Interpolation algorithm in designing of feed-forward robust precision control motion

Mochammad Rusli\textsuperscript{1*}, Moch Agus Choiron\textsuperscript{2}, Muhammad Aziz Muslim\textsuperscript{1}

\textsuperscript{1} Electrical Engineering Department, Faculty of Engineering, Brawijaya University
MT Haryono 167, Lowokwaru, Malang, Indonesia
\textsuperscript{*} Email: rusli@ub.ac.id

\textsuperscript{2} Mechanical Engineering Department, Faculty of Engineering, Brawijaya University
MT Haryono 167, Lowokwaru, Malang, Indonesia.

Abstract. Based on the structure and dynamic process of the ladder secondary double-sided linear induction motor (DSLIM) with asymmetry position of primary part of motor, the motor parameters may change with the secondary position, which directly cause the stability of electromagnetic thrust. It is difficult to meet the system control performances for designing of controller in the dynamic characteristics of the speed closed loop. This paper describes some solving algorithm by adopting the rotor field oriented control as the model matching strategy to achieve the smooth control of the electromagnetic thrust. The arrangement of model matching process is based on the Nevallina pick solution as linear interpolation method. Through the robust control concept and model matching control, the stability of the electromagnetic thrust during the motor step change process can be achieved. The simulation results verify the truth of the presented control strategies.

Keywords: double-sided linear induction motor with ladder secondary, robust control, interpolation algorithm

1. Introduction
Nowadays, the main control strategy for ladder secondary double-sided linear induction motor with asymmetry secondary is secondary field oriented control strategy [1-5]. However there are two main problem have to be given much more attention. Firstly, motor parameters was varied while position of secondary part is changed, which can effect instability of electromagnetic thrust. Secondly, the measurement of speed for outer loop in cascade structure of system need more accurate and fast response. However in high speed and large thrust, it is still difficult to detect the speed of motor with high accuracy and fast response. In addition the electromagnetic thrust is fluctuate. The one alternative of solution the problem is implemented the robust controllers.

A design of a control system is directed for two kind of problems come into consideration: reference tracking problem and disturbance rejection. Those problems are defined to be
calculated by the corresponding Sensitivity and Complementary Sensitivity - closed loop transfer functions. The disturbance rejection problem is recognized as a feed-forward problem (unknown disturbances can only be decreased by the use of feed-forward strategies), on the other side the reference tracking problem and stability are based on an closed-loop performance. Commonly both controllers can be solved easily by separated calculation. However for disturbance cogging force (periodical disturbance), it might be difficult to calculate both controllers simultaneously. Therefore both controllers can be solved simultaneously and more advantageously strategies with the use of a Two Degree of Freedom (2-DOF) control configuration [1].

The controller design for such a feed-forward controller (2-DOF) configuration has taken attention from previous researchers and can be seen in the literature from a wide spectrum of approaches, e.g. [2,3]. However the 2-DOF configurations provide more advantages compared to the 1-DOF configuration, a common analysis of the reference tracking problem in related to the influence of plant model uncertainty has not been completely conducted. This is the main reason of this research for implementing nevallina algorithm for robust-controller design using matching concept. [5],[6],[7],[8],[9].

2. Methods

2.1 Proposed precision closed loop motion control

Figure 1 shows a proposed motion control system, in which one controller is placed in forward path that is directly connected to set-point variable. The other one is connected to error variable of control system. Based on 2-DOF structure shown figure 1, that process design is divided into 2 objectives, such as tracking problem and disturbance rejection problem. Both problems commonly are solved separately.

The tracking problem requires as large as possible of the system gain. A large gain system provides an improvement of stability level. However noise signals in this case will flow in the inside of system which can generate internal disturbance of systems. For such motion control, a closed loop motion control system consist of two kind of controllers. The first controller $C_1$ is to handle the velocity error so that response system is quicker to achieve steady condition. The second controller input $C_2$ is aimed to coverage the internal (disturbance robust uncertainty) robust of system.
2.2 Matching and Nevanlinna pick problem

The model matching problem in this case is finding a stable transfer function \( C(s) \) as controller, so that difference between real plant and model is as minimum as possible. The finding of minimum difference is required a NORM mathematic process. The mathematical expression of this problem is to make minimum the equation:

\[
\min \| T_1 - T_2 C \|_\infty = \gamma
\]

where the minimum is taken over all stable \( Cs \). \( T_1 \) describes a proposed model and \( T_2 \) is controlled system which are a DSLIM and its driver. To solve this problem, it is required some theoritical mathemetics that is intrapolated from several input output data of a function with some requirement. The one method that can be used is the nevalinna Pick Problem. The Nevanlinna pick problem is the one method for intrapolation cases. This method is aimed for finding a function \( G \) in \( \mathcal{H} \) space – stand for the space of stable, proper, complex rational function. It must be satisfying two condition:

\[
\| G \|_\infty \leq 1, \text{ and } \quad G(a_i) = b_i, \quad i = 1, \ldots, n
\]

The latter equation expalins that \( G \) is to interpolate the value \( b_i \) at the point \( a_i \) or a function of \( G \) have to pass through points \( (a_i, b_i) \). The constraint of this algorithm is important: \( G \) have to be stable, proper and satisfy \( \| G \| \leq 1 \). For controller-design using matching concept, the closed loop control system should be arranged in suitable closed loop appropiate system. Plant (controlled system) is considered in a uncertainty structures. Uncertainty means the plant-mathematics is combined with the This structures consist of some weighting functions and nominal plant. The reel plant is described by nominal plant with error model which is represented by weighting function.

2.3 Controller design by Nevalinna pick problem

Speed controller design of DSLIM is based on the uncertainty plant or portubated plant \( P_g(s) \).

The one factor in designing speed controller is directed to guarantie the robust stability. Also to achieve the robust performance. The both objectives can be formulated into NORM-equation, which is shown by equation 4.

\[
\| \omega_1 S \|^2 + \| \omega_2 T \|^2 \|_\infty < 1
\]

Problem formulation can be defined as finding robust controller, so closed loop system achieve internally stablile and meet the inequality equation, which is shown by equation 5.
According to Figure 2, there are nominal and real plant. Real plant means as combination between nominal plant with some uncertainty model of plant. Mathematical model of DSLIM is approximated a second order systems as in DC motor. Because using rotor field oriented control, complicated model of linear induction motor can be approximated as second order system which is shown by equation 6.

\[ P_n(s) = \frac{K_f B_m}{(sT_c + 1)(sT_m + 1)}; \]  

(6)

It was mentioned in the previous paper[5] and based on pair of velocity and current of armature winding data, the all parameters was identified and results:

\[ K_f = 0.48; B_m = 0.53; T_c = 0.17; T_m = 0.83 \]

If the parameters are substituted into the equation of 6, nominal plant equation can be obtained as:

\[ P_n(s) = \frac{0.91}{0.14s^2 + s + 1}; \]  

(7)

and weighting function are referred to the performance equation [6], and equation 8 is aimed for the meeting the performance of controller design. The equation 8 shows that weighting functions.

\[ \omega_2(s) = \frac{2.5(0.33s + 1)}{0.1s + 1}; \omega_1(s) = \frac{a}{s + 1} \]  

(8)

Based on the three above equations, Model-matching equation is:

\[ U_3 = \frac{0.681a^2s^3 + 6.25a^2}{0.681s^4 - 6.941s^2 + (6.25 + a^2)} \]  

(9)

Determination of a-value is obtained by calculating Norm-\(\infty\) of \(U_3\), the next step is doing factorization. For this case, factorization terms are N=P;M=1;X=0;Y=1. The parameters can be used value of \(a=3\), it will be obtained the equation:

\[ F(s) = \frac{0.0057s^4 - 0.062s^2 + 0.456}{0.0002s^8 - 0.027s^6 + 0.755s^4 - 1.728s^2 + 1} \]  

(10)
Based the equation 10 can be achieved spectral equation:

\[
F_{sf}(s) = \frac{8.9785 + 5.34s + s^2}{(s + 9.85)(s + 5.96)(s + 1.20)(s + 1)}
\]

(11)

With the equation 11, with U-function can be obtained in two equations:

\[
T_1 = \frac{0.91a^2(s - 9.85)(s - 5.96)(s - 1.0427)(s + 1.0427)}{(s + 1)(0.17s + 1)(0.83s + 1)(8.98 + 5.34s + s^2)(s + 1.44)}
\]

\[
T_2 = \frac{0.14(s - 5.88)(s - 9.85)(s - 1.0427)(s + 1.0427)(8.98 - 5.34s + s^2)}{(s + 9.85)(s + 5.96)(s + 1.20)(s + 1)(0.17s + 1)(0.83s + 1)(s + 1.44)}
\]

(12)

(13)

The equations of 12 and 13 are used for calculating the matrix of \(L_c\) and \(L_0\). Using Lyapunov equation, both matrix can be found, which are shown in equation 14 and 15.

\[
AL_c + L_cA^T = BB^T
\]

And:

\[
A^T L_0 + L_0A = CC^T
\]

(14)

(15)

Where:

A = System Matrix of Plant

B= Input Matrix of Plant

C= Output Matrix of Plant

Using Matlab m-programming, matrix \(L_c\) and \(L_0\) can be obtained which are shown in equation 16 and 17.

\[
L_c = \begin{bmatrix}
22.4 & -40.38 & 52.8 & -40.38 & 0 & 0 & 52.8 & 0 & 0 \\
1 & 11.2 & 0 & 0 & -40.8 & 0 & 0 & 52.8 & 0 \\
0 & 1 & 11.2 & 0 & 0 & -40.8 & 0 & 0 & 52.8 \\
1 & 0 & 0 & -11.2 & -40.8 & 52.8 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0
\end{bmatrix}
\]

(16)

\[
L_0 = \begin{bmatrix}
22.4 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
-40.38 & 11.2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
52.8 & 0 & 11.2 & 0 & 0 & 1 & 0 & 0 & 0 \\
-40.38 & 0 & 0 & 11.2 & 1 & 0 & 1 & 0 & 0 \\
0 & -40.38 & 0 & -40.38 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & -40.38 & 52.8 & 0 & 0 & 0 & 0 & 1 \\
52.8 & 0 & 0 & 0 & 0 & 11.2 & 1 & 0 & 0 \\
0 & 52.8 & 0 & 0 & 0 & -40.38 & 0 & 1 & 0 \\
0 & 0 & 52.8 & 0 & 0 & 52.8 & 0 & 0 & 0
\end{bmatrix}
\]

(17)
The controller is:

\[ C_g(s) = 1.46 \frac{(0.83s + 1)(0.017s + 1)}{s(0.037s + 1)(0.004s + 1)} = 1.46 \frac{0.014s^2 + 0.847s + 1}{0.00015s^3 + 0.041s^2 + s} \]  

3. **Results and discussions**

The observation of controlled system response aimed to evaluate magnitude of overshoot of linear speed variable if motor currents is changed. Figure 3 shows that response of controlled system is widely varied. Figure 3 and 4 show that the actual linear speed response follows the
speed reference trajectory accurately. It illustrates also that the results of Matching 2-DOF controllers has been compared to response with only one DOF controller. Furthermore, it reaches the desired final linear speed at the specified settling time. The inset of the figure shows a close up view of the tracking with a linear speed resolution of 2 mm s⁻¹ per division. The speed curve in Figure 4 shows that the actual motion trajectory follows very well with the desired motion profile. From both Figure 3 and 4, we observe that the achievable error speed reaches 0.01% for 2-DOF structure and 2.2% for 1-DOF structure.

4. Conclusion
In this paper, High precision motion performance has been verificated by MATLAB-simulation. Design-algorithm guarantee the existence of the variety of parameter model (Robustness performance). Furthermore, it is illustrated that the desired matching scheme, in which the feed-forward controller is calculated using directly trajectory information only, provided several implementation advantages such as less on-line computation time, reduced effect of measurement noise, a separation of robust control design from parameter adaptation, and a faster adaptation rate in implementation. The results shown that the system provided a good tracking and steady state performance for both sinusoidal and exponential variation of set-point. Even though the damping ratio parameter of model have been changed from 0.9 to 1.5, the closed loop system show a stable condition and have good performance.

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