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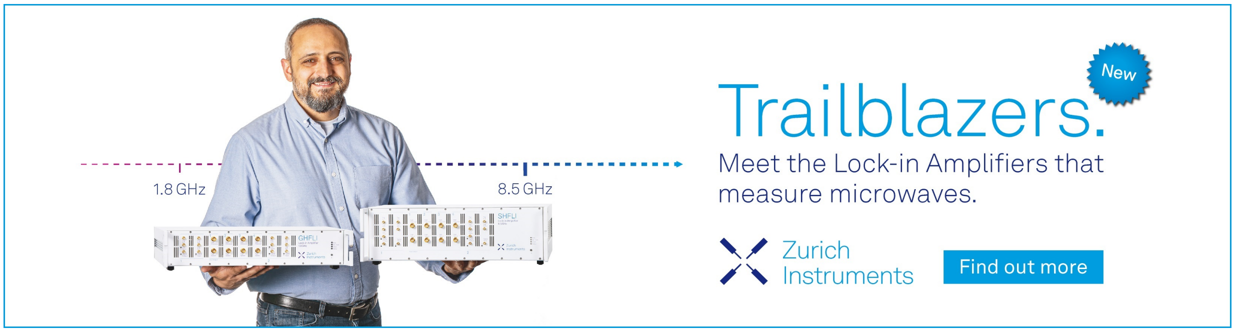

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The Effect of Multiple Changes in Motor Parameter Values Simultaneously on the PMSM Speed Sensorless Control System

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Abstract. One of the weaknesses in controlling the motor speed with the sensorless control method is the motor parameter values must be known precisely. The values of these motor parameters are inputted into the controller program. If the motor parameter values on the controller differ from the actual motor parameter values, it will cause errors in motor speed. The motor that is used is Permanent Magnet Synchronous Motor (PMSM). This study investigated the effect of more than one parameter values differences simultaneously. The motor parameters that are used in the sensorless control system are stator resistance, stator inductance, and magnetic flux. The combination of more than one parameters change in controller that can still reach the reference speed are: $R_s \leq 3\%$ - $L_{sq} \leq 200\%$, $L_{sd} \leq 300\%$ - $\Psi_F \leq 5\%$, $L_{sq} \leq 200\%$ - $\Psi_F \leq 30.8\%$, and $L_{sq} \leq 200\%$ - $\Psi_F \leq 30.8\%$ - $R_s \leq 3\%$.

INTRODUCTION

One type of controller still being developed is a control system without a controlled variable sensor or "sensorless control". Sensorless control systems are used to overcome difficulties in installing sensors such as sensor-based control systems. Sensors will raise prices and cause installation issues [1]. In this system, the controlled variable is not measured directly using a sensor [2], but it is estimated from the current input to the plant using an observer. One observer that has been widely used is the Model Reference Adaptive System (MRAS). It is because MRAS is a relatively mature identification method [3]. In this study, sensorless control will be used to control the speed of the Permanent Magnet Synchronous Motor (PMSM). The motor speed is estimated from the stator current.

PMSM in one of the Alternating Current (AC) motors. In controlling an AC motor, both the phase angle and the modulo current (the current vector) must be controlled [3]. It means vector control is needed, where the torque and flux that produce the current are decoupled to be controlled separately.

One of the weaknesses in controlling the motor speed with the sensorless control method is the motor parameter values must be known precisely. Parameter values must be well known because the values of these motor parameters are needed in the controller program so that this speed sensorless control can operate adequately. If the motor parameter values on the controller differ from the actual motor parameter values, it will cause errors in motor speed. Therefore, many researchers have proposed several methods of identifying parameter values [4–8]. It is also emphasized in the article [6] that the motor parameters are an essential factor and significantly affect motor control performance. In [9], the effect of induction motor parameters in the induction motor speed control system has been analyzed. This paper explains that the difference in parameter values will cause errors in motor speed. However, it is not stated in these experiments how much the speed controller will be affected by differences in motor parameter values. The difference in value between one of the motor parameters on the controller and the actual parameter on the motor will cause a motor speed error [10].

This article will discuss the effect of more than one parameter values differences simultaneously. If only one of the motor parameters has different values from the actual motor parameter value, each the motor parameter value

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difference does not result in a motor speed error. The parameters used are the stator resistance and inductance parameters and the magnitude of the magnetic flux.

SYSTEM AND METHOD

PMSM Speed Sensorless Control System

The PMSM speed sensorless control system is shown in the dotted box in Fig. 1 [11]. It is made up of the following blocks:

a. The motor using a PMSM with the specifications listed in Table 1 [10].
The PMSM model are

$$\frac{d}{dt} i_{sd} = \frac{V_{sd} - R_s i_{sd} + N\omega_r L_{sq} i_{sq}}{L_{sd}} \tag{1}$$

$$\frac{d}{dt} i_{sq} = \frac{V_{sq} - i_{sd} N\omega_r L_{sd} - R_s i_{sq} - N\omega_r \psi_F}{L_{sq}} \tag{2}$$

where R_s = stator resistance (Ω)

b. The observer using an MRAS to estimate motor speed
MRAS [12] is used to estimate the speed controlled variable of the stator current measured by the current sensor with the following equation:

$$\hat{\omega}_r = \left(K_{wrp} + \frac{K_{wri}}{s} \right) \left(\frac{L_{sq}}{L_{sd}} i_{sd} \hat{i}_{sq} - \frac{L_{sd}}{L_{sq}} i_{sq} \hat{i}_{sd} - \frac{\psi_F}{L_{sq}} \left(i_{sq} - \hat{i}_{sq} \right) + \hat{i}_{sd} \hat{i}_{sq} \left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}} \right) \right) \tag{3}$$

where

K_{wrp} = MRAS proportional gain
K_{wri} = MRAS Integrator gain
$\hat{i}_{sd}$, $\hat{i}_{sq}$ = estimated current in *d*-*q* frame
Ψ_F = magnetic flux (*V.s*/rad)

c. The current control using a Proportional Integral (PI) controller.
The PI equations are

$$u_{sd} = K_{pd} \left(i_{sd}^* - i_{sd} \right) + K_{id} \int \left(i_{sd}^* - i_{sd} \right) dt \tag{4}$$

$$u_{sq} = K_{pq} \left(i_{sq}^* - i_{sq} \right) + K_{iq} \int \left(i_{sq}^* - i_{sq} \right) dt \tag{5}$$

where

U_{sd}, U_{sq} = current output of current controller (A)
K_{pd}, K_{pq}, K_{id}, K_{iq} = current controller *d*-*q* frame.
i_{sd}^* = reference current stator in *d*-frame (A)
i_{sq}^* = reference current stator in *q*-frame (A)
i_{sd} = current stator in *d*-frame (A)
i_{sq} = current stator in *q*-frame (A)

d. The motor speed control using Integral Proportional (IP) controller

The IP controller equation is

$$i_{sq}^{*} = \int K_i\left(\omega_r^{*} - \hat{\omega}_r\right)dt - K_p\hat{\omega}_r = K_i X_{wr} - K_p\hat{\omega}_r \tag{6}$$

where

ω_r^* = reference rotor speed (rad/s),
$\hat{\omega}_r$ = estimated rotor speed (rad/s),
K_p, K_i = speed controller gain
X_{wr} = speed error integral where

$$\frac{d}{dt}X_{wr} = \left(\omega_r^{*} - \hat{\omega}_r\right) \tag{7}$$

TABLE 1. PMSM specifications.

Parameter	Values	Unit	Description
N	4	-	Pole pair
R_s	0.15	Ω	Stator Resistance
L_{sd}	0.29	mH	Stator Induktance in *d*-frame
L_{sq}	0.38	mH	Stator Induktance in *q*-frame
Ψ_F	0.013	*V.s*/rad	Magnetic Flux

Testing Method

As explained in the introduction, the sensorless control system will operate properly if the parameter values which include stator resistance, stator inductance, and flux on the controller are the same as the actual motor parameter values. In this study, the PMSM speed sensorless control system was tested by varying the motor parameter values in the controller so that they were different from the actual motor parameter values. Testing the PMSM speed sensorless control system is carried out for differences in values of more than one PMSM parameter value simultaneously. In the previous study [10], changes in each parameter value as shown in Table 2 did not result in an actual motor speed error. The value of this parameter is varied from small to large. When only one parameter in the controller differs from the value of the motor parameter according to Table 2 and the other parameters are correct, the motor continues to rotate at a speed according to the desired reference speed. In this study, it will be investigated whether if two or more parameters with changes in values as in Table 2 are applied simultaneously to the controller, it will cause an error or not.

TABLE 2. PMSM specifications.

Parameter	Percentage change (%)	Values	Unit
R_s	3	0.1545	Ω
	4	0.156	
	5	0.1575	
L_{sd}	300	1.2	mH
	500	1.5	
	600	1.8	
L_{sq}	200	1.2	mH
	300	1.6	
	500	2.0	
Ψ_F	5	0.01365	$\frac{V.s}{\text{rad}}$
	13.8	0.0148	
	15	0.01495	
	30,8	0.017	
	34.6	0.0175	

The system was tested using Simulink. The block diagram of the test system is shown in Fig. 1. In the figure, the values of the various parameters are inputted through the input port to the current controller. The desired speed is 100 rad/s with the control constants setting $K_p = 0.5$ and $K_i = 0.9$. The parameters used are the stator resistance and inductance parameters and the magnitude of the magnetic flux.

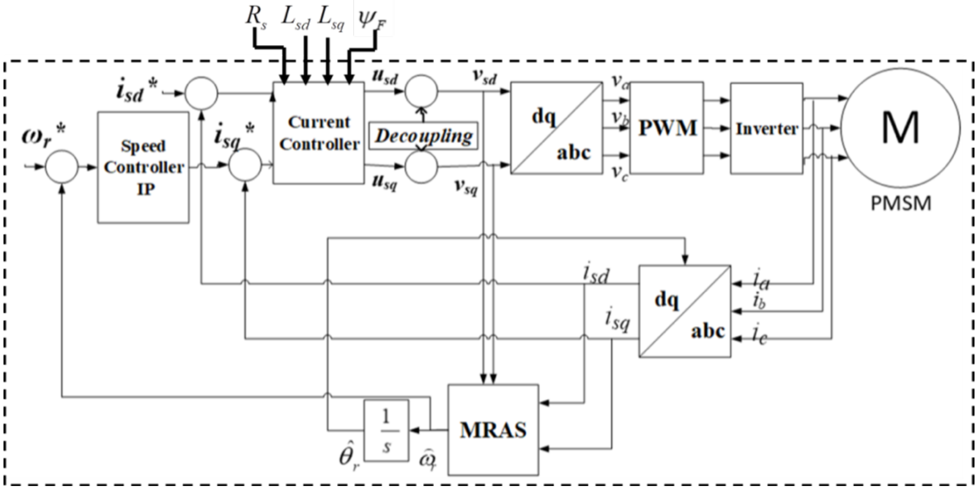


FIGURE 1. Speed sensorless control system with four-parameter inputs for testing.

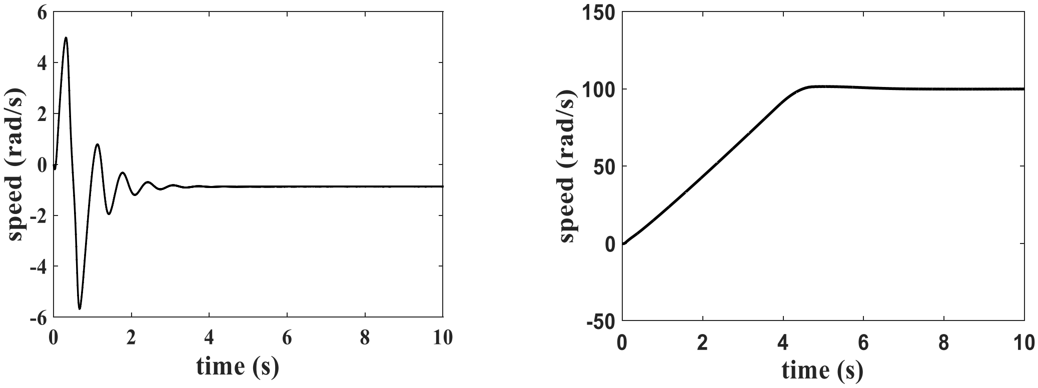
RESULT AND DISCUSSION

The variation of the test parameters is shown in Table 3. The test was carried out with 16 variations, with changes in 2 or 3 parameters. Overall test results are shown in Figs. 2–5. In the previous study [10], if the sensorless system is given a change in the value of each parameter, then the response speed remains following the specified reference speed, which is 100 rad/s. However, when two or more parameters with a change in value occur in the sensorless control system simultaneously, responses will occur as shown in Fig. 2–5. Variations in the value of this parameter are selected from the values of Table 2 starting from small to large changes until an error occurs in the motor speed. Therefore, not all variations of the values in Table 2 are used. If a small value causes an error, then the test is not continued to a larger value changing. The combination of 3 parameters changing is selected when the combination of 2 parameters changing simultaneously does not cause speed errors.

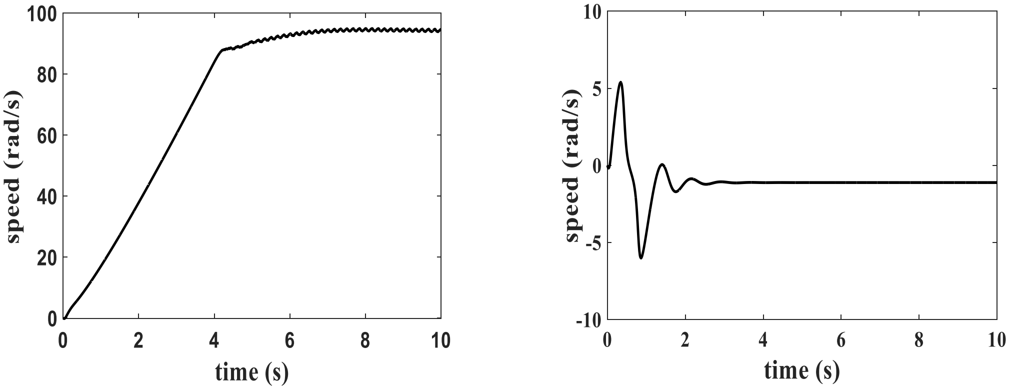
TABLE 3. Parameter testing each figure.

Figure Number	Percentage change (%)			
	R_s	L_{sd}	L_{sq}	Ψ_F
2(a)	3	300	-	-
2(b)	3	-	200	-
2(c)	3	-	300	-
2(d)	3	-	-	5
3(a)	-	300	200	-
3(b)	-	300	-	5
3(c)	-	300	-	13.8
3(d)	-	300	-	15
4(a)	-	-	200	5
4(b)	-	-	200	30.8
4(c)	-	-	200	34.6
5(a)	3	-	200	30.8
5(b)	4	-	200	30.8
5(c)	3	300	-	5
5(d)	4	300	-	5
5(e)	3	-	200	34.6

In Fig. 2, the motor speed response with changes R_s = 3% and other parameters is shown. In Fig. 2a, with changes R_s = 3% and L_{sd} = 300%, the motor speed becomes negative with oscillation in the transient. This means that the motor rotates in the opposite direction. It also occurs when the magnetic flux differs by 5%, as shown in Fig. 2d. In Fig. 2(b), with a R_s difference equal to 3% and L_{sq} = 200%, the motor still operates at the reference speed, which is 100 rad/s. When L_{sq} it is enlarged with a difference in the value of 300% (see Fig. 2(c)), the motor speed cannot reach the reference speed. In this condition, there has been a steady-state error of 5%.



(a) R_s - L_{sd} (b) R_s - L_{sq} 200%

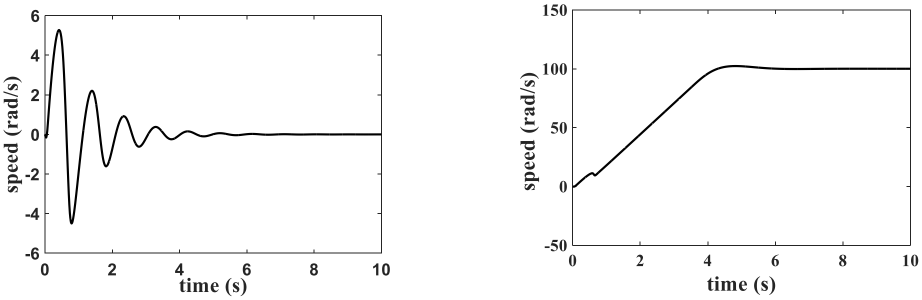


(c) R_s - L_{sq} 300% (d) R_s - Ψ_F

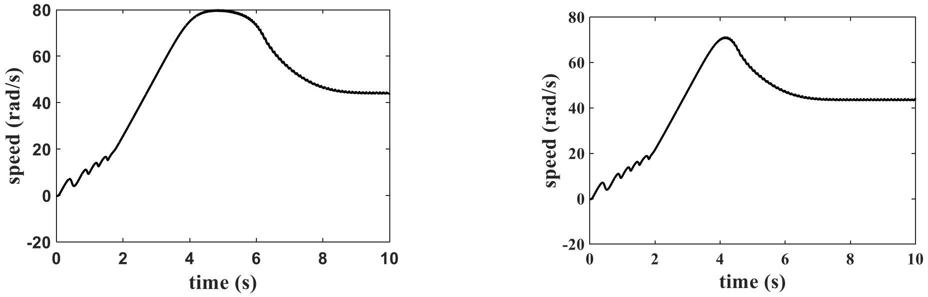
FIGURE 2. Speed responses between R_s = 3% change and other parameters.

In Fig. 3, the motor speed response is shown with a change L_{sd} = 300% and other parameters. With a L_{sq} change of 200%, the motor stops, indicated by a motor speed of 0 rad/s, with large oscillations during the transient (see Fig. 3a). This means the motor vibrates with a larger first vibration which then gradually decreases until it stops. In Fig. 3b, with a 5% change in magnetic flux, the motor still operates at the reference speed, which is 100 rad/s. However, when the magnetic flux is enlarged with a difference in values of 13.8% (see Fig. 3(c)) and 15% (see Fig. 3(d)), the motor speed is stable, but it cannot reach the reference speed. The motor speed in both images is around 45 rad/s, even though the desired motor speed is 100 rad/s. In this condition, there has been a large steady-state error of 50%.

In Fig. 4, the motor speed response is shown with a change of L_{sq} = 200% and other parameters. With a magnetic flux change of 5% (see Fig. 4(a)) and 30.8% (see Fig. 4(b)), the motor speed is stable, and the motor still operates at a reference speed of 100 rad/s. However, when the magnetic flux is enlarged with a difference of 34.6% value (see Fig. 4(c)), the motor speed oscillates at about 30 rad/s.

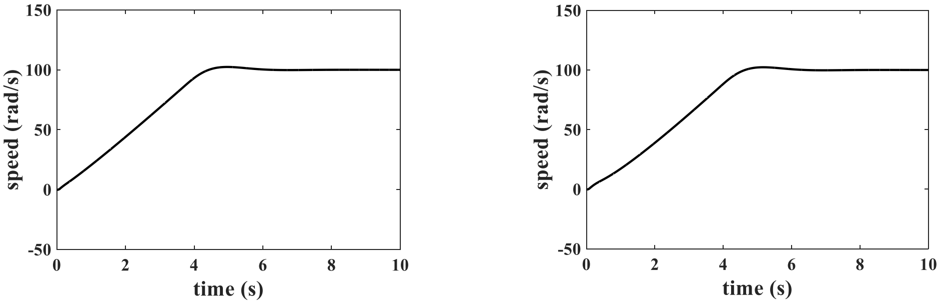


(a) L_{sd} - L_{sq} (b) L_{sd} - Ψ_F 5%

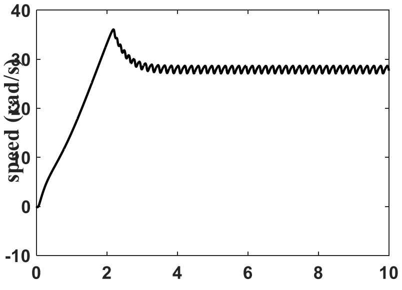


(c) L_{sd} - Ψ_F 13.8% (d) L_{sd} - Ψ_F 15%

FIGURE 3. Speed responses between L_{sd} = 300% change and other parameters.



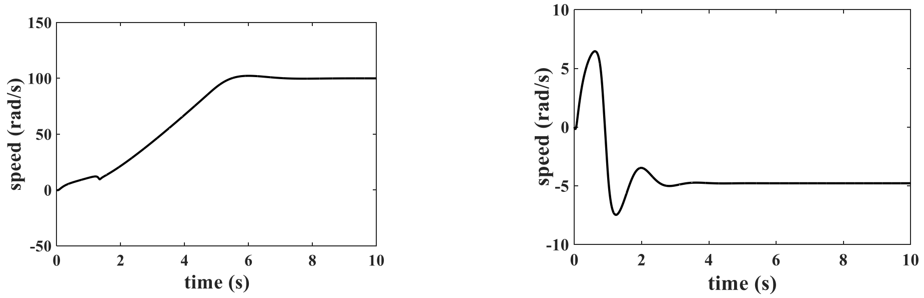
(a) L_{sq} - Ψ_F 5% (b) L_{sq} - Ψ_F 30.8%



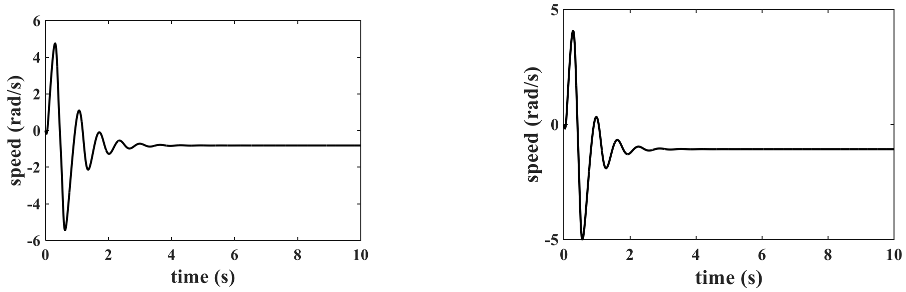
(c) L_{sq} - Ψ_F 34.6%

FIGURE 4. Speed responses between L_{sq} = 200% change and other parameters.

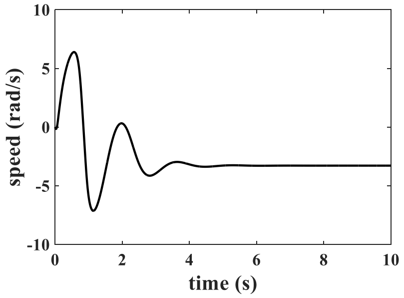
In Fig. 5, the motor speed response is shown with three changes in parameter values. The selection of these three parameters is based on the motor speed response when changes in the values of the two parameters still result in a motor speed response following the reference speed, which is 100 rad/s. Figure 5(a) shows the response with a difference of L_{sq} = 200% and Ψ_F = 30.8% as shown in Fig. 4(b), then added with a change in the value of R_s of 3%. It appears that the motor speed is stable, and the motor still operates at the reference speed, which is 100 rad/s. However, the settling time is longer, namely 6.5 s, wherein in normal conditions, the settling time is 5s. (10). When the R_s change is increased to 4% (see Fig. 5(b)), the motor speed becomes –5 rad/s. It means that the motor rotates in the opposite direction.



(a) L_{sq} - Ψ_F 30.8% - R_s 3% (b) L_{sq} - Ψ_F 30.8% - Ψ_F 4%



(c) L_{sd} - Ψ_F 5% - R_s 3% (d) L_{sd} - Ψ_F 5%- R_s 4%



(e) R_s - L_{sq} 200% - Ψ_F 34.6%

FIGURE 5. Speed responses between three parameters change.

Changes in the value of the pair R_s - L_{sq} - Ψ_F are also performed in Fig. 5(e). In the figure, the parameter values in the current controller are set with changes in values R_s = 3%, L_{sq} = 200%, and Ψ_F = 34.6%. Determination of the change in the value of this parameter is based on the response of Fig. 2(b), where with a change in value R_s = 3% and L_{sq} = 200%. The response still reaches the desired value of 100 rad/s. With the addition of = 34.6%, the motor speed also becomes negative.

The choice of pairs L_{sd} - Ψ_F - R_s (Fig. 5c and 5d) was based on the responses L_{sd} = 300% and Ψ_F =5% shown in Fig. 3(b). In this figure, with a change in value L_{sd} = 300% and Ψ_F = 5% the response still reaches the desired value of 100 rad/s. In Fig. 5(c), the difference in value is R_s = 3%, while in Fig. 5(d), the difference in R_s value is 4%. It can be seen in both figures that the motor speed becomes negative, with the motor speed in Fig. 5(d) being faster than in Fig. 5(c).

CONCLUSION

Changes in the value of more than one parameter can cause the motor speed to become unstable, and the motor cannot reach the reference speed value. It means that motor parameters are important in the sensorless control system. The combination of more than one parameters change in this research that can still reach the reference speed are: $R_s \leq$ 3% - $L_{sq} \leq$ 200%, $L_{sd} \leq$ 300% - $\Psi_F \leq$ 5%, $L_{sq} \leq$ 200% - $\Psi_F \leq$ 30.8%, and $L_{sq} \leq$ 200% - $\Psi_F \leq$ 30.8% - $R_s \leq$ 3%.

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