2019 26th International Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED), Moscow, Russia. Jan 30 – Feb 02, 2019

Extended Algorithm of Electrical Parameters Identification via Frequency Response Analysis

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本文提出了一种通过频率响应获得总响应延迟的方法

***Abstract*—Current control loop Bode diagrams of servo drives are commonly used for electrical resistance and inductance identification. Apart from these parameters the Bode diagrams contain the information on the total delay time of the loop. The study considers identification of this delay, the value being important during the development stages for proving the servo drive is functioning properly as well as for preliminary parameter setup. In the paper a robust algorithm for current control loop identification is proposed. Theoretical evaluations are proved by the simulation and experimental results obtained from a servo drive with coupled to a 3 level inverter implementing two different PWM strategies.**

***Keywords*—motion control, parameter identification, frequency response analysis, auto-tuning, three-level inverter, nonlinearity compensation**

I. Introduction

The constantly increasing demand on motion quality and usability forces the developers to increase accuracy and automatization degree of identification and auto-tuning procedures of servo drives. When speaking of tuning procedures, these often include parameter self-identification of the servo drive, and frequency response analysis (FRA) is one of the great possibilities for that [1, 2]. Current control loop has a critical influence on servo drive performance, including the outer control loops dynamics, exact tracking precision, servo jitter etc. [3, 4]. As the current loop of a typical servo drive is an aggregation of non-linear objects – motor, PWM-driven voltage source inverter (VSI), measuring system, digital control system, identification of the current control loop is still of a great interest nowadays [5].

Servo drive current plant comprises permanent magnet synchronous motors (PMSM) [5], PWM-driven voltage source inverters [6], and the current feedback circuit. Obtaining parameters via FRA usually means obtaining motor impedance from the current plant Bode diagrams [1, 2, 7]. So a lot of research is carried out on the algorithms of the electrical parameter identification [8, 9].

However, the inverter modulation technique, control system update rate and the feedback acquisition circuit performance impact the performance of the control. All these introduce additional delay which can be estimated analytically as done in [10]. In some cases, when testing and tuning a newly developed servo drive the experimental validation of the current control loop delay can expedite the process. It's a way to check all of the components function as should.

In this study a method to obtain total current delay time via FRA is proposed. The method can be further extended to the outer control loops the identification of these is especially important when a drive is being operated within a distributed control system and the feedback as well as data transmission delays are not easy to calculate analytically.

The paper is structures as follows. The 2nd section is devoted to the delay time origin in PWM driven VSI. In the 3rd section the two analyzed PWM strategies are described, the equations for estimation of the current control loop delay are obtained. The 4th part describes the proposed identification algorithm and identification process. The 5th section presents the simulation and experimental results obtained from a three-level VSI, both being compared to the theoretical estimations. Finally, section 6th concludes the paper.

II. Current Control Loop Delay

Fig. 1 illustrates the structure of servo drive current loop consisting of the current plant (a PWM-driven VSI, motor, feedback measurement system including current sensors and filters) with transfer function (1) and of the current controller. The parameters of current plant are electrical resistance R_p and inductance L_p, as well as the current control loop delay time $T_{\Sigma i}$ [3]:

$$W_p(\mathrm{p}) = \frac{1/R_p}{1 + L_p/R_p\mathrm{p}} \cdot \mathrm{e}^{-\mathrm{p}T_{\Sigma i}}. \tag{1}$$

This delay strongly depends on the PWM and current measurement strategy and comprises the delay introduced by the analog filters T_f, the discrete current processing T_{discr}. This current processing consists of the current measurement technique (T_{meas}), the motion control calculation (T_{calc}) and, finally, the PWM modulation (T_{impl})

$$T_{\Sigma i} = T_f + T_{discr} = T_f + T_{meas} + T_{calc} + T_{impl}. \tag{2}$$

There are a lot of works dedicated to the reduction of the delay $T_{\Sigma i}$ (by the given PWM frequency) it impacting the bandwidth of the current control [10] and limiting the performance of the whole system. The delay reduction can be done by introducing current observers, programmable logic, high rate of control calculations oversampling, etc. [11, 12]. The goal of the research is to develop a means to measure the delay and this way to prove the designers of the power drive system have achieved the predicted performance. In Fig. 2 two of the many possible current control synchronization approaches with the PWM triangular reference signal are presented.

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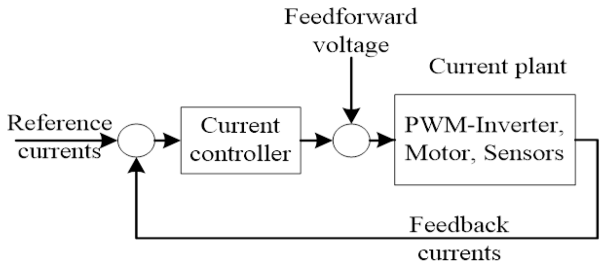

Fig.1. Current loop

The current feedback is measured with period T_s – twice each PWM period for both of the approaches. The start of the measurement corresponds to the extremums of the reference signal. To increase the current resolution each measurement comprises several consequent current measurements being averaged. It is to mention, that by $T_{meas} << T_s$ the current aliasing effects can be neglected.

When averaging the N measurements with period T_{ADC} the measurement delay can be calculated as:

$$\boxed{T_{meas1} = (N-1)\,T_{ADC}/2.} \tag{3}$$

For the 1st case (PWM-1) presented in Fig. 2, a) the new PWM references are updated T_s after the ADC conversion start. This means the calculation time can be calculated as:

$$T_{calc} = T_s - 2T_{meas}. \tag{4}$$

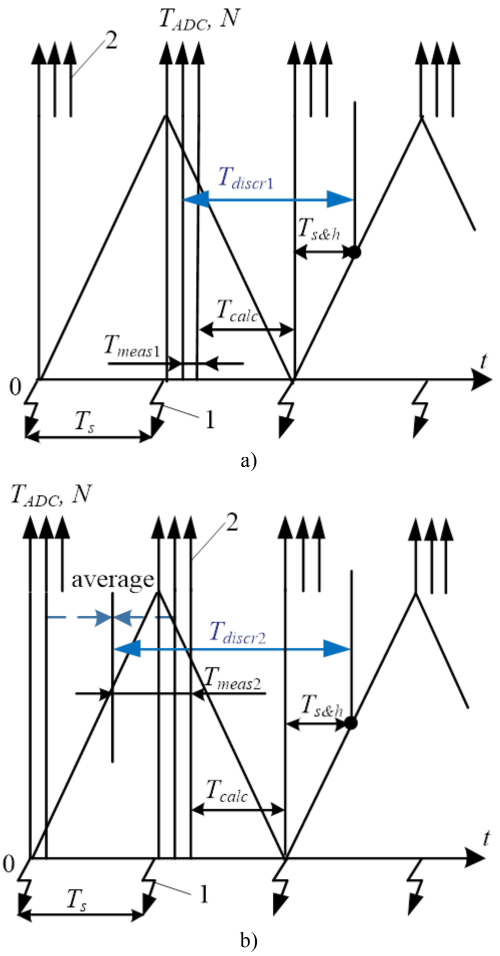

Fig. 2. Applied PWM strategies. a) – PWM-1, b) – PWM-2. 1 – start of interrupt, 2 – single current measurement.

The new references are applied with the additional delay

$$T_{impl} = 0.5T_s. \tag{5}$$

The resulting delay for this case can be obtained as:

$$T_{\Sigma i1} = T_f + 1.5T_s - (N-1)T_{ADC}/2. \tag{6}$$

For the 2nd case (PWM-2) presented in Fig. 2, b) the feedback measurement in two extremums is additionally averaged, this resulting in feedback measurement time increase:

$$T_{meas2} = (N-1)\,T_{ADC}/2 + T_s/2. \tag{7}$$

The resulting delay for the 2nd case can be obtained as:

$$T_{\Sigma i2} = T_f + 2T_s - (N-1)T_{ADC}/2. \tag{8}$$

Equations (6) and (7) allows to estimate $T_{\Sigma i}$ for the described PWM strategies and will be used to validate the identification results obtained further in the study.

III. Identification of Electrical Parameters via FRA

Conventional identification methods allow to obtain only plant impedance and total delay time stays estimated analytically, whereas it is possible to identify all plant parameters analyzing current plant Bode diagrams. Fig. 3 demonstrates a simplified design of current control applied for measurement of plant Bode diagrams in the current closed loop operation mode [8, 13].

In case of linearized inverter [14] or by negligible voltage disturbances on the inverter-output obtained Bode magnitude contains information about plant impedance and the influence of $T_{\Sigma i}$ can be neglected:

$$\mathrm{L}(f) \cong 20\log_{10}\frac{1}{\sqrt{R_p^2 + L_p^2(2\pi f)^2}}, \tag{9}$$

whereas Bode phase characteristics depends on the total delay time:

$$\Phi(f) = -\tan^{-1}\left(\frac{2\pi f L_p}{R_p}\right) - 2\pi f T_{\Sigma i}. \tag{10}$$

Thus approximation of FRF magnitude can be used to identify resistance and inductance of plant and Bode phase – to identify total delay time $T_{\Sigma i}$. The proposed full identification algorithm consists of the following steps:

1) approximation of Bode magnitude (Fig. 4 a):

$$\mathrm{L}(f\to 0) = \mathrm{L}_0 = 20\log_{10}\frac{1}{R_p}, \tag{11}$$

$$\mathrm{L}(f\to\infty) \cong 20\log_{10}\frac{1}{L_p 2\pi f}. \tag{12}$$

2) plant resistance and induction calculation

$$R_p = 10^{-\mathrm{L}_0/20}, \tag{13}$$

$$L_p = \frac{R_p}{2\pi f_0}. \tag{14}$$

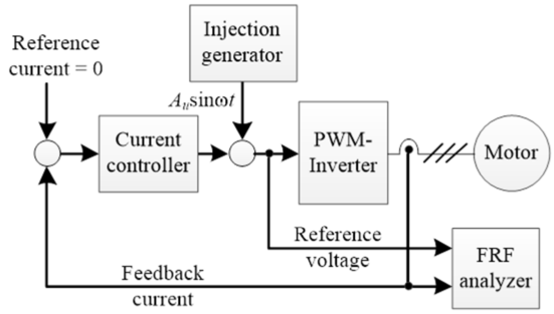

Fig.3. FRF acquisition diagram [13]

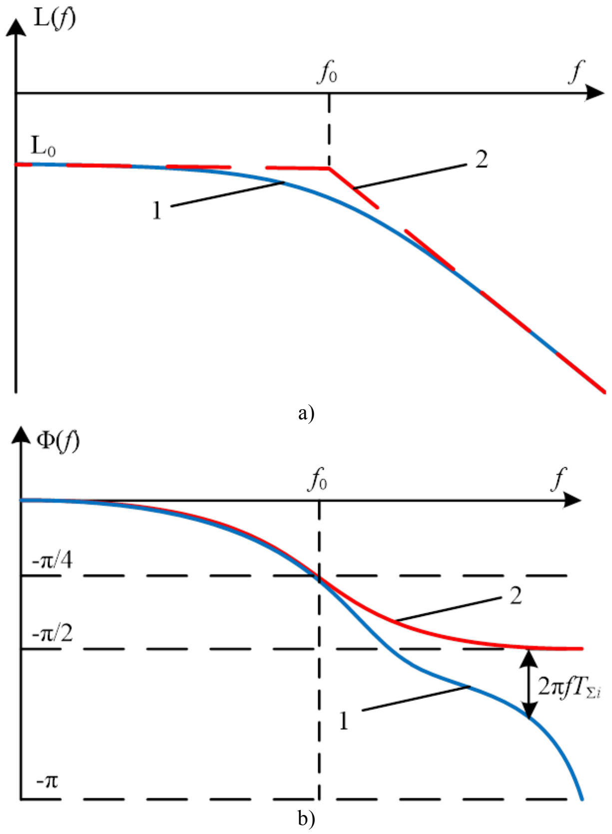

Fig. 4. Qualitative approximation of current plant FRF. a) FRF Magnitude, b) FRF phase. 1 – obtained FRF, 2 – approximation.

3) measurement of current plant Bode diagrams.
4) Calculation of total delay time $T_{\Sigma i}$ as (Fig. 4 b)):

$$T_{\Sigma i} = \sum \left(\frac{\mathrm{tg}^{-1}\left(\frac{2\pi f_k L_p}{R_p}\right) - \Phi(f_k)}{2\pi f_k} \right), \qquad (15)$$

where f_k – frequencies of obtained Bode plot points.

The proposed identification algorithm can be used to prove the servo drive is functioning properly as well as for preliminary parameter setup.

IV. Simulation and Experimental Results

Identification algorithm described in the third part of the study was simulated in MatLab and then realized for test bench based on the linear PMSM LMF64 [15] coupled with PWM-inverter D5A [16]. PMSM LMF64 is presented in the Fig. 5. Its parameters are presented in Table I. Using the described algorithm, a series of experiments have been made for two different PWM strategies in order test the parameter identification procedure. Fig. 6 demonstrates current plant Bode diagrams, measured for PWM-1. Obtained identification results are denoted in Table II.

The difference between measured and estimated values of current loop delay time can be attributed to the uncertainty of measurement time estimation. The period of AD conversion was approximately calculated as time duration of conversion of 8 ADC channels. So there is an uncertainty of T_{meas} depending on the moment of current measurement inside of T_{ADC}. Inaccuracy of (3) and (7) is up to T_{ADC}. Hence, the obtained experimental results supposed to be accurate.

The next experiment tests the efficiency of auto-tuning based on the proposed identification algorithm. In this test servodrive current loop was set up according the identified parameters and tuning strategy described in [10]. Desired closed loop current control bandwidth was set to 2000 Hz.

TABLE I. Parameters of the Test Bench

Parameter, units	Value
PWM-inverter	
DC-bus voltage, V	650
PWM-frequency, kHz	16
PMSM	
Phase resistance (R_p), Ohm	0.55
Phase inductance (L_p), mH	4.3
Control loop	
CS sampling time (T_s), μs	31.25
Consequent current measurements being averaged (N)	8
Period of AD-conversion (T_{ADC}), μs	1.5
Time constant of analog filter (T_f), μs	3

TABLE II. Identified Parameters

Parameter, units	Data sheet	Identification	
R_p, Ohm	0.55	0.564(PWM-1)	0.573(PWM-2)
L_p, mH	4.3	4.4 (PWM-1)	4.3 (PWM-2)
$T_{\Sigma i1}$ (PWM-1), μs	44.6	42.6	
$T_{\Sigma i2}$ (PWM-2), μs	60.25	57.7	

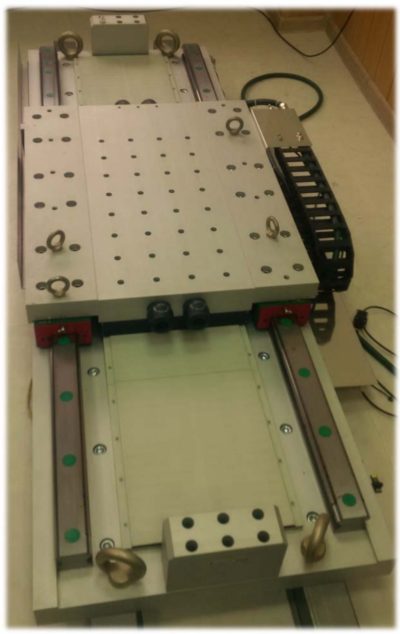
Fig. 5. The test bench PMSM

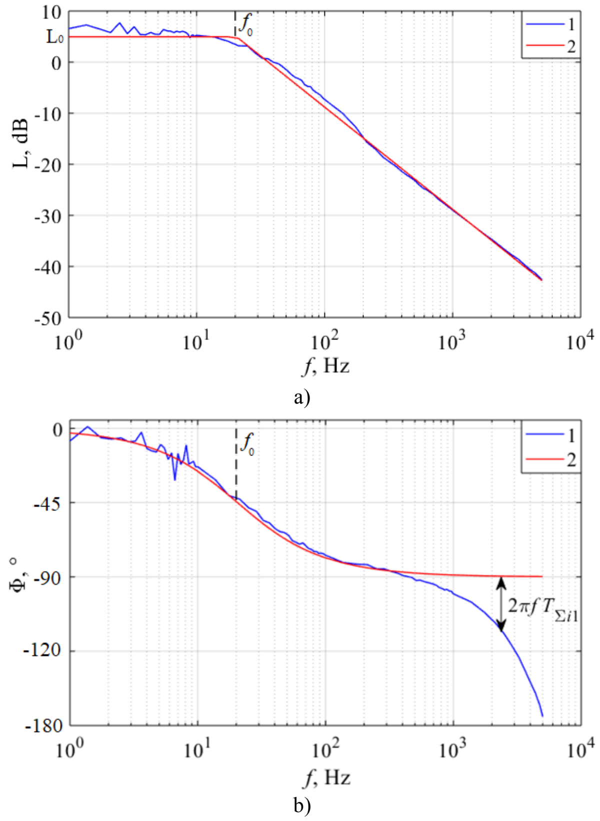

Fig. 6. Current plant FRF. a) FRF Magnitude, b) FRF phase. 1 – obtained FRF, 2 – approximation.

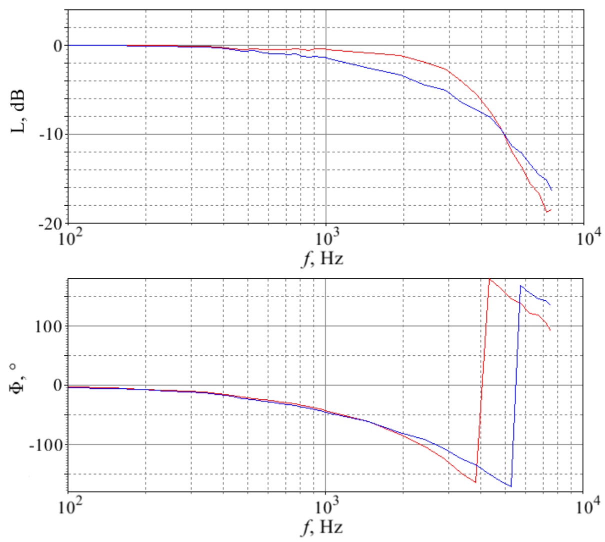

Fig. 7. Closed loop current control FRFs for two PWM strategies: blue – PWM-1, red – PWM-2.

Then Bode diagrams of closed current loop were measured and its real bandwidth was compared with desired one. It appears from Fig. 7 that auto-tuning with proposed identification algorithm enables to achieve desired bandwidth.

CONCLUSIONS

Proposed identification algorithm allows to obtain values of motor impedance and total delay time of current loop. Experimental results prove the efficiency of the identification for various PWM strategies. Algorithm suits for the integration in the auto-tuning strategies and for proving the servo drive during development stage.

To avoid influence of PWM-inverter nonlinearities on the identification process it is desired to measure current plant Bode diagrams with voltage dc-component higher than sum of used amplitude of AC-voltage reference and inverter voltage drop.

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