Calculation of Maximum Torque Operating Conditions for Inverter-Fed Induction Machine Using Finite Element Analysis

Haiwei Cai, Member, IEEE, Le Gao, Member, IEEE, Longya Xu, Fellow, IEEE

Abstract—A procedure to calculate the maximum torque to current ratio operating conditions for the inverter-fed induction machine is proposed. The proposed procedure minimizes the finite element analysis computation load by identifying the variation range of stator current and slip frequency for the entire torque-speed map. Thus, the total calculation time for machine steady state performance estimation can be significantly reduced. The effectiveness of the proposed procedure is validated by experiment.

Index Terms—Finite Element, Flux Weakening, Induction Machine, Maximum Torque Per Ampere, Maximum Torque Per Volt, Optimal, Slip Frequency, Stator Current, Torque.

I. INTRODUCTION

INDUCTION Machines (IMs) have been widely used in all kinds of applications for many years. Because the operating torque-speed range of the inverter-fed IM is limited by the DC bus voltage, maximum stator current and maximum rotor speed, many optimal operating criteria have been proposed, which include maximum power transfer [1], maximum efficiency [2], and optimal power factor [3].

In this paper, the optimal operating criterion means the IM can provide the desired torque-speed output with maximum torque to current ratio. To satisfy this criterion, Maximum Torque Per Ampere (MTPA) control [4], Flux Weakening (FW) control [5] and Maximum Torque Per Volt (MTPV) control [6] should be adopted at low, medium and high speeds respectively. Even though the feasibility of this operating criterion has been well-proven by experiment [7], [8], the estimation of steady state machine performance under this criterion in the machine design stage remains an open topic.

Since Finite Element Analysis (FEA) can achieve a great balance between accuracy and cost when compared with analytical method [9]–[11] and experimental method [12], it is frequently used in electric machine performance estimation. However, the FEA calculation can become impractically time consuming for IM analysis due to two reasons. First, the large electrical time constant of the cage rotor introduces possible long transient response before reaching steady state. Second, a large number of operating conditions need to be estimated as raw data before finding the optimal ones by interpolation.

To mitigate the first issue, four measures were proposed in [13] to reduce the transient response calculation time without sacrificing the accuracy in steady state. However, there is still transient response in the rotor bars because the transient FEA is adopted. To completely avoid the transient dynamic, a strategy based on the magnetostatic FEA was proposed in [14]. This strategy suggests imposing current sources to stator windings and rotor bars at the same time. It is fast and capable of capturing the saturation effect, but the accuracy could be degraded because the skin effect in rotor bars is not considered. Besides, to consider the tooth/slot effect, this strategy has to calculate machine performance at every rotor angle, which is against the time-saving purpose of this strategy.

Meanwhile, there are limited publications addressing the second issue at the machine design stage. It is mentioned in [15] that a non-linear optimization method is used to search for the optimal input control vector of [stator voltage, synchronous frequency, slip percentage]. However, there is no detail discussion on the performance of the non-linear optimization method. An IM design methodology involving FEA calculation to obtain the entire torque-speed map is reported in [16]. However, the approach to select those FEA calculation points has not been discussed.

Because the accuracy of the interpolation depends on the density of the raw data points and each raw data point is expensive, it is not an ideal solution to find the optimal
operating conditions by exhausted search. To solve this issue, this paper proposes a procedure to quickly identify the ranges of stator current and slip frequency for the optimal operation in the entire torque-speed map. Thus, the number of raw data points can be minimized without sacrificing the interpolation accuracy. Note that the proposed procedure focuses only on the steady state performance of the IM and the analysis will focus on the fundamental components.

The content of this paper is organized as follows. In Section II, the steady state model of the IM is presented. The ranges of stator current and slip frequency are discussed and identified in Section III. The proposed procedure is presented in Section IV and evaluated by an example IM in Section V. Section VI summarizes this paper.

II. steady state model in DQ reference Frame

The steady state model of an IM in synchronous d–q reference frame can be expressed by (1)-(9).

\[ v_{ds} = R_s i_{ds} - \omega_e \lambda_{qs} \]  
\[ v_{qs} = R_s i_{qs} + \omega_e \lambda_{qr} \]  
\[ 0 = R_r i_{dr} - \omega_e \lambda_{qr} \]  
\[ 0 = R_r i_{qr} + \omega_e \lambda_{dr} \]  
\[ \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \]  
\[ \lambda_{qs} = L_s i_{qs} + L_m i_{dr} \]  
\[ \lambda_{dr} = L_r i_{dr} + L_m i_{ds} \]  
\[ \lambda_{qr} = L_r i_{qr} + L_m i_{qs} \]  
\[ T_s = \frac{\text{poles}}{2} \left( \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} \right) \]  

In rotor flux reference frame, \( \lambda_{qr} \) equals zero. Consequently, (10)-(14) can be derived from (3)-(9).

\[ \lambda_{qs} = \left( L_s - \frac{L_m^2}{L_r} \right) i_{qs} \]  
\[ \lambda_{ds} = L_s i_{ds} \]  
\[ \lambda_{dr} = L_m i_{ds} \]  
\[ \omega_{slip} = \omega_e - \frac{R_r i_{qs}}{L_r i_{ds}} \]  
\[ T_e = \frac{\text{poles}}{2} \frac{3}{2} i_{ds}^2 L_m^2 \left( \frac{1}{L_r} + \frac{R_r}{L_r \omega_{slip}} \right)^2 \]  

If the linear machine model is used, MTPA control can be achieved when \( i_{ds} = i_{qs} \). As machine speed increases, DC bus voltage becomes another constraint for the output torque. Then the IM will enter FW region by decreasing \( i_{ds} \). At high speed, MTPV control is achieved when \( v_{qs} = \omega_e L_s \left( 1 + \frac{R_r}{\omega_e L_r} i_{qs} \right) i_{ds} \) \( (R_s \text{ is neglected}) \) [6]. The corresponding current trajectory in the \( i_{ds} - i_{qs} \) plane is indicated by the dash lines in Fig. 1.

It should be pointed out that the classical dq model with fixed parameters provides a good base for theoretical analysis. It also yields good performance estimation result when the saturation and skin effect are not significant. Besides, there are many control algorithms that are not sensitive to machine parameters changes [17], [18]. Consequently, the classical dq model is still a good fit in these cases. However, it does not provide the same level of accuracy when compared with FEA model for estimating the IM performance in the design stage.

If saturation and skin effect are considered, the parameters of the IM become highly nonlinear. It is well-known that \( R_r \) increases as \( \omega_{slip} \) increases due to skin effect and the inductances decreases as saturation level increases. The nonlinear MTPA, FW and MTPV curves will shift to the high slip frequency side of linear ones as indicated by the solid lines in Fig. 1, which is also reported in [7], [8]. (10)-(14) show that flux, inductance and torque are functions of \( i_{ds} \) and \( i_{qs} \), which can be calculated based on (13) once \( I_s \) and \( \omega_{slip} \) are known. Hence, \( I_s \) and \( \omega_{slip} \) can be used to determine the parameters and performance of an IM.

III. OPTIMAL OPERATING CONDITIONS OF IM

A. MTPA control at low speed.

When the IM speed is low, MTPA control is commonly used because \( I_s \) is the only constraint for torque production. However, the MTPA curve shown in Fig. 1 does not tell how the important quantities of the IM, such as \( \lambda_s \) and \( T_e \), are affected by \( \omega_{slip} \) and \( I_s \). Hence, these nonlinear relationships are further illustrated in Figs. 2 and 3.

As shown in Fig. 2, \( \omega_{slip} \) along the MTPA curve starts from a low value (\( \omega_{slip, min} \)) when \( I_s \) is low. As \( I_s \) increases, the MTPA slip frequency also increases due to saturation. At maximum stator current \( I_{s,max} \), the maximum torque \( T_{e,max} \) is achieved at \( \omega_{slip,B} \).

Note that the operating points on the low slip frequency side of the MTPA curve do not need to be considered. This is because these operating points require higher \( \lambda_s \) for generating the same torque when compared with the corresponding high slip frequency operating points under the same \( I_s \).

B. FW Control at Medium Speed.

FW control is needed when rotor speed increases and the IM can no longer operate along the MTPA curve due to DC bus voltage limit. It can be observed in Fig. 3 that increasing \( \omega_{slip} \) will reduce \( \lambda_s \) when \( I_s \) is constant. Hence, increasing \( \omega_{slip} \) is equivalent to performing FW control, which will allow the IM to operate at a higher speed at the price of lower torque production. To avoid over weakening the stator flux, it is important to know the highest speed possible for any \( \omega_{slip, I_s} \) operating point in Figs. 2 and 3. The stator voltage, as expressed by (15), is derived from (1), (2) and (9).
Slip Frequency
Torque
MTPA
Ismax
0.9Ismax
0.8Ismax
Tmax
slip0 slipB

Fig. 2. Torque v.s. slip frequency at various current values.

Flux
Ismax
0.9Ismax
0.8Ismax
slip0 slipB

Fig. 3. Stator flux v.s. slip frequency at various current values.

\[ v_s^2 = (R_s i_{ds} - \omega_e \lambda_{qs})^2 + (R_s i_{qs} + \omega_e \lambda_{ds})^2 \]
\[ = R_s^2 i_s^2 + 8R_s^2 \left( \frac{\omega_r + \omega_{slip}}{3 \text{pole} \epsilon_s} \right) T_e + (\omega_r + \omega_{slip})^2 \lambda_s^2 \]  \hspace{1cm} (15)

If the data in Figs. 2 and 3 are available, the highest speed for any \([\omega_{slip}, I_s]\) combination can be calculated from (15) by letting \(v_s = \frac{V_{dc}}{\sqrt{3}}\) (assume SVPWM is adopted [19]). In the following discussion, these “highest” speeds will be called the boundary speeds. The boundary speed for the maximum torque point is the well-known base speed (\(\omega_{rB}\)).

All \([\omega_{slip}, I_s]\) combinations sharing the same boundary speed are connected by the black solid lines in Figs. 4 and 5. These boundary speed curves start from the MTPA curve and end at the \(I_{smax}\) curve. Obviously, these boundary speed curves are the optimal operating points (maximum torque to current ratio) in the FW control region.

C. MTPV Control at High Speed.

MTPV control is often used to achieve the maximum torque in the high speed region, which is also called the Deep Flux Weakening (DFW) region since the stator flux is further decreased. As shown in Fig. 6, when the rotor speed goes beyond a certain value, i.e., \(\omega_{rDFW}\), each boundary speed curve will have a maximum torque point where the stator current is lower than \(I_{smax}\). Hence, the constraint from \(I_{smax}\) will be gone, and the DC bus voltage will become the only factor limiting the torque production. Obviously, \(\omega_{rDFW}\) separates the medium and the high speed regions. The solid line connecting these maximum torque points is the MTPV curve, which intersects the \(I_{smax}\) curve at Point C (\(\omega_{slipDFW}, I_{smax}\)) and the \(\omega_{rmax}\) curve at Point F (\(\omega_{slipF}, I_{sF}\)).

D. Optimal Operating Region.

Based on the analysis in the subsections above, the optimal operating conditions of the IM can be summarized. As indicated in Figs. 4 and 5, the area confined by the MTPA, the \(I_{smax}\), the MTPV and the \(\omega_{rmax}\) curves represents the optimal operating region of the IM. The operating points inside this region can achieve the desired torque-speed output with the lowest stator current under the DC bus voltage and maximum current constraints. The relationship between the optimal stator current and slip frequency at various rotor speeds is shown in Fig. 7, where all the black solid lines are at the same voltage (maximum stator voltage).
IV. PROCEDURE FOR OPTIMAL OPERATING POINT CALCULATION

Because the torque production and the flux level of the IM are functions of $I_s$ and $\omega_{\text{slip}}$ regardless of the rotor speed $\omega_r$, calculating the machine performance at various $[\omega_{\text{slip}}, I_s]$ combinations inside the optimal operating region at one rotor speed will provide enough information to generate the optimal torque-speed map. The goal of this section is to propose a procedure to quickly identify this optimal operating region by minimum amount of computation effort.

As shown in Fig. 7, if the four boundaries of the optimal operating region (MTPA, $I_{s\text{max}}$, MTPV and $\omega_{r\text{max}}$) are identified, the calculation range of $[\omega_{\text{slip}}, I_s]$ combinations will be minimized. However, obtaining the accurate MTPA and MTPV curves is not a quick task because it requires a search in the $\omega_{\text{slip}} - I_s$ plane. In contrast, the machine performance on the $I_{s\text{max}}$ and $\omega_{r\text{max}}$ boundaries can be calculated directly by varying only $\omega_{\text{slip}}$. So it will be easier to start from the $I_{s\text{max}}$ and $\omega_{r\text{max}}$ boundaries. Based on this observation and the discussion in the previous sections, the procedure with the following steps is proposed.

Step 1: Calculate the maximum speed boundary by varying slip frequency at maximum rotor speed and maximum stator voltage. The highest torque occurs at Point F ($\omega_{\text{slip},F}, I_{sF}$).
  - If $I_{sF} = I_{s\text{max}}$, then the machine operates in FW region (Fig. 8). The maximum slip frequency $\omega_{\text{slip},\text{max}}$ equals $\omega_{\text{slip},F}$.
  - If $I_{sF} < I_{s\text{max}}$, then the machine operates in MTPV region. To include the MTPV curve in the calculation region, the straight line connecting Point O (the origin) and Point F is extended to intersect with $I_{s\text{max}}$ at Point G ($\omega_{\text{slip},G}, I_{s\text{max}}$) (Fig. 9). $\omega_{\text{slip},\text{max}} = \omega_{\text{slip},G} = \frac{I_{s\text{max}}}{I_{sF}} \omega_{\text{slip},F}$ in this case.

Step 2: Calculate the maximum current boundary by varying slip frequency between 0 and the maximum slip frequency. The maximum torque occurs at Point B ($\omega_{\text{slip},B}, I_{s\text{max}}$).

Step 3: Calculate machine performance with all $[\omega_{\text{slip}}, I_s]$ combinations inside the optimal operating region.

Two extra lines are added to ensure the MTPA curve is included in the calculation. The first one is line OB, which defines the lower boundary of slip frequency. The second one is the line connecting Point B and Point D ($\omega_{\text{slip},B}, 0$), which intersects the maximum speed boundary at Point E.

If $I_{sF} = I_{s\text{max}}$, the calculation region shaded in yellow as shown in Fig. 8 is proposed. If $I_{sF} < I_{s\text{max}}$, the calculation region shaded in yellow as shown in Fig. 9 is proposed. Following the three steps above, it is obvious that all the optimal $[\omega_{\text{slip}}, I_s]$ combinations will be included in the proposed calculation region. The flowchart of the proposed procedure is shown in Fig. 10. The corresponding boundary speeds and stator voltage can be then calculated by (15).

The proposed calculation region contains minimal amount of non-optimal points (Triangle AED, CFG in Fig. 9). Eliminating these non-optimal points can further reduce the $[\omega_{\text{slip}}, I_s]$ combinations needed in Step 3. However, this approach can be counter-productive because it requires extra effort to identify the accurate MTPA and MTPV curves. Hence, it could be faster and more convenient to just simply include those non-optimal points.

To quantify the computation time saved for analysis, we can assume $\omega_{\text{slip},\text{max}}$ is already known. Without the proposed method, the calculation area for $[\omega_{\text{slip}}, I_s]$ combinations equals $\omega_{\text{slip},\text{max}} * I_{s\text{max}}$. With the proposed method, the calculation area can be further narrowed down by about 50% as shown by the shaded areas in Figs. 8 and 9. Considering the calculation range of the slip frequency is usually much larger than $\omega_{\text{slip},\text{max}}$ without the proposed method, the improvement is even more significant. Hence, the proposed method can easily reduce the FEA computation load by more than 50%.
IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS

Fig. 10. Flowchart of the proposed procedure.

Fig. 11. Cross-section of the example induction machine (one pole pair).

TABLE I
SPECIFICATIONS OF THE EXAMPLE INDUCTION MACHINE

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Poles</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Stator/Rotor Slot Number</td>
<td></td>
<td>36/44</td>
</tr>
<tr>
<td>Stack Length</td>
<td>mm</td>
<td>138</td>
</tr>
<tr>
<td>Stator OD/ID</td>
<td>mm</td>
<td>220/141</td>
</tr>
<tr>
<td>Rotor OD/ID</td>
<td>mm</td>
<td>140.1/70</td>
</tr>
<tr>
<td>DC Bus Voltage</td>
<td>V</td>
<td>300</td>
</tr>
<tr>
<td>Maximum Stator Current Peak A</td>
<td></td>
<td>360</td>
</tr>
<tr>
<td>Maximum Rotor Speed RPM</td>
<td></td>
<td>6000</td>
</tr>
<tr>
<td>Stator Phase Resistance ohm</td>
<td></td>
<td>0.028</td>
</tr>
</tbody>
</table>

V. VALIDATION OF PROPOSED PROEDURE

The two issues reported in the Introduction section are especially severe when the IM uses a copper cage rotor, which has a larger rotor time constant and consequently more sensitive to variation of slip when compared with an aluminum cage rotor. Hence, a copper cage IM is used as an example to validate the proposed procedure. The cross-section of the machine is shown in Fig. 11. The dimensions and parameters of the machine are listed in Table I.

A commercial FEA software, ANSYS/Maxwell, is selected to calculate the performance of the IM. The two-dimensional quasi-static transient FEA solver in ANSYS/Maxwell is used because it considers saturation, skin effect and motion of the rotor [20], [21]. Hence, the accuracy of the raw data is guaranteed. An electric circuit representing the end ring is used to connect the copper bars of the rotor. The resistance and inductance between adjacent rotor bars are calculated by analytical method. Note that the proposed method can also be applied to the magnetostatic FEA. For example, it can be combined with the method proposed in [14] to further reduce the calculation time by neglecting the skin effect. But this option will not be further discussed in this paper.

A. Optimal Operating Region of Example Machine

According to the proposed procedure, the results for the three steps are presented as follows.

Step 1: Calculate \( \omega_{r_{\text{max}}} \) boundary by varying \( \omega_{s_{\text{lim}}} \) at 6000 RPM and \( v_s = \frac{300V}{\sqrt{3}} \) (assume SVPWM control).

Balanced three-phase voltages are applied to the stator windings (\( v_{ia} = \frac{300V}{\sqrt{3}} \sin(\omega_r t + \omega_{s_{lim}})V \), where \( \omega_r = 1256.6\text{rad/s} \). The average torque and stator current magnitude in steady state are calculated by FEA as shown in Figs. 12 and 13 respectively.

The maximum torque is achieved at \( \omega_{s_{lim}F} = 2\pi \times 9 \text{ rad/s} \) when \( I_{sF} = 244A \). Because \( I_{sF} < I_{s_{\text{lim}}} \), so the proposed calculation region in Fig. 9 is adopted. The location of Point F is (9Hz, 244A) in Fig. 13. The maximum slip frequency \( \omega_{s_{lim}G} = \frac{I_{s_{\text{lim}}} - I_{sF}}{I_{sF}} \omega_{s_{lim}F} = \frac{300}{244} \times 2\pi \times 9 = 2\pi \times 13.3\text{rad/s}. \)
Step 2: Calculate the maximum current boundary by varying slip frequency between 0 and \(2\pi \times 13.3\text{rad/s} \). The rotor speed is selected to be 500 RPM in this step for shorter transient time. Balanced three-phase currents are applied to the stator windings \(I_{\text{st}} = 360\sin(\omega_r + \omega_{\text{slip}})I_\text{s}\), where \(\omega_r = 104.7\text{rad/s}\). The average torque and stator flux magnitude in steady state are calculated by FEA as shown in Figs. 14 and 15 respectively. The maximum torque is achieved at Point B \(3.9\text{Hz}, 230\text{Nm}\).

Step 3: Calculate machine performance at all \([\omega_{\text{slip}}, I_\text{s}]\) combinations inside the optimal operating region.

Two extra lines, OB and BD, are added to the calculation region. The location of Point D and Point E are \((3.9\text{Hz}, 0)\) and \((3.9\text{Hz}, 139)\) respectively. The range of slip frequency for each current level is defined by the boundaries of the area shaded in yellow as shown in Fig. 16.

The stator voltages and boundary speeds for the optimal operating points are calculated by \((15)\) based on the result from Step 3.

To get a high resolution and smooth torque-speed map, stator current at every 15A and slip frequency at every 0.2Hz are selected for calculation. Hence, 532 calculation points are selected based on the shaded area shown in Fig. 16. If no special technique is adopted to reduce the transient response time, the average calculation time for each operating point to reach steady state is near one hour. It means the total FEA calculation time is around 532 hours if all operating points are calculated sequentially by one computer core (532 core hours). In contrast, without the proposed procedure, 1608 calculation points are needed provided the maximum slip frequency is already known (the calculation region of stator current and slip frequency will be in rectangular shape). The total FEA calculation time would be 1608 core hours instead. Thus, the FEA simulation time is reduced by 67% (1076 core hours) by the proposed procedure.

The corresponding torque-speed map profile based on Fig. 16 is shown in Fig. 17. As shown, base speed of the machine is 2600RPM and maximum torque is 230Nm. The torque/speed at Point C and Point F are 131Nm/4000RPM and 59Nm/6000RPM respectively.

B. Predicted Machine Performance

To get the desired torque-speed output, the predicted stator current, slip frequency, flux and stator voltage input maps are shown in Figs. 18, 19, 20 and 21, respectively. To maintain the same torque when rotor speed increases, stator voltage needs to increase while stator current, slip frequency and flux are constant in the MTPA region. In the FW and MTPV regions, slip frequency increases together with stator current while flux decreases. The increment of current is mainly used to compensate for the reduction in flux in order to maintain the same torque.

There is only one operating condition serving as the transition point, Point C, between the FW and MTPV regions in these predicted performance maps. As a reminder, Point C is the highest speed operating point with maximum stator current. In contrast, a clear boundary between the MTPA and FW regions can be observed in these maps. The transition patterns in the stator current and slip frequency maps are quite similar.
The constant value curves change from horizontal to a descending slope. Meanwhile, the constant stator flux curves in Fig. 20 change from horizontal to almost vertical once they enter the FW region. This is because the stator voltage becomes constant, the stator flux must be almost constant when the voltage drop on stator resistance is small.

The slip frequency on the MTPV curve is almost constant (Figs. 6 and 19) mainly for two reasons. First, if the machine parameters are constant, the slip frequency needs to increase as rotor speed increases [6]. Second, as rotor speed increases, the deepened flux weakening will reduce the saturation level. Thus, the contribution of d-axis flux on torque increases, which brings down the current angle and the slip frequency. Because these two reasons tend to change the slip frequency in different directions, the result is a near constant slip frequency along the MTPV curve. Since the high slip frequency area (>7.5 Hz) in Fig. 19 is very small, it will be reasonable to ignore the high slip frequency operating points in Step 3, which will obviously reduce the computation time without noticeable influence on the accuracy.

C. Comparison between Proposed Procedure Result and Experimental Result

A photo of the test setup is shown in Fig. 22. The IM presented in Fig. 11 and Table I is connected to a dynamometer for testing. The speed and output torque of the dynamometer can be accurately controlled and monitored by a torque sensor (error < 0.25Nm) and a speed sensor (ripple < 2RPM). The machine performance at every 10Nm and 100RPM are selected as testing points.

The test results for current and slip frequency under maximum torque condition are presented in Figs. 23 and 24 respectively. The test result ($A_{Test}$) is compared with the result from the proposed procedure ($A_{Predicted}$). The error percentage is defined by (16). The corresponding error percentage maps are shown in Figs. 25 and 26 respectively.

$$\epsilon = \frac{A_{Predicted} - A_{Test}}{A_{Test}} \times 100\%$$

As shown, the current error $\epsilon_I$ is less than 4% at most of the tested torque-speed points while the slip frequency error $\epsilon_{\omega_{slip}}$ is smaller than 10%. There are some reasons for the errors. First, the predicted results are calculated by two-dimensional FEA rather than three-dimensional FEA. Consequently, the
fringing effect error can be expected. Second, temperature dependency of material property, especially the conductivity of rotor bars, has not been fully considered in the simulation.

As indicated in (14), when $R_r$ increases with temperature, the same maximum torque can be achieved as long as $I_s$ and the corresponding $\frac{R_r}{\omega_{s\text{lip}}}$ remain the same, which can be easily satisfied by increasing $\omega_{s\text{lip}}$ together with $R_r$. Hence, $I_s$ is less sensitive to parameter changes than $\omega_{s\text{lip}}$. As a result, $\epsilon_{I_s}$ is smaller than $\epsilon_{\omega_{s\text{lip}}}$ in general. Since the predicted $\omega_{s\text{lip}}$ is lower than the test result in low and medium speeds, it is reasonable to believe that the rotor bar temperature assumed in the simulation is lower than the actual temperature in experiment.

Because a small change in torque will require big change in slip frequency at high speed (Fig. 4), the slip frequency is sensitive to torque variation. Consequently, it tends to pick the lowest current value and slip frequency in experiment to achieve the desired torque. As a result, the errors become positive values in the high speed region.

**VI. Conclusion**

A procedure to quickly narrow down the calculation region of slip frequency and stator current ($\omega_{s\text{lip}}$ and $I_s$) for maximum torque performance of the inverter-fed IM by FEA is proposed in this paper. To achieve the optimal steady state machine performance, MTPA, FW and MTPV control are assumed for low, medium and high speeds respectively. Because the $[\omega_{s\text{lip}}, I_s]$ combinations outside of the optimal performance region are minimized by the proposed procedure, the required FEA computation load to obtain the torque-speed map is reduced by more than 50%. The effectiveness of the proposed method is validated by comparing the predicted results with the test results.

It should be pointed out that the core loss has not been considered in the proposed procedure. Obviously, the efficiency is not optimized in this case. However, once the stator current and slip frequency are identified by the proposed procedure, the core loss and efficiency at any desired torque-speed point can be further calculated.

Even though the machine parameters can be further calculated once the steady state performance is estimated by the proposed procedure, the parameter calculation is not in the scope of this paper. However, it will be an interesting topic for future research.

**References**


IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS


