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The Control of PMSM Motor to Drive Propeller in Ship Propulsion System

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Abstract. Electric propulsion has advantages such as high maneuverability, good safety and reliability, being able to operate optimally with a control system. It is a future green technology which is environmentally friendly. The application of electric propulsion for ship is that the propeller is driven by using electric motor by regulating speed and/or torque. in this research, an permanent magnet synchronous motor (PMSM) is used to drive propeller of ship propulsion. The controller of proportional integral (PI) scheme is proposed to drive electric motor. The method of Ziegler Nichols stability margin tuning rule algorithm is performed to search the controller parameters. The optimal working point of propeller is determined by the cross intersection between the propeller loading curve to the coefficient of thrust curve of open water test propeller. The speed from the result of propeller working point analysis is set as control input reference. Based on the results of simulation, the proposed control of electric propulsion using PMSM motor is able to achieve the reference of speed.

1. Introduction

Climate change affected by pollution of vehicle transportation has become a worldwide concern. The International Maritime Organization has issued in order to limit the emissions gas from the combustion of marine vessels [1]. However, the emission of gas in maritime transport become more stringent in the future. Hence, the alternative energy source will have potential application in maritime transport such green energy source like solar, wind energy, and hydrogen energy to drive electric propulsion of ship. Technological engineering of electric propulsion is a green technology which is to reduce environmental pollution to zero carbon emissions [2]. Supported by the advanced technology of power electronics, the sources of electricity has a high potential to be developed and applied for propulsion system using many alternative energy sources [3].

Technological developments in electronics, propulsion systems, electric motors, control systems and information technology have a dominant role in the application of electric propulsion system technology. Several electric motors have been proposed for propulsion drives such as BLDC motors [4], induction motors [5] and synchronous motors with permanent magnets [6]. The PMSM has the advantages such as light weight, small size, , economical fuel consumption, high power density and has a good dynamic response, making it very suitable for the use of ship propulsion systems [7]. In addition, compared to induction motors, PMSM has higher efficiency with smaller motor losses. However, the challenge of control system to use PMSM motors are non-linear model. It is a complex functional relationship between output torque and stator current and model transformations for control applications.

Several research applications have been proposed regarding the use of electric motors for ship electrical propulsion including sensor-less of PMSM applied in real time to electric propulsion prototypes as propulsors [6], PMSM motor starting techniques for ship propulsion [8], speed tracking controller based on prediction model was proposed by using PMSM for propulsion [9]. Several control methods have been developed to drive PMSM with proportional integral (PI) [10][11], Sliding mode controller on PMSM motor [12], and neural network-based control system [13]. In this research, we develop the design of a speed control system to drive propeller of ship propulsion system. The controller is designed using PI control method. The optimal working point of the propeller is calculated using ANLOVA software. Hence, the working point of the propeller is used as a reference to adjust the speed of the PMSM motor.

2. Methodology

The steps to design the speed control system in ship propulsion consists of 1) The calculation related to determine the optimum operating point of the propeller, 2) Design of PMSM motor speed control.

2.1. Ship resistance and propeller selection

The working point of the propeller is based on the characteristics of the ship resistance using the resistance data from the results of towing tank test of model. The data of model and full scales ship with the length ratio between ship and model is 8 are shown in Table 1. Meanwhile, the resistance of model by towing test and the calculation results of ship resistance in full scale are shown in Table 2.

Table 1. Dimension of ship vs model

PARAMETER	SHIP	MODEL
Loa (m)	11.4	1.425
Lwl (m)	10.73	1.34125
Lpp (m)	10.34	1.2925
B (m)	5.7	0.7125
H (m)	2	0.25
T (m)	1.8	0.225
Vs (knot)	7	
Prism Coef	0.643	0.643
Block coef	0.505	0.505

Table 2. The resistance of model from the results of towing tank test and ship resistance

RUN	Vm (m/s)	Vs (m/s)	Rtm (kg)	Rts (kg)
1	0.177	0.501	0.0634	423.67
2	0.284	0.803	0.0932	650.6
3	0.403	1.14	0.1914	1325.73
4	0.432	1.222	0.3121	2094.88
5	0.585	1.655	0.5013	3387.40
6	0.773	2.186	0.7425	5070.71

The performance of the propeller is calculated using ANLOVA software. The inputs of ANLOVA software to calculate the operating point of propeller are ship resistance, gearbox ratio, propeller properties like diameter, expanded area ratio, number of blades and pitch of propeller. The ship resistance is calculated based on model test results using towing test or is calculated based on numerical method the Holtrop, Van Oortmerssen, Savitsky, Latiharju and others. However, the type of propeller used is the B series propeller in which the propeller performance modelled under mathematic polynomial model. Polynomial model is a good model to express the open water test characteristic of B series propeller model. The Polynomial model expresses the thrust coefficient and the torque coefficient with the input variables can be pitch-diameter ratio (P/D), number of blades (Z), blade area ratio (AE/A0), and advance coefficient (J) [14]. The operating point of propeller is the point of intersection between the propeller loading curve and the thrust coefficient curve of open water test propeller curve.

To calculate the operating point of the propeller, the first step is the calculation of the ship's resistance which can be expressed as

$$Rt = kV^2 \tag{1}$$

V = Ship speed (m/s)

k = coefficient of drag
Rt = total resistance (kg)

The performance characteristics of propeller can be expressed by constants that describe the performance of the propeller which can be represented by an open water test propeller graph written by

$$Kt = \frac{T}{\rho . n^2 D^4} \tag{2}$$

$$Kq = \frac{Q}{\rho . n^2 D^5} \tag{3}$$

$$J = \frac{V_a}{nD} \tag{4}$$

$$\eta = \frac{Kt . J}{2\pi . Kq} \tag{5}$$

$$R = T(1-t) \tag{6}$$

$$V_a = V(1-w) \tag{7}$$

Where the notations are expressed as Kt = Thrust coefficient, Kq = torque coefficient, J = Speed of advance, η = propeller efficiency. The equation of propeller loading curve is the subtitution between the equation (1) until equation (7) that can be written by,

$$Kt = \frac{c}{\rho .(1-t).(1-w)^2 .D^2} \left[\frac{Va}{n.D} \right]^2 \tag{8}$$

The characteristics of the open water test propeller is a propeller performance curve presented by propeller efficiency, torque constant and thrust constant as a function of speed of advance. The propeller loading curve presented in equation (8) is plotted against the open water test propeller characteristic graph. The point of intersection between the thrust constant of the propeller loading curve and the thrust constant of the open water test propeller characteristics is the propeller working point. Based on the working point of the propeller, the performance of propeller will be known such as efficiency, torque, thrust, delivered horse power (DHP) and propeller cavitation symptoms. The requirements of cavitation are also considered to select the propeller. It is calculated using Burril method that can be expressed as follow,

$$\frac{P}{D_{\max}} \leq \frac{1.067 - \left(\frac{A_p}{A_d} \right)}{0.229} \tag{9}$$

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2.2. Modelling and control system of PMSM motor

PMSM has a constant magnetic flux so that the control system is more efficient designed using vector control techniques on the magnetic rotor. The PMSM motor dynamic system modeling with d-q coordinates is as follow [15],

$$\frac{di_d}{dt} = \frac{1}{L_d}u_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_r i_q \tag{10}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}u_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}p\omega_r i_d - \frac{mp\omega_r}{L_q} \tag{11}$$

$$T_e = 1.5[\lambda i_q + (L_d - L_q)i_d i_q] \tag{12}$$

$$\frac{d\omega_r}{dt} = \frac{1}{J_L}(T_e - F\omega_r - T_m) \tag{13}$$

$$\frac{d\theta}{dt} = \omega_r \tag{14}$$

Where, L_d, L_q, u_d and u_q denote the inductance and stator voltage of d-q axes respectively. The notation of R, J_L, T_e, T_m, F, p, m, ω_r denote the resistance of stator, inertia of motor, electromagnetic torque, torque of load, number of poles, the amplitude of flux, and the rotor speed respectively.

To detect the angular position of the rotor shaft, the synthesis of a three-phase stator current vector controller on the q-axis is carried out using the d-q transformation. This technique is simpler than vector control applied to asynchronous motors. The synthesis of the current vector controlling inverter with the d-q transformation technique is expressed as

$$i_a = i_s \cos\left(\theta + \frac{\pi}{2}\right) = -i_s \sin(\theta) \tag{15}$$

$$i_b = i_s \cos\left(\theta + \frac{\pi}{2} - \frac{2\pi}{3}\right) = -i_s \sin(\theta - \frac{2\pi}{3}) \tag{16}$$

$$i_c = i_s \cos\left(\theta + \frac{\pi}{2} + \frac{2\pi}{3}\right) = -i_s \sin(\theta + \frac{2\pi}{3}) \tag{17}$$

Where, i_a, i_b and i_c are the currents of three-phase coil. The stator currents in the d-q vector has a phase angle difference of 90^0. There are two control schemes using vector control method, namely 1) if i_{sd} =0, then the speed setting for controller is set as constant torque, and 2) if i_{sd} <0, then speed setting for controller is set as constant power. Therefore, for speed regulation with constant torque, it can be indicated by the block diagram in Figure 1.

Vector control applied to PMSM motor allows for better control performance compared to that is applied to AC motor in order to reduce torque pulses for the motor. It is due to the lack of slip frequency current of the induction motor and being slightly affected by the rotor parameters. Hence, vector control is more feasible for PMSM. The control structure of PMSM is presented on Figure 2.

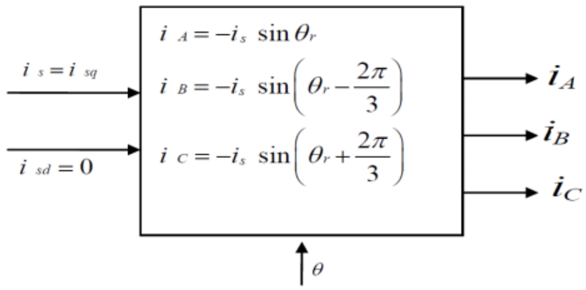

Figure 1. The rotor flux orientation of PMSM with $i_{sd} = 0$

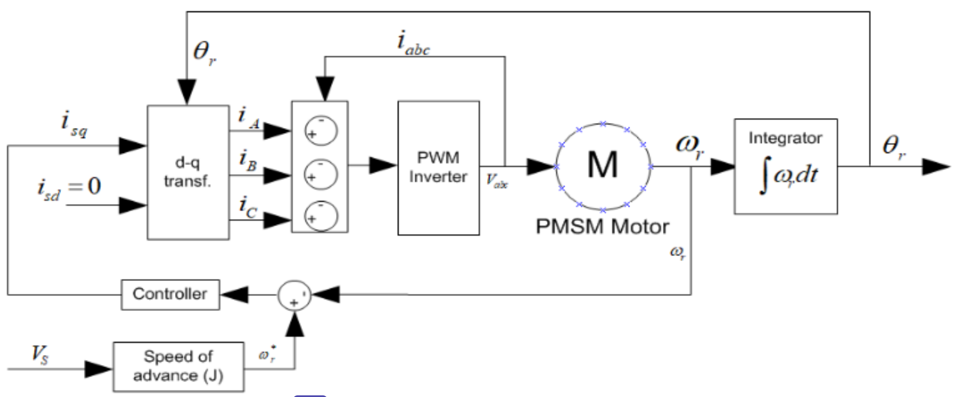

Figure 2. Block diagram of vector control system of PMSM motor

The vector control is derived using the direction coordinates of force field. This component consists of an excitation current to produce the magnetic flux and torque to produce current. The magnetic flux position of PMSM is determined by checking the actual position of the rotor. Hence, the important point of PMSM vector control is the control of phase and spatial amplitude of the vector rotor electricity.

In order to design a speed controller of PMSM motor, a PI controller scheme is proposed. The continuous PI controller can be stated as,

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{18}$$

where the controller parameters of PI consist of Kp is the proportional gain and Ki is the integral gain. The auto tuning method is used to regulate the parameter based on Ziegler Nichols stability margin tuning rules. The selection of controller parameter is based on gain and phase margin of Ziegler – Nichols Stability Margin Tuning Rule that the parameters are shown in Table 3. In order to search gain margin and frequency margin, the gain of closed system is regulated until the response of system has full oscillation then the gain is set as gain margin and the frequency of oscillation is set as frequency margin.

Table 3. The tuning rule parameters of PI controllers

Parameter	Kc	Ti
P	0.5 Kcu	.-
PI	0.45Kcu	Pu/1.2
PID	0.6Kcu	Pu/2

The parameter of Kcu is the ultimate gain margin and $Pu = \frac{2\pi}{\omega_c}$, ω_c denotes frequency margin. The transfer function form of PI controllers can be written as,

$$g_c(s) = Kc\left(1 + \frac{1}{Ti.s}\right) \tag{19}$$

3. Results and discussion

The Analysis and optimization of the ship propulsion is related to search the propeller working point with optimum efficiency. The tool used to optimize the optimum working point of propeller is ANLOVA. The input of software is ship's resistance, the propeller size and specification, and gearbox ratio. The output of software is propeller working point, the estimated propulsion power, and cavitation. Furthermore, the optimum propeller working point is set as the reference to design the controller of electric propulsion using PMSM motor. The steps to design the controller of ship electric propulsion is as follows,

1. PMSM motor dynamic modelling: In this step is the identification of PMSM motor dynamic modelling. The components of the PMSM motor modelling system are the inverse d-q coordinate transformation. These models are formed in a block diagram of the overall model for speed and/or torque regulation.
2. Design of control law: Control law is derived based on the model obtained from identifying the system with numeric simulation. The controller parameters will be searched to obtain the best transient and steady state response.
3. The last step is to simulate the controller design parameters. Controller performance is measured by several control system performance such as maximum overshoot and undershoot, time to steady state, steady state error, rooted mean square error.

3.1. Propeller working point analysis

The data used in order to estimate the propeller working point is the existing propeller of traditional shipyard that is as follows: type of B Series Propeller, number of propellers = two, number of blades = 3 blades, expanded area ratio = 0.5, pitch per diameter = 0.8, diameter = 0.6 m. The input of ship resistance is that shown in Table 1. and Table 2. Using the ANLOVA software, the results of propeller working point are shown in Figure 3. The results obtained by plotting the propeller loading curve against the propeller open water test in Fig 3. is as follows: propeller efficiency = 0.389, propeller rpm = 2800/3337 = 840 rpm, power = 40 kW, speed of advance (J)= 0.31, thrust coefficient (Kt) = 0.228, coefficient of torque (Kq) = 0.029. The ship's propulsion characteristics can be stated by the function of power to rpm written as

$$DHP = 6.96x10^{-8} N_p^3 \tag{20}$$

Where DHP denotes delivered power in kW and N_p denotes the propeller speed in rpm.

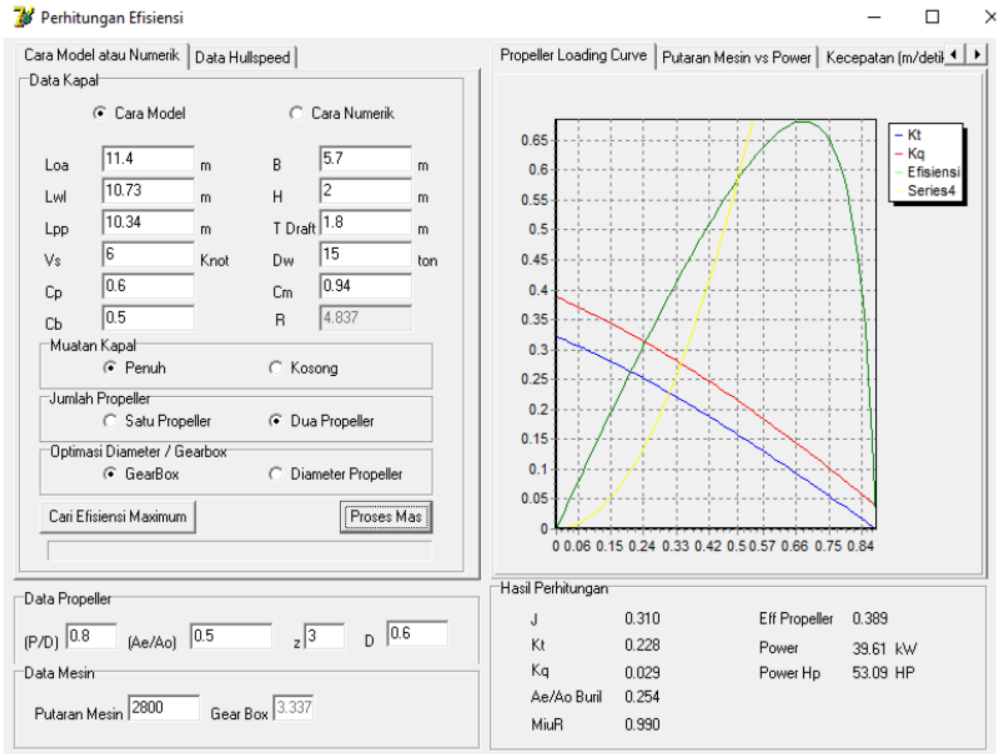

Figure 3. Tool of ANLOVA software used to estimate working point of propeller

3.2. Control system simulation

The PMSM vector control is modelled by using SIMULINK-MATLAB under PI control strategy. The transformation using Clarke and Park coordinate is performed in vector control. Vector control is derived according to the transformations between three-phase stator coordinates (a,b,c) to stationary two-phase coordinates (α,β) and two-phase rotational coordinates (d, q). The block diagram simulation of PMSM control under simulink-matlab is shown in Figure 4.

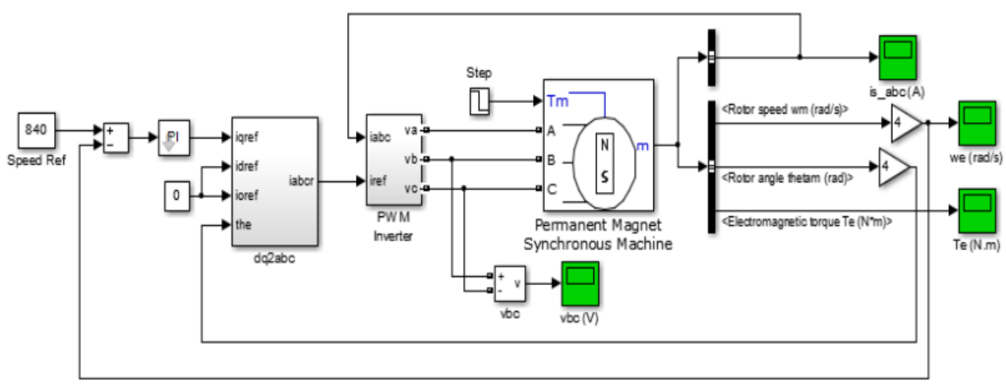

Figure 4. The simulation of PMSM control by matlab simulink

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The motor parameters are selected by voltage rating of 380 V, winding resistance of stator Rs=2.875, the inductance of winding phase of d-q denoted by Ld equal to Lq = 8.5 10^{-3} H, magnetic flux of rotor f = 0.175 Wb, inertia J= 0.8 10^{-3} kg·m2, pole number P=4. The simulation is used to test the control system with a low rotor speed according to the ship's propulsion characteristics. The running of simulation is under conditions with a fixed ship speed of 6 knots related to 840 rpm of propeller speed. The simulation results obtained are shown in Figure 5, Figure 6, Figure 7 and Figure 8. The reference speed can be achieved by 0.26 second from first start shown in Figure 5. By changing the torque of propeller shown in Figure 6, the controller is also able to keep the speed reference by changing electromagnetic torque shown in Figure 7. The control performance is measured by the RMS error shown in Figure 8. Based on the RMS error curve, it can be stated that the error converges to zero.

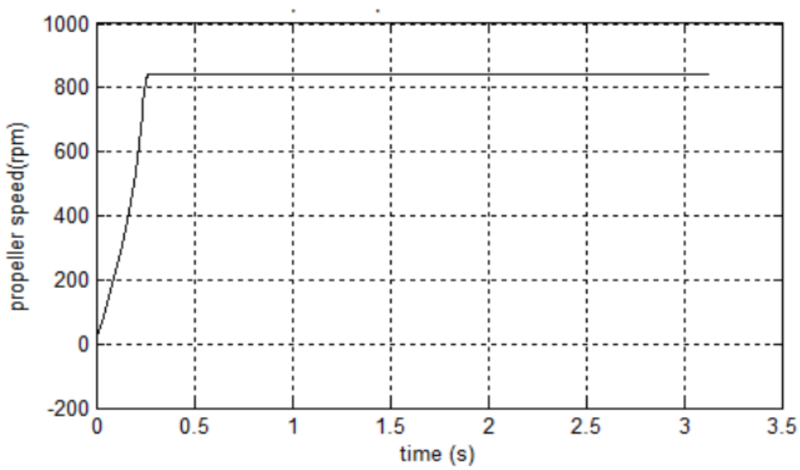

Figure 5. Response of control system of speed controller

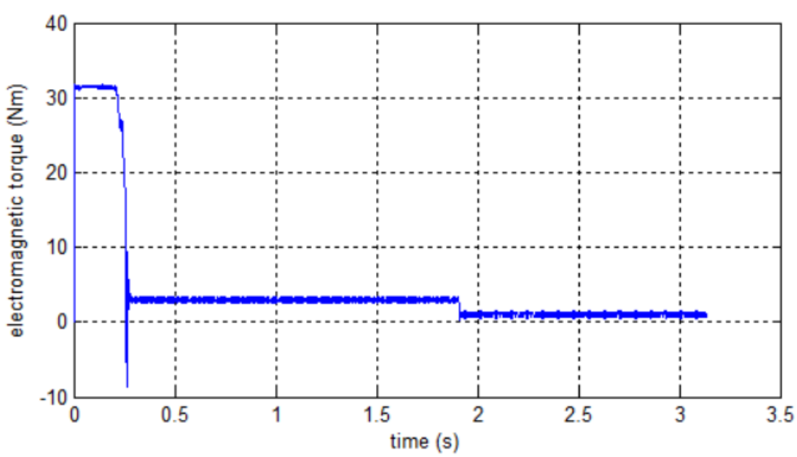

Figure 6. Response of electromagnetic torque

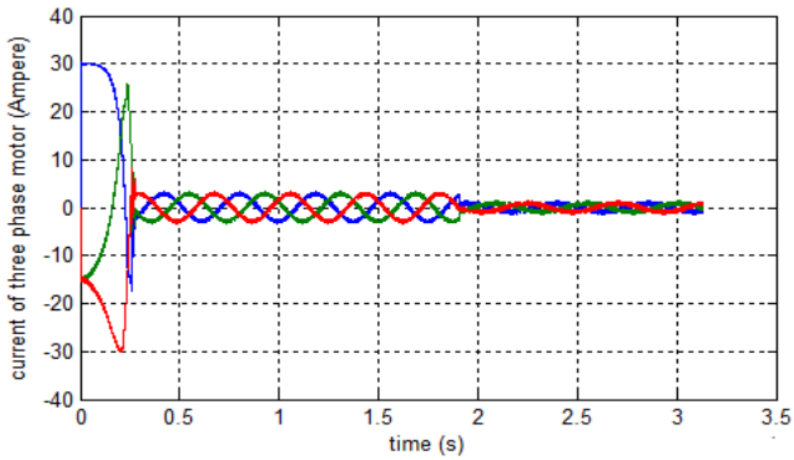

Figure 7. Response of three phase currents Iabc

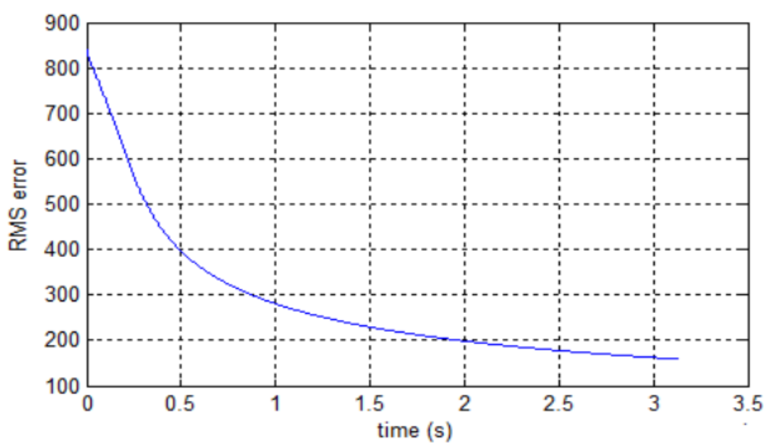

Figure 8. RMS error of speed controllers

4. Conclusions

In this research, a PMSM motor speed control system is studied for driving an electric propulsion system. Ship data is used to design the control system of electric propulsion is as follows: the overall length of the ship 11.4 meters, width 5.7 m, draft 1.8m, with a full load speed of 6 knots. The propeller data used is Type B Series with two propellers, 3 blades, expanded area ratio = 0.5, pitch per diameter = 0.8 and diameter = 0.6m. Based on the results using ANLOVA software the propeller should be operated by 840 rpm. Hence the control system is set by 840 rpm of propeller speed. From the simulation results shows that the controller is able to follow the speed reference with RMS error 158.85. The RMS error of control system converges to zero that the controller has stable performance.

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