Model Predictive Torque Ripple Reduction with Weighting Factor Optimization Fed by an Indirect Matrix Converter

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Model Predictive Torque Ripple Reduction with Weighting Factor Optimization Fed by an Indirect Matrix Converter

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Abstract—Model predictive control has emerged as a powerful control tool in the field of power converter and drive’s system. In this article, a weighting factor optimization for reducing the torque ripple of induction machine fed by an indirect matrix converter is introduced and presented. Therefore, an optimization method is adopted here to calculate the optimum weighting factor corresponding to minimum torque ripple. However, model predictive torque and flux control of the induction machine with conventionally selected weighting factor is being investigated in this article and is compared with the proposed optimum weighting factor based model predictive control algorithm to reduce the torque ripples. The proposed model predictive control scheme utilizes the discrete phenomena of power converter and predicts the future nature of the system variables. For the next sampling period, model predictive method selects the optimized switching state that minimizes a cost function based on optimized weighting factor to actuate the power converter. The introduced weighting factor optimization method in model predictive control algorithm is validated through simulations and shows potential control, tracking of variables with their respective references and consequently reduces the torque ripples corresponding to conventional weighting factor based predictive control method.

1. INTRODUCTION

Direct torque control (DTC) for induction machine is very much appropriate with variable-speed drives when torque control is more dominant than speed control due to its fast transient torque responses. But, field-oriented control is more suited for minimum torque ripple due to some limitations of hysteresis characteristics in DTC. However, improved torque ripple performances can be achieved in the DTC by reducing the sampling interval, which further causes high switching frequency losses. These losses can be controlled with proper utilization of space vector (SV) modulation and imposing the predictive torque control (PTC) method. In [1], the
combination of DTC and predictive control has been carried out with better performance. Consequently, the model predictive control (MPC) algorithm is considered to be the method in which power converters and the drive system give a better performance [2]. On the other hand, AC-to-AC power converters are very much important and extensively used in industries and different topologies on AC-to-AC power converter have been investigated in the literature and classified into three main groups: cycloconverter, direct matrix converter (DMC), and indirect matrix converter (IMC) [3]. Among all investigated AC-AC converters, the IMC is more suitable because it is simpler and less complex to control than the DMC, allowing secure commutations of the system [4]. In [5], a modified DTC scheme utilizing the SV switching pattern to control of induction machine is investigated and compared with the classical DTC method. An inquisition regarding the minimization of torque ripples was carried out by imposing combined control (DTC and SV modulation) to a diode-clamped multi-level inverter in [6]. Also, a new torque controller with fixed switching frequency for DTC of induction motor was proposed in [7]. Furthermore, in [8] torque ripples minimization was presented with a new stator flux estimation method, and some other important applications were investigated with DMCs in [9–12]; a neural network was applied to control the doubly fed induction generator for speed estimation [13]. Different applications of torque-flux and current control in voltage source inverter, an active front end rectifier, a matrix converter (MC), and an IMC with predictive control have been successfully investigated [2, 4, 14–18]. Also, some recent applications with a multi-level inverter were investigated in [19–21].

The performance of the predictive control scheme mostly depends on weighting factor values that are used in the multiple variables and constraint based single cost function. Therefore, weighting factor selection is the most important issue in the predictive control algorithm. To date in the literature, there are no analytical or numerical methods or control design theories to adjust the weighting factor, they are currently evaluated with the iterative evaluation method [22]. This procedure is highly used to adjust the weighting factor; however, with this method, the weighting factor can be adjusted and potential performances can be attained but is quietly approximated. Therefore, this weighting factor should be optimized to get the optimum best performance of the system. Recently, an optimization method for the optimum weighting factor calculation imposed in a three-phase voltage source inverter fed induction motor was introduced [23]. In [24], a ranking approach based multi-objective optimization was been proposed to replace the single cost function at the predictive horizon, which allows predictive control of torque and flux without weighting factors. The most important feature of this predictive control method is that it does not use the linear and non-linear controllers or modulators, as in classical control methods. In this investigation, less time is needed to track the reference speed of the induction machine and with no overshoots as compared to [6]. Therefore, in this investigation, the response time of speed is more faster and other variables, such as torque and stator flux being controlled successfully as well as minimization of torque ripples. In this article, a weighting factor optimization method is applied in the predictive torque and flux control of an IMC-fed induction machine for minimization of the torque ripples, which is the new contribution of this investigation.

This article is organized as follows. Section 2 is related to the mathematical modeling of the IMC topology and inductive load of the system. Section 3 presents proposed model predictive torque ripple reduction and flux control algorithm with weighting factor optimization method. Section 4 states verification results and discussion of the proposed method to minimize the torque ripples corresponding to conventional weighting factor based model predictive algorithm. Finally, a fruitful conclusion is drawn in Section 5.

2. INDUCTION MACHINE FED IMC TOPOLOGY

2.1. Mathematical Modeling of IMC

The IMC topology is shown in Figure 1. It consists of a rectifier and an inverter part with an intermediate virtual DC-link and it has 24 possible switching states. An input inductor-capacitor (IC) filter is used to avoid the over-voltages [4] and filtering the effect of high-order harmonics of input currents. The modeling equations of the IMC are given as:

\[ V_{dc} = \begin{bmatrix} S_{1r} - S_{4r} & S_{5r} - S_{6r} & S_{5r} - S_{2r} \end{bmatrix} V_i, \] (1)

\[ I_{ri} = \begin{bmatrix} S_{1r} - S_{4r} \\ S_{3r} - S_{6r} \\ S_{5r} - S_{2r} \end{bmatrix} I_{dc}, \] (2)

\[ V_o = \begin{bmatrix} S_{1i} - S_{4i} \\ S_{3i} - S_{6i} \\ S_{5i} - S_{2i} \end{bmatrix} V_{dc}, \] (3)

\[ I_{dc} = \begin{bmatrix} S_{1i} & S_{3i} & S_{5i} \end{bmatrix} I_o, \] (4)

where rectifier switching states \( S_{\alpha} \) to \( S_{\alpha} \), input voltage \( V_i = \begin{bmatrix} V_i^a \\ V_i^b \\ V_i^c \end{bmatrix} \), rectifier input current \( I_i = \begin{bmatrix} I_i^a \\ I_i^b \\ I_i^c \end{bmatrix} \), output voltage \( V_o = \begin{bmatrix} V_o^a \\ V_o^b \\ V_o^c \end{bmatrix} \), and output current \( I_o = \begin{bmatrix} I_o^a \\ I_o^b \\ I_o^c \end{bmatrix} \).

2.2. Inductive Load Model

A two-dimensional SV can be represented from three phase quantities \( (y_A, y_B, \text{and } y_C) \) of the converter to obtain the system
of the model which can be presented as follows:

\[ y = y_\alpha + jy_\beta, \]  

(5)

where

\[ y_\alpha = \frac{1}{3}(2y_A - y_B - y_C), \quad y_\beta = \frac{1}{\sqrt{3}}(y_B - y_C) \]  

(6)

The model of the induction machine (IM) referred to stator and fixed coordinate rotor and stator voltage equations are presented as:

\[ V_o = R_s I_o + L_s \psi_s, \]  

(7)

\[ V_r = R_r I_r + L_r \psi_r - j\omega \psi_s, \]  

(8)

\[ \psi_s = L_s I_o + L_m I_r, \quad \psi_r = L_r I_r + L_m I_o, \]  

(9)

\[ T_e = \frac{3}{2} p(\psi_s \times I_o), \]  

(10)

where

- \( R_s \) is the stator resistance;
- \( R_r \) is the rotor resistance;
- \( p \) is the number of pole pairs;
- \( \omega \) is the rotor angular frequency;
- \( L_s, L_r \) are the self-inductances;
- \( L_m \) is the mutual inductance;
- \( T_e \) is the electrical torque; and
- \( \psi_s \) is the stator flux of the induction machine.

### 3. PROPOSED MODEL PREDICTIVE TORQUE RIPPLE REDUCTION AND FLUX CONTROL ALGORITHM

The proposed weighting factor optimization based MPC control scheme and algorithm are presented in Figures 2(a) and 2(b), respectively. Predictive controller satisfies the following five steps. (1) For the \( k \)th sampling instant, supply voltage \( V_s^k \), input voltage \( V_i^k \), stator voltage \( V_o^k \), stator current \( I_o^k \), and speed \( \omega^k \) of the induction machine are measured. (2) Stator reference flux \( \psi_{ref} \) and reference speed \( \omega_{ref} \) are known values. A proportional-integral (PI) controller is used to set nominal torque \( T_{nom} \) from the error signal between the measured and reference speeds of the induction machine. (3) A flux estimator has been used to estimate the stator and rotor flux. (4) For each valid switching state of IMC, values of torque \( T_e^{k+1} \) and stator flux \( \psi_s^{k+1} \) are predicted in the next sampling time period \( (k + 1) \). (5) All the predictive values are compared with their respective references and determine the cost functions for all possible switching states based on conventionally selected weighting factor and with optimized weighting factor. Optimum weighting factor is determined in every sampling interval once and is used in the cost function for all the possible 24 switching states of the converter. Finally, the switching state corresponds to the minimum cost function is selected in the next sampling time period.
3.1. Predictive Torque and Flux Calculation

The induction machine model has explained in Eqs. (7)–(10) are used with first-order approximation for derivatives along with the first-order nature of state equations:

\[ y = y^{k+1} - y^k \frac{T_s}{T_s}, \]  

where \( T_s \) is the sampling period. Stator and rotor flux can be estimated from Eqs. (7) and (8), resulting in

\[ \psi_s^k = \psi_s^{k-1} + V_o^k T_s - R_s I_o^k T_s, \]  

\[ \psi_r^k = I_o^k \left( \frac{L_m - L_s}{L_m} \right) + \frac{L_r}{L_m} \psi_r^{k-1}. \]  

Predictive modeling equations are as follows:

\[ \psi_s^{k+1} = \psi_s^k + V_o^{k+1} T_s - R_s I_o^{k+1} T_s, \]  

\[ I_o^{k+1} = I_o^k \left( \frac{V_o^{k+1} + \tau r k_r - j k_r \omega^k}{\tau s} \right) \frac{T_s}{\tau s} + \frac{1}{L_s} \left( 1 - \frac{R_s}{\tau s} \right) T_s, \]  

\[ T_e^{k+1} = \frac{3}{2} \beta \left( \psi_s^{k+1} \times I_o^{k+1} \right), \]

\[ m_1 = K \left[ V_{oq} \psi_{rd} - V_{od} \psi_{rq} \right] - \frac{R_r}{L_s} \frac{R_s}{\tau s} T_s. \]  

\[ T_r^2 = \frac{1}{T_s} \int_0^{T_s} (D_T + m_1 t)^2 \, dt, \]  

where \( m_1 \) is related to the weighting factor because only this parameter is related to \( (V_{od}, V_{oq}) \). As a result, \( T_r^2 = T_r^2(m_1), m_1 = m_1(V_o), \) and \( V_o = V_o(W_{opt}) \); therefore,

\[ T_r^2 = T_r^2(W_{opt}). \]  

In Appendix B, the relation between the weighting factor and stator voltages is explained. To find the optimum weighting factor in the cost function, the derivative of the torque ripple must be zero; therefore,

\[ \frac{d}{dT_s} T_r^2 = 0, \]  

resulting in the optimum weighting factor corresponding to minimum torque ripples (refer to Appendix C):

\[ G = \frac{1}{K} \left( \frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r} \right) T_s + \frac{3D_T}{2KT_s} + \omega^k \left( \psi_{sd} \psi_{rd} + \psi_{sq} \psi_{rq} \right), \]  

\[ W_{opt} = \frac{\beta_2 \psi_{rd} - \beta_1 \psi_{rq}}{G + \psi_{rq}(\alpha_1 + V_{oq,k-1}) - \psi_{rd}(\alpha_2 + V_{oq,k-1})}. \]

3.3. Cost Function Calculation

The predicted torque with its nominal value and predicted flux corresponding to the reference flux can be combined in a single term to express the cost function. A conventional weighting factor based cost function in predictive torque and flux control algorithm is as follows:

\[ g_i^{k+1} = A_1 \left| (T_e^{k+1} - T_{nom}) \right| + A_2 \left| (\psi_s^{k+1} - \psi_{ref}) \right|, \]  

\[ i = 1, 2, 3, \ldots, 24, \]  

where \( (A_1, A_2) \) are the weighting factors,

\( T_e^{k+1} \) is the predicted torque,

\( \psi_s^{k+1} \) is the predicted flux,

\( T_{nom} \) is the nominal torque,

\( \psi_{ref} \) is the reference flux, and

\( i \) is the number of possible switching states of the IMC.

In case of weighting factor optimization based predictive control, the cost function can be considered as

\[ g_{i,w}^{k+1} = \frac{1}{2} \left( \left| T_e^{k+1} - T_{nom} \right|^2 + W_{opt} \left| \psi_s^{k+1} \right|^2 - \left| \psi_{ref} \right|^2 \right)^2, \]  

\[ i = 1, 2, 3, \ldots, 24, \]  

where \( W_{opt} \) is the optimized weighting factor that determines the importance of flux control compared to torque control. Different values of the cost functions have been calculated by Eqs. (24) and (25) corresponding to all the possible switching states. The switching state that produces minimum cost function is selected in the next sampling interval \( T_s \) as in [2, 4, 14] to actuate the IMC for both the cases of verifications.
4. VERIFICATION RESULTS AND DISCUSSION

The finite control set of MPCs of the induction machine fed by IMC is verified in MATLAB Simulink (The MathWorks, Natick, Massachusetts, USA) to justify the performance of the proposed control scheme; the MATLAB Simulink model is presented in Figures 3(a) and 3(b). To verify the features of the proposed weighting factor optimization in the MPC control scheme corresponding to the conventional MPC, both methods have been investigated separately. The parameters used in verification are given in Table 1, and the simulations have been carried out with sampling time \( T_s = 20 \mu s \). To investigate torque ripple behavior, two cases are analyzed here. First, the validation of the predictive control scheme is analyzed with a conventionally selected weighting factor, presented in Figure 4, while in the second case, weighting factor optimization has taken into consideration, and the results are given in Figure 5. In both cases, the induction machine starts at 0.01 sec without any load torque, varying the reference speed from 0 to 149.75 rad/s, and the torque is limited to 51 Nm. In Figures 4(a) and 5(a), the motor speeds are tracking the reference speed with a high-speed tracking response time to attain its rated speed corresponding to recent investigation in [6, 23]; this time it is only 0.18 sec, whereas in [6], the time required to attain reference full speed is 0.43 sec for a conventional DTC drive system and 0.48 sec for SVM-controlled DTC drives. Therefore, the speed response time of this investigation is faster compared to the recent references. The results show the motor is started at 0.01 sec, and the measured speed increases toward the reference rated speed at 149.75 rad/s. At time of 0.19 sec, the motor attains full rated speed, which is kept close to the reference speed without any overshoot as corresponds to [6].

Furthermore, at time of 0.35 sec (Figures 4(a) and 5(a)), the nominal speeds are changed to the reverse direction and the measured induction machine speed follows the reverse nominal speed starting at 0.35 sec with reverse maximum torques shown in Figures 4(b) and 5(b). At 5.5 sec, the induction machine attains its full reverse speed. This is the regeneration mode of the induction machine. Therefore, the measured speed of the motor follows the reverse reference speed of –149.75 rad/s with potential control. Figures 4(b) and 5(b) present the induction machine measured torque versus nominal torque responses. The figures clearly present the sharp torque response without any delay between the measured and nominal torque corresponding to [6]. A load torque of 40 Nm is applied at time of 0.25 sec, and a reverse torque at 0.35 sec is applied to change the speed in the reverse direction from 149.75 rad/s to –149.75 rad/s. At 0.25 sec, the induction machine developed a 40-Nm load torque to mitigate the load demand keeping the constant speed. In this work, stator reference flux has been assumed as 1.1 Wb and the measured stator flux is sharp of 1.1 Wb throughout the verification, which are shown in Figures 4(c) and 5(c). Therefore, the speed controller generates torque references at transients, which is different from zero and can be appreciated as a good tracker of speed.

**TABLE 1. Simulation parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time</td>
<td>( T_s )</td>
<td>20 ( \mu s )</td>
</tr>
<tr>
<td>Supply phase voltage (RMS)</td>
<td>( V_S )</td>
<td>500 V</td>
</tr>
<tr>
<td>Supply frequency</td>
<td>( f_s )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Input filter resistance</td>
<td>( R_f )</td>
<td>0.5 ( \Omega )</td>
</tr>
<tr>
<td>Input filter inductance</td>
<td>( L_f )</td>
<td>400 ( \mu H )</td>
</tr>
<tr>
<td>Input filter capacitance</td>
<td>( C_f )</td>
<td>21 ( \mu F )</td>
</tr>
<tr>
<td>Reference speed</td>
<td>( \omega_{ref} )</td>
<td>149.75 rad/s</td>
</tr>
<tr>
<td>Nominal torque</td>
<td>( T_{nom} )</td>
<td>51 Nm</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>( L_s )</td>
<td>0.2861 mH</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>( R_s )</td>
<td>1.35 ( \Omega )</td>
</tr>
<tr>
<td>Number of poles</td>
<td>( p )</td>
<td>2</td>
</tr>
<tr>
<td>Weighting factor</td>
<td>( A_1 )</td>
<td>63</td>
</tr>
<tr>
<td>Weighting factor</td>
<td>( A_2 )</td>
<td>13,500</td>
</tr>
</tbody>
</table>
FIGURE 4. Verification results without weighting factor optimization: (a) motor measured speed ($\omega$, rad/s) and reference speed ($\omega_{ref}$, rad/s), (b) motor measured torque ($T_e$, Nm) and nominal torque ($T_{nom}$, Nm), (c) stator flux ($\psi_s$, Wb) and stator reference flux ($\psi_{ref}$, Wb).

FIGURE 5. Verification results with weighting factor optimization: (a) motor measured speed ($\omega$, rad/s) and reference speed ($\omega_{ref}$, rad/s), (b) motor measured torque ($T_e$, Nm) and nominal torque ($T_{nom}$, Nm), (c) stator flux ($\psi_s$, Wb) and stator reference flux ($\psi_{ref}$, Wb).

4.1. Torque Ripples Reduction with Weighting Factor Optimization

Forward Direction of Speed (Case 1)

Figures 6(a) and (b) presents the zoom torque ripple behavior of both cases in the forward speed of induction machine. Figure 6(a) shows the maximum value of the torque ripple (Figures 4(a) and 5(a)), of torque (Figures 4(b) and 5(b)), and of stator flux (Figures 4(c) and 5(c)) in both the conventional and proposed optimum weighing factor based MPC schemes, respectively.

FIGURE 6. Motor torque ripples (forward speed): (a) torque ripples (Nm) in conventional weighting factor based MPC scheme and (b) improved torque ripples (Nm) with imposed weighting factor optimization.
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FIGURE 7. Motor torque ripples (reverse speed): (a) torque ripples (Nm) in conventional weighting factor based MPC scheme and (b) improved torque ripples (Nm) with imposed weighting factor optimization.

Reverse Direction of Speed (Case 2)

Figures 7(a), and (b) show the torque ripples behavior for both analyses in the reverse speed region of the induction machine. In Figure 7(a), the maximum value of the torque ripple is 41.46 Nm and the minimum value is 38.4 Nm. Therefore, the torque ripple pulsation is 7.97% in the reverse speed region of the induction machine on the conventionally selected weighting factor based MPC scheme. Figure 7(b) shows the torque ripples for the optimized weighting factor based MPC platform in which the maximum magnitude of torque ripples is 40.5 Nm and the minimum torque ripple is 39 Nm. As a result, variation of torque ripples is found as 3.85% for the proposed weighting factor optimization scheme. In conclusion, the proposed weighting factor optimization method has been improved the results by (7.97–3.85%) 4.12% torque ripples of the induction machine for the rated forward-speed direction corresponding to conventional weighting factor based MPC algorithm.

5. CONCLUSIONS

This article proposed a novel approach of weighting factor optimization method for minimization of torque ripples of the induction machine fed by an IMC as well as stator flux control in the finite control set MPC platform. The predictive control scheme utilizes the discrete features of input filter, power converter, and inductive load to predict the future behavior of the torque and flux of the system. It has also been employed to obtain the cost functions for all 24 possible switching states. The switching state is selected corresponding to minimum cost function from among the all determined cost functions. The system behavior is highly changeable with the values of the weighting factor in the cost function of control scheme. This article is highlighted with an optimized weighting factor calculation method to reduce the torque ripples of the induction machine fed by an IMC corresponding to the conventional weighting factor based predictive control scheme. From the above results investigated in this verification, the optimum weighting factor is calculated corresponding to the response of stator flux and torque ripples in all the sampling intervals, and each optimum weighting factor is utilized in the cost function for the 24 possible switching states of the IMC. The results shows that in the forward speed of the induction machine, the torque ripple is 10.08% if conventional weighting factor is used in the cost function of predictive control, whereas with the optimum weighting factor, it is only 5.51%. In the reverse mode of speed, conventional torque ripple is 7.97% and the optimum is 3.85%. Therefore, from the analysis of the results it is found that the proposed method decreases 4.57% of torque...
ripples for the rated forward speed of the induction machine compared to the conventional weighting factor based predictive control scheme, and for reverse rated speed, it gives 4.12% torque ripples reduction. It can be concluded that the results of this investigation are justified with high response time with no overshoots and accurate reference tracking with smooth shapes of torque, flux, and speed; as well as minimum torque ripples of the induction machine. Finally, this article proved the feasibility of the proposed weighting factor optimization method for minimization of torque ripples of induction machine fed by an IMC with satisfactory results, and this is the new contribution of this article.

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REFERENCES

APPENDIX A: CALCULATION OF ASCENDING SLOPE OF THE TORQUE

The torque for the induction machine can also be determined by the following relation:

\[ T_e = T = K (\psi_{sq} \psi_{rd} - \psi_{sd} \psi_{rq}) \]  \hspace{1cm} (A1)

The first derivative of Eq. (A1) implies the slope of the torque as follows:

\[
\frac{dT}{dt} = K \left( \frac{d}{dt} \psi_{sq} \psi_{rd} + \frac{d}{dt} \psi_{rd} \psi_{sq} - \frac{d}{dt} \psi_{sd} \psi_{rq} - \frac{d}{dt} \psi_{rq} \psi_{sd} \right). \]  \hspace{1cm} (A2)

Considering the induction motor dynamic model from Eq. (A2),

\[
\frac{dT}{dt} = K \left[ (V_{eq} + W_2)^* \psi_{rd} + W_3^* \psi_{sq} - (V_{sd} + W_1)^* \psi_{rq} - W_4^* \psi_{sd} \right]. \]  \hspace{1cm} (A3a)

\[
\begin{bmatrix}
W_1 \\
W_2 \\
W_3 \\
W_4
\end{bmatrix}
= \begin{bmatrix}
Q_{11} & Q_{12} & Q_{13} & Q_{14} \\
Q_{21} & Q_{22} & Q_{23} & Q_{24} \\
Q_{31} & Q_{32} & Q_{33} & Q_{34} \\
Q_{41} & Q_{42} & Q_{43} & Q_{44}
\end{bmatrix}
\begin{bmatrix}
\psi_{sd} \\
\psi_{sq} \\
\psi_{rd} \\
\psi_{rq}
\end{bmatrix},
\]  \hspace{1cm} (A3b)

where \( Q_{11} = Q_{22} = \frac{R}{\sigma L_s}, \quad Q_{13} = Q_{24} = \frac{R(1 - \sigma)}{\sigma L_m}, \)
\( Q_{31} = Q_{42} = \frac{R \sigma}{\sigma L_m}, \quad Q_{21} = Q_{12} = Q_{32} = Q_{41} = Q_{14} = Q_{23} = 0, \quad Q_{34} = Q_{43} = 0, \quad \text{and} \quad Q_{44} = -\frac{R}{\sigma L_r}. \)

The ascending slope of the torque can thus be depicted with the following equation:

\[
V_{eq} = V_{eq} \quad \text{and} \quad V_{sd} = V_{sd}.
\]

\[
\frac{dT}{dt} = \frac{K}{\sigma L_s} \left[ (V_{eq} \psi_{rd} - V_{sd} \psi_{rq}) - \omega^k (\psi_{sd} \psi_{rd} + \psi_{sq} \psi_{rq}) \right]
- \left( \frac{R}{\sigma L_s} + \frac{R}{\sigma L_r} \right) T_e = m_1 \]  \hspace{1cm} (A4)

where \( K = \frac{3}{2} p \) and \( \sigma = 1 - k_s k_s = 1 - \frac{j}{L_s T_e}. \)

APPENDIX B: RELATIONSHIP BETWEEN WEIGHTING FACTOR AND STATOR VOLTAGE OF INDUCTION MACHINE

The Taylor expansion is applied around the nominal values in Eq. (25) to express the model predictive variables in a linear manner as follows:

\[
T_e = T_{nom} + K (\psi_{rd}^o \Delta \psi_{sq} + \psi_{sq}^o \Delta \psi_{rd} - \psi_{sd}^o \Delta \psi_{rq} - \psi_{rq}^o \Delta \psi_{sd}), \]  \hspace{1cm} (B1)

\[
|\psi_1|^2 = |\psi_{ref}|^2 + 2 \psi_{sd} \psi_{rd} + 2 \psi_{sq} \psi_{rq}. \]  \hspace{1cm} (B2)

Hence, Eq. (25) becomes

\[
g_w^{k+1} = \frac{1}{2} [(\Delta T)^2 + W_{eq} (\Delta \psi_s)^2] \]  \hspace{1cm} (B3)

Torque and flux displacements are related to stator and rotor flux as follows:

\[
Y(t_k) = G_X(t_k), \]  \hspace{1cm} (B4a)

\[
Y = \begin{bmatrix}
\Delta T_e \\
\Delta |\psi_s|^2
\end{bmatrix},
\]

\[
G = \begin{bmatrix}
-K \psi_{rd}^o & K \psi_{sq}^o & K \psi_{sd}^o & -K \psi_{rq}^o \\
2 \psi_{sd}^o & 2 \psi_{sq}^o & 0 & 0
\end{bmatrix}.
\]

and \( X = \begin{bmatrix}
\Delta \psi_{sd} \\
\Delta \psi_{sq} \\
\Delta \psi_{rd} \\
\Delta \psi_{rq}
\end{bmatrix}. \)  \hspace{1cm} (B4b)

On the other hand, in a stationary reference frame induction machine, the discrete model can be described as

\[
X(t_{k+1}) = R.X(t_k) + S.U(t_k), \]  \hspace{1cm} (B5a)

\[
X = \begin{bmatrix}
\Delta \psi_{sd} \\
\Delta \psi_{sq} \\
\Delta \psi_{rd} \\
\Delta \psi_{rq}
\end{bmatrix}, \quad U = \begin{bmatrix}
\Delta V_{od} \\
\Delta V_{eq}
\end{bmatrix}, \quad S = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
0 & 0
\end{bmatrix}, \]  \hspace{1cm} (B5b)

\[
R = T_s. \]

\[
R = \begin{bmatrix}
\frac{1}{T_e} + Q_{11} & Q_{12} & Q_{13} & Q_{14} \\
Q_{21} & \frac{1}{T_e} + Q_{22} & Q_{23} & Q_{24} \\
Q_{31} & Q_{32} & \frac{1}{T_e} + Q_{33} & Q_{34} \\
Q_{41} & Q_{42} & Q_{43} & \frac{1}{T_e} + Q_{44}
\end{bmatrix} \]  \hspace{1cm} (B5c)

The parameters regarding matrix \( R \) have been introduced before in Eq. (A3b). For the discrete nature of the system considering the next sampling periods, the previous equation gives:

\[
Y(t_{k+1}) = G.X(t_{k+1}) = G.R.X(t_k) + G.S.U(t_k). \]  \hspace{1cm} (B6)

The appropriate input vector satisfies the following set of equations

\[
\frac{\delta}{\delta \Delta V_{od}} g_w = 0, \]  \hspace{1cm} (B7)

\[
\frac{\delta}{\delta \Delta V_{eq}} g_w = 0.
\]
From Eq. (25), Eqs. (B6) and (B7) lead to the following voltage displacement:

$$\Delta V_{od} = \alpha_1 + \frac{\beta_1}{W_{opt}}, \quad \text{(B8a)}$$
$$\Delta V_{eq} = \alpha_2 + \frac{\beta_2}{W_{opt}}, \quad \text{(B8b)}$$

where

$$\alpha_1 = -\frac{f_1(e_{11}^2e_{12} - e_{12}e_{11})}{(e_{11}e_{21} + e_{12}e_{22})^2},$$
$$\beta_1 = \frac{f_2(e_{12}e_{21} - e_{11}e_{22})}{(e_{11}e_{22} + e_{12}e_{21})^2},$$
$$\alpha_2 = -\frac{f_1(e_{11}^2e_{12} - e_{12}e_{11})}{(e_{11}e_{21} + e_{12}e_{22})^2},$$
$$\beta_2 = \frac{f_2(e_{12}e_{21} - e_{11}e_{22})}{(e_{11}e_{22} + e_{12}e_{21})^2}. \quad \text{(B9a)}$$

$$\begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = G.R. \begin{bmatrix} \Delta \psi_d \\ \Delta \psi_{dq} \\ \Delta \psi_{rd} \\ \Delta \psi_{rq} \end{bmatrix}, \quad \text{(B9b)}$$

$$\begin{bmatrix} e_{11} e_{12} \\ e_{21} e_{22} \end{bmatrix} = \begin{bmatrix} -K T_e \psi_{rd}^o \\ 2 T_e \psi_{rd}^o \\ K T_e \psi_{rd}^o \\ 2 T_e \psi_{rd}^o \end{bmatrix}. \quad \text{(B9c)}$$

These equations express the stator voltage and weighting factor relationship.

**APPENDIX C: OPTIMIZATION OF WEIGHTING FACTOR**

Let the derivative of the torque ripples with respect to weighting factor equal zero:

$$\frac{d T_r^2}{d W_{opt}} = \frac{d}{d W_{opt}} \left( m_1 \frac{T_r^2}{3} + m_1 D_T T_s + D_T^2 \right) = 0; \quad \text{(C1)}$$

therefore,

$$\frac{d m_1}{d W_{opt}} = 0 \quad \text{(C2)}$$

and

$$\left( m_1 \frac{2}{3} T_s^2 + D_T T_s \right) = 0, \quad \text{(C3a)}$$
$$m_1 = \frac{-3 D_T}{2 T_s}. \quad \text{(C3b)}$$

From Eqs. (18) and (C2), the relation below is obtained:

$$\frac{d m_1}{d W_{opt}} = \frac{d}{d W_{opt}} \left[ K \left( V_{od} \psi_{rd} - V_{od} \psi_{rq} \right) + \omega^k \left( \psi_{od} \psi_{rd} + \psi_{eq} \psi_{rq} \right) \right] \middle| \left( \frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r} \right) T_e. \quad \text{(C4a)}$$

which gives

$$\psi_{rd} \frac{d}{d W_{opt}} V_{od} = \psi_{eq} \frac{d}{d W_{opt}} V_{od}. \quad \text{(C4b)}$$

The derivatives of the stator voltage to the weighting factor are obtained as

$$\frac{d}{d W_{opt}} V_{od} = \frac{d}{d W_{opt}} \left( V_{od}^o + \Delta V_{od} \right) = \frac{d}{d W_{opt}} \left( \Delta V_{od} \right) = -\frac{\beta_1}{W_{opt}}. \quad \text{(C5a)}$$
$$\frac{d}{d W_{opt}} V_{eq} = \frac{d}{d W_{opt}} \left( V_{eq}^o + \Delta V_{eq} \right) = \frac{d}{d W_{opt}} \left( \Delta V_{eq} \right) = -\frac{\beta_2}{W_{opt}^2}. \quad \text{(C5b)}$$

As a result, Eq. (C2) is not a suitable equation to calculate the optimized weighting factor parameter because of the cancelation from both sides of Eq. (C4). Therefore, Eqs. (C3a) and (C3b) are the best criterion for weighting factor optimization, and thus

$$-\frac{3 D_T}{2 T_s} = K \left[ \left( V_{od} \psi_{rd} - V_{od} \psi_{rq} \right) - \omega^k \left( \psi_{od} \psi_{rd} + \psi_{eq} \psi_{rq} \right) \right] \middle| \left( \frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r} \right) T_e. \quad \text{(C6)}$$

where

$$G = V_{od} \psi_{rd} - V_{od} \psi_{rq}. \quad \text{(C7)}$$

Equation (C7) is the criterion for weighting factor optimization. By combining Eqs. (B8) and (C7), the optimized weighting factor is obtained.

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