 100 and 150 rad/s, respectively. The COF presented faster settling time and smaller steady-state error compared to the OLSC. The COF could also settle around 0.1 second faster than OLSC.

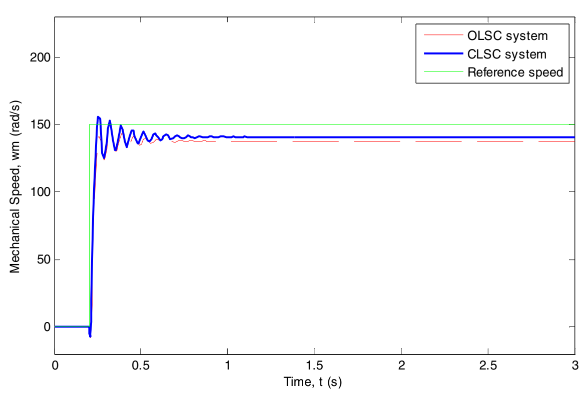
At low speed (20 rad/s), as shown in Fig. 8(a), OLSC cannot produced any mechanical output, while at higher speed (100 rad/s and 150 rad/s), both COF and OLSC insisted the IM to produce mechanical power besides they had very close steady state error. Nevertheless, both these two methods had higher percentage of steady-state error when speed was set at 20 rad/s. At 20 rad/s, the percentage of steady-state error reached approximately 10%, whereby at 150 rad/s, the percentage of steady-state error reached around 6.7%. When speed was set at 100 rad/s, obvious steady state difference could be observed between OLSC and COF methods. Though both methods failed to reach zero steady-state error, COF presented much better steady state error (8%) than OLSC (18%).



(a) at $T_L = 7\ Nm$ and $\omega_e = 20\ rad/s$



(b) at $T_L = 7\ Nm$ and $\omega_e = 100\ rad/s$



(c) at $T_L = 7\ Nm$ and $\omega_e = 150\ rad/s$

Fig. 8 Dynamic response of angular mechanical speed

Fig. 9 shows the stator current response as evidence of the effectiveness of MTA approach in the proposed COF. From the figure, it can be seen that the stator current could be reduced when COF method was used. The stator current started to decrease lower than that of the OLSC when speed reached 56 rad/s onwards. This is due to the limitation of OLSC which could not produce any mechanical output when the operating speed is at the low speed ranges. Therefore, the losses could be successfully reduced when the motor rotated at higher speed.

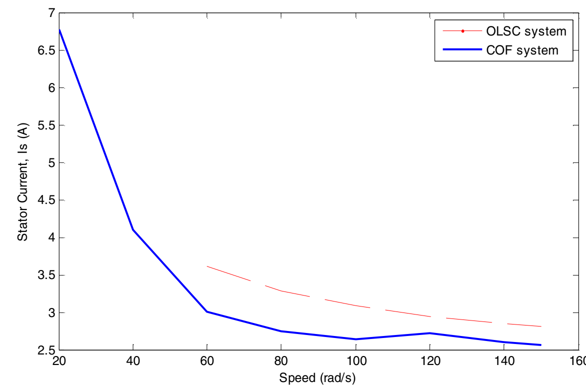


Fig. 9 Stator current dynamics responses during motoring mode

The efficiency comparison between OLSC and COF methods of the IM during motoring mode is plotted in Fig. 10. The figure shows that COF method presented higher efficiency than the OLSC method, particularly at higher speeds. This agrees well with the results shown in Fig. 7. For the different load conditions, with the observation of Fig. 5, it can be argued that the efficiency of IM using COF control method can be slightly decreased as the load torque increased but still managed to beat the effectiveness of OLSC system.

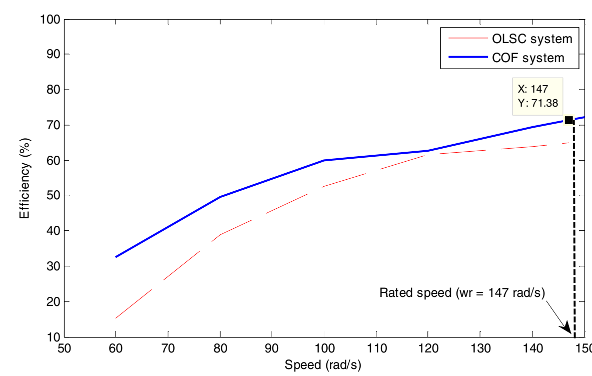


Fig. 10 Efficiency of the OLSC and COF methods at each operating speed during motoring mode

IV. Conclusions

A dynamic model of a three-phase squirrel-cage of 1.1 kW induction machine has been developed and simulated using Matlab/Simulink software to evaluate the performance of OLSC and COF methods in IM operation. From the finding, it can be concluded that the COF method, which is adapted using vector control and based on the MTA approach, presents better performance in terms of settling time and steady-state error performance than the OLSC when the flux is optimised at each operating speed. Using COF with the employment of MTA approach, the efficiency of an IM can also be increased or improved, as the power losses in the winding machine can be minimized when the stator current is proven minimized.

ACKNOWLEDGMENT

This work was supported by Ministry of Higher Education (MOHE), Malaysia and Universiti Teknologi Malaysia (UTM) for the financial support provided under Research University Grant (RUG) Q.J130000.2523.05H18) to carry out this research.

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