A Novel Design of Low Pass Filter in Disturbance Observer for Speed Tracking of Permanent Magnet Synchronous Motors

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***Abstract*-- This work proposes an approach to find an appropriate bandwidth of a first-order low pass filter (LPF) used in a DOBC. It is established that an observer in the DOBC can guarantee precise estimation if its bandwidth is set as high as possible in order to reject disturbances in a broad frequency range. On the other hand, there is an upper bandwidth limitation due to the system robustness and potential noises; hence, the bandwidth is required to set to be smaller than the limit. In this work, we propose a method of selecting proper bandwidth for the LPF in the DOBC. To show the effectiveness of the proposed method the experimental studies are carried out using the permanent magnet synchronous motor (PMSM)..**

***Index Terms*--Permanent Magnet Synchronous Motor (PMSM), disturbance observer based control (DOBC), low pass filter (LPF), time constant, bandwidth.**

I. Introduction

The invention of materials such as neodymium-iron-boron (NdFeB), ferrite, and other elements with superior magnetic properties helps to widely use the permanent magnet synchronous motors (PMSMs) in most industrial fields. Different sources of disturbance such as external disturbance, parameter variations, noises of measuring devices, and unknown internal frictions exist in the PMSM [1]. A sum of those disturbances creates a total disturbance which is required to estimate to proper control of the PMSM. Since the invention disturbance observer (DOB) by Ohnishi in his work [2], the disturbance observer based control (DOBC) become as a powerful control approach to estimate disturbances and uncertainties in order to compensate them in control loop. With this technique it was possible to design a robust and stable control systems in industrial applications. Successful application of the different disturbance observers for the PMSMs can be found in [3-7]. Among these proposed methods, despite its cons (knowledge of a nominal plant and properly selected bandwidth), the low-pass filter based DOB is shown to be practical. In general, the robustness of a DOBC system mainly depends on the dynamics of a nominal plant and the LPF [8]. It is presented that a sufficiently large bandwidth of the LPF provides a robustness of a control system; however, unmodelled dynamics in the plant model create limitations on unnecessary increasing of the bandwidth of the LPF [2]. Furthermore, in previously presented studies, the selecting of the proposed bandwidth threshold is achieved through extensive simulations studies or by trial and error.

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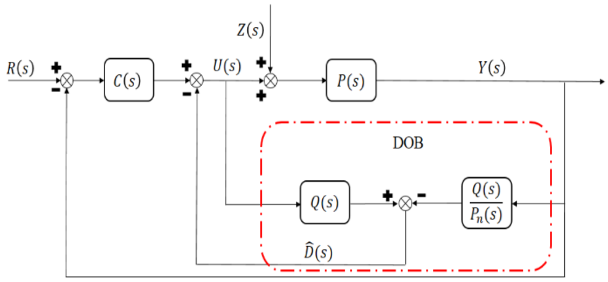

Fig. 1: Disturbance observer based control (DOBC) scheme.

In this study, we present an approach of selecting practical bandwidth value of the LPF based on the spectrum analysis of electromagnetic torque of the PMSM. It is shown by the equation that, in steady-state, a total disturbance should converge to the electromagnetic torque [1]. Therefore, it is possible to extract the frequency component of the electromagnetic torque by spectral analysis method and obtain a frequency of the applied load torque. It should be noted that the frequency component of the electromagnetic torque differs depending on the type of an external load torque applied to the motor. In this work, we have considered three common load torque shapes such as step, sinewave, and triangular with different frequencies. We compare the results of the first-order LPF with bandwidth obtained by the proposed method and the second-order LPF used in [7] with bandwidth obtained by trial and error. The experimental results show that the first-order LPF which shows better dynamics and estimation performance comparing to the second-order LPF in [7] might be considered as a sufficient solution in the DOBC scheme to control PMSMs.

II. Speed Loop Model of the PMSM and DOBC Scheme

A mathematical model of the PMSM's rotor is given as below:

$$J\omega_m = T_e - d \tag{1}$$

where J – rotor's moment of inertia; ω_m – rotor's mechanical speed; T_e – an electromagnetic torque; d – a total disturbance, and $d = T_{vis} + T_{fr} + T_{pull} + T_l$, in which T_{vis}, T_{fr}, and T_{pull} are torque due to the viscous and Eddy current pulling force, torque due to the friction force, and torque due to the flux, respectively; T_l – a load torque. The next assumptions are used to design a control scheme.

Assumption 1. 1) ω_m, i_q, i_d, and T_e are available; 2) total disturbance d and its components shown in (1) are unknown.

Fig. 1 shows the general scheme for DOBC system. According to Fig. 1, $C(s)$ – controller, $P(s)$ – actual plant, $R(s)$ – reference signal, $Y(s)$ – output signal, $Z(s)$ – external disturbance, $P_n(s)$ – nominal plant, $U(s)$ – reference control input to the plant, $Q(s)$ – a first-order low-pass filter. The disturbance effect is compensated in the feedforward loop after its estimation, once the disturbance is eliminated, any linear controller can be used as the controller $C(s)$ in Fig. 1. In this study, we utilize a PI controller as $C(s)$. The first-order low-pass filter $Q(s)$ used in this study has a form:

$$Q(s) = \frac{\mu}{s+\mu} \tag{2}$$

where µ – a bandwidth of the low-pass filter. In general, the proper selection of µ plays a crucial in role design of the LPF-based DOBC, i. e. small value µ can reveal poor estimation performance, whereas too large value µ may negatively affect to the system robustness and performance. In [7], a second order low-pass filter of the following form is utilized

$$Q_2 = \frac{m_2}{s^2+m_1 s+m_2} \tag{3}$$

where m_i (i = 1, 2) are the parameters of the filter to be adjusted. Actually, these parameters of the filters are defined such that the response of the observer is faster than the response of the speed controller. The configuration of the second order filter DOBC is the same as Fig. 1, where the Q is replaced by Q_2.

In the following, we will present how to select a proper µ to design the first-order LPF using spectrum analysis of the electromagnetic torque T_e.

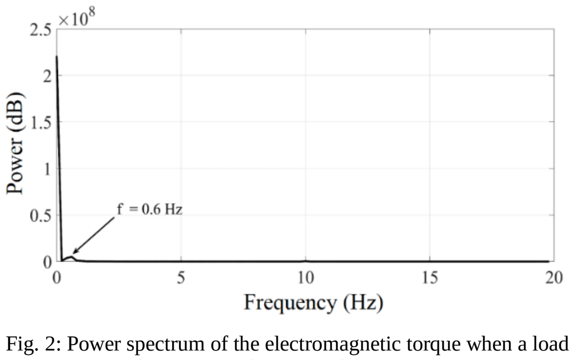

Fig. 2: Power spectrum of the electromagnetic torque when a load torque of a sinewave form with f = 0.6 Hz is applied

III. Proper Value of LPF's Bandwidth Based on Spectrum Analysis of Electromagnetic Torque

In this section, we show the method of finding the practical value of the filter's bandwidth using the available value of T_e. Result of the power spectral analysis performed on the measured T_e is shown in Fig. 2. This figure demonstrates the power spectrum of the electromagnetic torque when a sinusoidal load torque is applied to the rotor's shaft. Recall that the frequency of the sinewave signal and the angular frequency are related each other by the next equation

$$\omega = 2\pi f \tag{4}$$

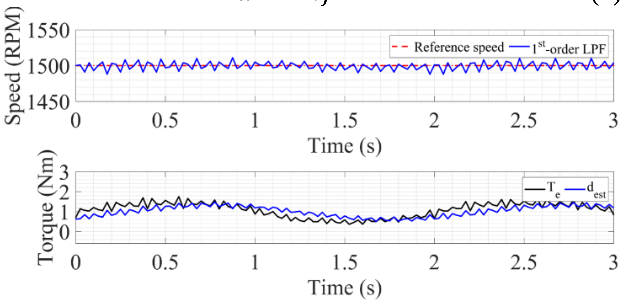

Fig. 3. Disturbance estimation: upper plot – speed response, lower plot – disturbance estimation.

In this case, the applied load torque is $T_l = T_{l,rated}(sin3.768t)$ Nm with the speed reference is set to be constant at 1500 rpm. As seen in this figure, the dominant frequency is 0.6 Hz. Based on the relationship of the frequency and angular frequency in (4) the LPF is designed with the bandwidth equal to the angular frequency of the load torque signal. Fig. 3 shows the speed tracking performance and disturbance estimation performance of the 1st-order LPF, respectively.

Hence, the algorithm of selecting the bandwidth of the 1st-order LPF is summarized as

Algorithm for selecting of the bandwidth of the LPF

1) Plot the spectrum of T_e;
2) Obtain the dominant frequency in the signal of T_e;
3) Based on (4), obtain the bandwidth of the LPF.

IV. Comparative Experimental Results

Based on the aforementioned method for selecting the bandwidth of LPF, here we show several cases of load torque at different frequency with constant speed reference. Figs. 4-7 show the disturbance estimation and speed tracking performance under two type of load torque: sinusoidal with frequency of 2.5 Hz and triangular with frequency of 2.4 Hz. According to the algorithm shown in Section 3, the bandwidths of the 1st-order LPF for each load type are $15.7\frac{rad}{s}$ and $15.072\frac{rad}{s}$, respectively. We remind that the bandwidth of the second order LPF is selected via extensive simulation studies [7] with different waveforms of load torque. The speed response comparison shows that the speed dynamics obtained by proposed method is more stable comparing to the second-order LPF-based DOBC under the different types of the load. In this case, the bandwidth of the second-order LPF is $9\frac{rad}{s}$.

The superiority of the proposed method is shown from the disturbance estimation plot. At steady state, estimations of the both methods try to closely converge to the electromagnetic torque T_e. However, the electromagnetic torque generated in the proposed control scheme has smaller amplitude comparing to the traditional one. The performance comparisons in terms of the root mean square deviation (RMSD) of the speed response for each load case are provided in Table 1. Finally, we add one more case of load torque which is step-change to compare the proposed 1st order LPF and the 2nd order one, the results are presented in Fig. 4 with the statistic performance is also summarized in Table I. In Fig. 4, the bandwidth of the 1st order LPF is obtained as $7.536\frac{rad}{s}$.

The comparison here is to illustrate the advantage of the proposed method for designing the filter for the DOB. Here what we learn is that, to optimize the estimation performance, when the bandwidth of the filter of the DOB is designed based on the power spectrum of the disturbance, the performance is improved. This is meaningful in some applications which the disturbance is periodic.

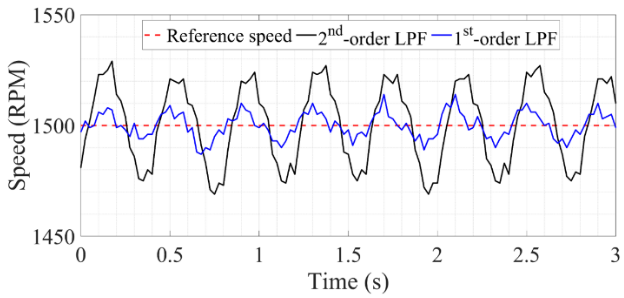

Fig. 4: Comparative results under the load torque of a 2.5 Hz sinewave form - Speed response.

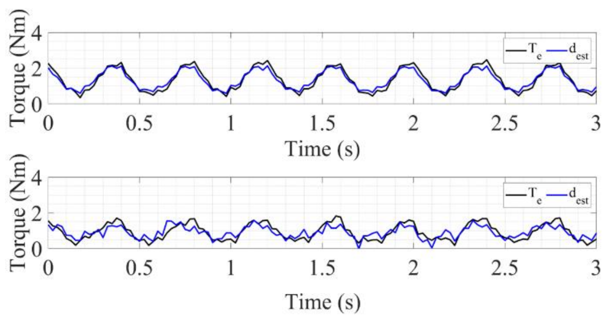

Fig. 5. Disturbance estimation: upper plot - 2nd-order LPF, lower plot - proposed 1st-order LPF.

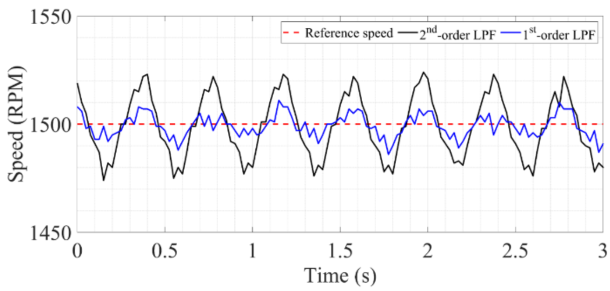

Fig. 6. Comparative results under the load torque of a 2.4 Hz triangular form - Speed response.

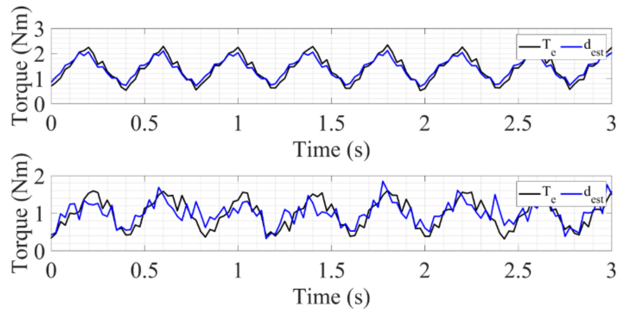

Fig. 7. Disturbance estimation: upper plot - 2nd-order LPF, lower plot - proposed 1st-order LPF.

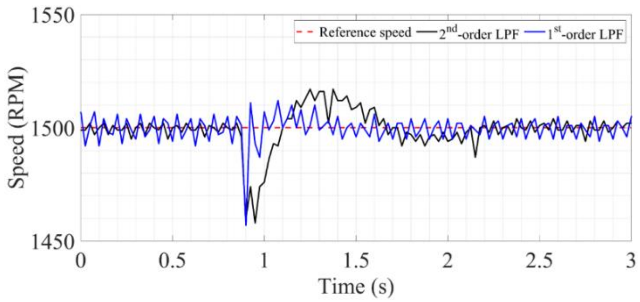

Fig. 8. Comparative results of under the step load torque - Speed response.

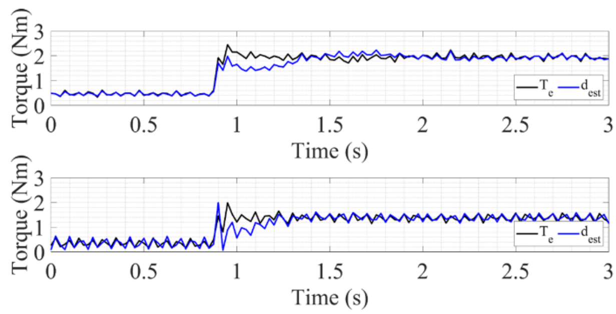

Fig. 9. Disturbance estimation: upper plot - 2nd-order LPF, lower plot - proposed 1st-order LPF.

TABLE I
ROOT MEAN SQUARE DEVIATION OF THE SPEED RESPONSE

Methods	RMSD value
Sinewave load with f = 2.5 Hz : 2nd –order LPF/1st-order LPF	18.0061 rpm/5.7736 rpm
Triangular load with f = 2.4 Hz: 2nd –order LPF/1st-order LPF	14.4452 rpm/5.2168 rpm
Step load with f = 1.2 Hz: 2nd –order LPF/1st-order LPF	6.9069 rpm/5.3132 rpm

V. CONCLUSION

In this article, we show the experimental approach of obtaining the proper bandwidth for the first-order LPF of the DOBC. The experimental validations have been performed and compared with the results of the second-order LPF-based DOBC. The main idea of the study is to show a method of proper selection of the bandwidth of the LPF in the DOBC approach. Furthermore, it is validated by experiments that the first-order LPF is enough to obtain more accurate results comparing to the second-order LPF, and no further increase of filter's order is required. As it is revealed from the RMSD values, with the experimentally obtained value of the bandwidth, the first-order LPF shows better tracking performance and disturbance estimation comparing to the second-order LPF in speed response especially under the load with high frequency.

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