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Speed Sensorless Fault Tolerant Control for DC Servo Motor with Current Sensor Fault

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Abstract – *This paper discusses the application of a fault tolerant control scheme in sensorless speed control for dc motors. The sensorless speed system works by estimating the speed using the current measurement value. The novelty of the proposed scheme is a speed estimator capable of accommodating current sensor faults, which is the only measurement information. The technique used is a modification of the Extended State Observer (ESO) where the residual is not only used to estimate the state, but also to estimate the load torque. In this case, the load torque is treated as a changing input parameter and it is estimated using the observer's normal approach. The modified ESO estimation result is in the form of speed and current estimate, and then fed to the state feedback control with the integrator in order to maintain the speed at the setpoint value. In order to test the proposed control system, numerical simulations are carried out and comparisons are made between the control system with ESO and with modified ESO. From the results of this simulation experiment, the conclusion is that the modified ESO control system is proven to be able to overcome changes in load torque and setpoint as well as sensor faults that occur.* ***Copyright © 2022 The Authors.***

***Keywords**: Sensorless, Motor Servo, Extended State, Observer, Fault Detection, Technological Capabilities*

Nomenclature

A	State matrix
A_a	Augmented state matrix
b	Motor viscous friction constant
B	Input matrix
B_a	Augmented input matrix
C	Output matrix
c	Constant threshold for FDI
e	Error signal
E_a	Fault vector
f_s	Sensor fault
i_a	Motor armature current
J	Moment of inertia of the rotor
K	Electromotive force and motor torque constant
K_i	Controller integral gain
K_p	Controller proportional gain
L	Electric inductance
L_1	Controller gain vector
L_2	Observer gain vector
L_f	Observer fault gain
L_x	Observer state gain
n	Integer
r	Electric resistance
$O_{m\times l}$	Null matrix (m rows l columns)
R	Ratio of variance
R_{cr}	Ratio of variance threshold
t	Time
T_L	Motor mechanical load
T_s	Sampling time
u	Control input vector
V	Motor input voltage
x	State vector
x_a	Augmented state vector
x_s	Residual/disturbance state
$x_{sf,i}$	Filtered residual
x_{sh}	Reconstructed residual signal using zero order hold
x_μ	Residual and fault estimation deviation
$x_{\mu h}$	Reconstructed residual and fault estimation deviation using zero order hold
y	Output variable
z	Filtered output
$\delta_{f,i}$	Second variance for FDI
λ_1	Residual filter constant
λ_2	First variance constant
λ_3	Second variance constant
$\nu_{f,i}$	First variance for FDI
ω	Rotational speed
ω_{ref}	Rotational speed setpoint of motor

I. Introduction

Along with technological developments, DC servo motors are still used in the industry as the prime mover given the advantages they have. In many different applications, such as mills, robotics, electrical vehicles,

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and others where continuous or low-speed torque and adjustable speed are needed, DC motor drives are a common type of electrical machine. There are several different methods used today to regulate the speed of electrical machines [1]. At the beginning, a closed-loop speed control system with known motor state variables has been needed to provide effective speed control.

Therefore, a variety of mechanical sensors is needed to measure all of the system's state variables, which reduce the resilience and dependability while also growing the system's size, complexity, and expense. Currently, the use of a DC servo motor has led to sensorless operation, where the DC servo motor works at a certain speed as desired without using a speed sensor, otherwise known as a speed sensorless dc motor. This technology offers advantages in the form of reduced hardware costs and increased reliability [2]. Nowadays, the researchers are concentrated on sensorless control method together with intelligent control for best responsiveness in order to reduce the number of sensors and system complexity [3]. This is one of the efforts to realize technology capability in solving problems.

Without degrading dynamic performance, speed sensorless control of DC motor eliminates mechanical sensors, particularly for speed and position estimates. For high-performance DC motor, mechanical sensors with high resolution are typically the preferred option. However, economic, environmental, and sensor characteristics as well as environmental factors (cost and lifetime) affect performance. During the two past decades, many methods have been used in developing speed sensorless motor technology, as described in [4]-[10] for induction motor and [11]-[14] for dc motor. The method commonly used is to estimate speed using an observer instead of a speed sensor. In this method, the observer requires measurement values for other related variables. With the aid of pertinent electrical signals, an observer or estimator estimates the motor speed in sensorless control techniques. State estimation methods that are frequently employed include sliding mode observer [13]-[15], model reference adaptive system [16], [17], Luenberger observer [18], [19], Kalman filter (KF) [19], [20], and extended Kalman filter (EKF) [21]-[23], [33]-[35]. In order to estimate the speed and the position of a motor, the observer applies a mathematical equation to some measured motor states (current, voltage). For the case of DC servo motors, the commonly used measured variable is the armature current. Problems arise if there is a fault in the current sensor, which causes the observer to produce an incorrect speed estimate so that the control system can no longer produce a good response, which is generally a steady state error. In this paper, a control system that can solve the above problems, namely overcoming faults, commonly called Fault Tolerant Control (FTC), is proposed. The FTC is a type of control method that, in the event of a problem, can retain the intended performance and stability while automatically accommodating the fault component [24].

There have been several approaches suggested for the FTC system, in fact. A compensation approach using fault estimates to correct the fault effect has recently been devised, and it is known as active FTC method. Since the fault detection and reconfigurable control method are developed in an integrated manner in this case [25], a significant computational cost can be avoided. The FTC method is generally used for typical control systems that use sensors to get the controlled variable value, and actuators to manipulate the plant, as discussed in [26]-[28] for the case of DC motors. In [26], [27], sensor faults are seen as disturbances at the output whereas actuator faults are seen as input faults. Although the controlled variable is speed, there are two measurements, namely speed measurement and motor current measurement. This aims to overcome the observability problems that arise when building an observer to estimate one sensor fault and one actuator fault. In other words, two pieces of information are required to estimate two faults. The use of FTC for speed sensorless technology is still rare, especially in the case of DC servo motors. This is because there is no way to solve the problem of lack of measurement data, which causes unobservability problems. One of the efforts is the FTC for a speed sensorless system proposed in [29], where the FTC system works correctly only when the load torque changes only, but the FTC generates an error when a current sensor fault occurs. Alternatively, in other cases, the FTC produces a good response only when a sensor fault occurs but with the limitation that it operates at a constant or known load torque as discussed in the system description section of this paper. In this study, the problems described above have been solved by using a new technique (novelty) with the aim that the speed sensorless control can overcome sensor faults and changes in load torque at once. The rest of the paper is organized into four parts. The first one describes the speed sensorless control on a DC motor, as a nominal representation of the system under review. In this case, the problems that arise in the nominal system are described if there is a fault in the only sensor used (i.e. the current sensor) and if there is a change in the load torque from the initial value used in the estimator. In the second part, the proposed method to overcome the above problem, namely speed sensorless Fault Tolerant Control (FTC), is described. Modifications made to the nominal system are in the estimator, hereinafter referred to as the modified Extended State Observer (ESO). For this purpose, a Fault Detection and Identification (FDI) algorithm is needed. Then, the proposed method is tested for its performance through numerical simulation in the third part. Finally, the fourth section concludes the results of research on this novelty FTC method.

II. System Description

Previous speed control systems on DC servo motors have used speed measurement information, using a sensor such as an encoder or tachometer, as a feedback signal to the controller. The deviation of the measured speed value and the setpoint velocity value is the error information used by the controller to generate a control signal to the servo amplifier circuit as an actuator. In speed sensorless technology, speed information is no longer obtained from measurement results, but through estimation results. The speed sensorless control system structure for a DC servo motor is shown in Figure 1. The estimator uses existing variable information such as current i_a and voltage V to estimate speed ω. Several ways are used in this case, with a dynamic approach or with a spectral approach [30]. In this paper, dynamics is used where the results of current measurements are used as input for the observer as an estimator. The observer also uses the control signal as well as load torque T_L as input. The dynamic model in the form of state space from the DC servo motor is as follows:

$$\begin{bmatrix} \dot{\omega} \\ i_a \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{b}{J} & \frac{K}{J} \\ -\frac{K}{L} & -\frac{r}{L} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \omega \\ i_a \end{bmatrix}}_{x} + \underbrace{\begin{bmatrix} 0 & -\frac{1}{J} \\ \frac{1}{L} & 0 \end{bmatrix}}_{B} \underbrace{\begin{bmatrix} V \\ T_L \end{bmatrix}}_{u} \qquad (1)$$

Two states, speed and current, can be estimated using the Luenberger observer with the following equation:

$$\dot{\hat{x}} = A\hat{x} + Bu + L_1(i_a - \hat{\imath}_a) \qquad (2)$$

where L_1 is an observer gain that can be obtained in several ways such as pole placement or optimal way (such as linear quadratic regulator). It should be noted that for the sensorless case, only the current is measured.

The load torque and the input voltage are not measured. However, the information about the input voltage can be obtained from the control signal generated by the controller. Thus, this observer can only work properly if there is information about the load torque handled by the control system. The control algorithm used in this study is state feedback with an integrator:

$$u = K_p x + K_i \int e\, dt \qquad (3)$$

where e is the error between the set point ω_{ref} and the speed estimate, K_p and K_i are the gain controllers. It is generally known that the performance of the control system depends on the information that comes into it. If there is a sensor fault in the current measurement, the current information that goes to the observer is wrong so that the speed estimation results from the observer are wrong. This means that the control system also gets speed information that does not match reality.

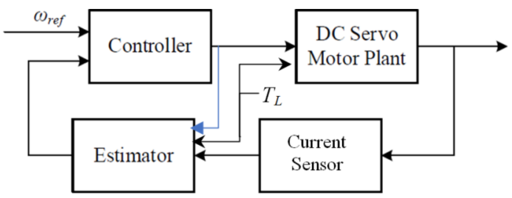

Fig. 1. Schematic of speed sensorless control system for DC servo motor

As a result, the control system does not provide the correct actuation signal and produces a response that is not at the desired speed, as shown in Figure 2. A steady state error occurs when a current sensor fault occurs at time of 25 s. Furthermore, the observer needs the load torque T_L information as one of the inputs u, in addition to the control signal V, as stated in Equation (2). Thus, load change information should be provided to the observer. If the load change information is incorrect, then the observer's estimation results are also wrong, so that, once again, it can cause the speed sensorless control system to no longer track the setpoint value. This is illustrated in Figure 3 where the change in load torque from 10 Nm to 15 Nm that occurs at 150 seconds is not known by the observer. The use of a torque sensor can indeed overcome this, but of course, this will increase the complexity of the system and the cost. Therefore, this load torque should also be estimated.

III. Speed Sensorless FTC

Based on the description in the previous section, two problems need to be solved, namely current sensor faults and the need for load torque information, without being measured of course to reduce the costs. For the first problem, the sensor fault can be estimated with the extended state observer scheme as in [27]. Here, the current sensor fault is treated as an additional state, and the observer used is known as the Extended State Observer (ESO). However, this technique still requires the availability of the load torque data.

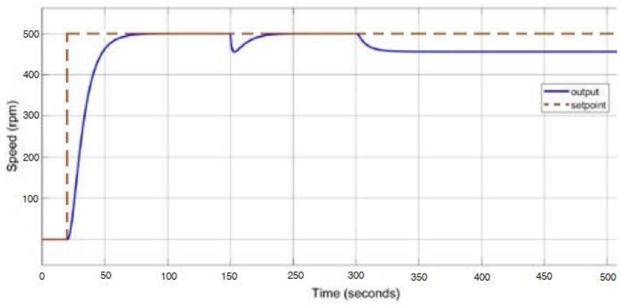

Fig. 2. The speed response of the sensorless speed control when a current measurement fault occurs

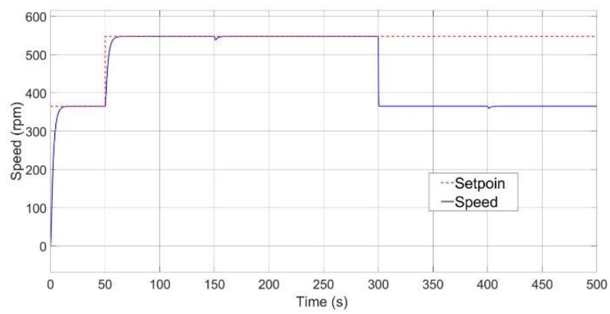

Fig. 3. The speed response of the sensorless speed control when the load torque changes

For the second problem, the load torque can be considered as a state variable, and then three states are estimated using one measured current information.

However, this method will fail when a current sensor fault occurs, as the only supplier of information to the observer. Therefore, this technique cannot be used to build a speed sensorless system that can accommodate sensor faults and changes in load torque at once.

Therefore, the load torque should not be included as part of the estimate state, but as a variable estimated outside the observer. The current sensor fault and the load torque can be considered as disturbances to the system, which affect the deviation of the system from its nominal condition. Since only one information is available, namely through the current measurement, an additional algorithm is needed to determine whether the system deviation that occurs is due to change in load or sensor fault. For this purpose, a Fault Detection and Identification (FDI) algorithm is required. The speed sensorless FTC system proposed in this paper is shown in Figure 4.

III.1. Modified Extended State Observer

The output y equation when a current sensor fault f_s occurs is written as follows:

$$y = \underbrace{[0 \quad 1]}_{C} x + f_s \tag{4}$$

A new variable is defined:

$$\dot{z} = y - z = Cx + f_s - z \tag{5}$$

so that the augmented state space equation is obtained:

$$\dot{x}_a = A_a x_a + B_a u + E_a f_s \tag{6}$$

$$y_a = C_a x_a = z \tag{7}$$

where:

$$x_a = \begin{bmatrix} x \\ z \end{bmatrix}, f_s = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, A_a = \begin{bmatrix} A & 0 \\ C & -1 \end{bmatrix},$$
$$B_a = \begin{bmatrix} B \\ 0 \end{bmatrix}, E_a = \begin{bmatrix} O_{2\times1} \\ 1 \end{bmatrix}, C_a = [O_{1\times2} \quad 1]$$

Equation (6) has represented the variable f_s in the state equation. This equation becomes the observer model in estimating state x and its deviation from nominal condition. Of course, this deviation is detected at the output i.e., the measured current, so it is called a disturbance output x_s. However, this output deviation can be caused by two things, namely a current sensor fault or a change in load torque. Thus, the modified augmented state equation on the observer is:

$$\dot{\hat{x}}_a = A_a \hat{x}_a + B_{av} V + E_a \hat{x}_s + B_{aL} \hat{T}_L \tag{8}$$

$$\hat{y}_a = C_a \hat{x}_a = \hat{z} \tag{9}$$

where:

$$B_{av} = \begin{bmatrix} B(:,1) \\ 0 \end{bmatrix} \text{ and } B_{av} = \begin{bmatrix} B(:,2) \\ 0 \end{bmatrix}$$

$\hat{x}_s$ is used to determine both the sensor fault ($\hat{f}_s$) and the load torque ($\hat{T}_L$). The dynamic of the disturbance is assumed to occur so slowly that it can be modeled as:

$$\dot{\hat{x}}_s = 0 \tag{10}$$

By combining (10) to (8), the modified extended state space equation for the observer (ESO) is obtained as follows:

$$\begin{bmatrix} \dot{\hat{x}}_a \\ \dot{\hat{x}}_s \end{bmatrix} = \begin{bmatrix} A_a & E_a \\ O_{1\times2} & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_a \\ \hat{x}_s \end{bmatrix} + \\ + \begin{bmatrix} B_a \\ O_{1\times2} \end{bmatrix} \begin{bmatrix} V \\ \hat{T}_L \end{bmatrix} + \begin{bmatrix} L_x \\ L_f \end{bmatrix} (z - \hat{z}) \tag{11}$$

$$\hat{z} = [C_a \quad 0] \begin{bmatrix} \hat{x}_a \\ \hat{x}_s \end{bmatrix} \tag{12}$$

where $L_2 = [L_x \quad L_f]^T$ is the ESO gain that can be determined using pole placement method or Linear Quadratic Regulator (LQR) principle. The modified ESO structure is shown in Figure 5. Based on [27], this observer's stability is guaranteed. However, the first problem, the load torque information should be known without being measured, still exists. Therefore, the value of the load torque will be computed using $\hat{x}_s$ generated by the observer.

$$\hat{x}_s = [0 \quad 0 \quad 0 \quad | \quad 1] \begin{bmatrix} \hat{\omega} \\ \hat{\imath} \\ \hat{z} \\ -- \\ \hat{x}_s \end{bmatrix} = \\ = [O_{1\times3} \quad | \quad 1] \begin{bmatrix} \hat{x}_a \\ -- \\ \hat{x}_s \end{bmatrix} \tag{13}$$

However, this variable value is also be affected by fault that occur in the current sensor. Therefore, a fault type detection scheme (FDI) is needed to be able to distinguish between the sensor fault and the torque load change

III.2. Fault Detection and Identification

The FDI scheme proposed in this paper is based on the ratio of variances, R-statistic technique [31]. First, the $\hat{x}_s$ signal generated by the observer is reconstructed in discrete form $\hat{x}_{sh}$ using the zero order hold method with the following equation:

$$\hat{x}_{sh}(t) = \sum_{n=-\infty}^{\infty} \hat{x}_s[n] rect\left(\frac{t - \frac{T_s}{2} - nT_s}{T_s}\right) \tag{14}$$

$$rect(t) = \begin{cases} 0, & \text{if } |t| > \frac{1}{2} \\ \frac{1}{2}, & \text{if } |t| = \frac{1}{2} \\ 1, & \text{if } |t| < \frac{1}{2} \end{cases} \tag{15}$$

where t is time, T_s is sampling time, and n is integer.

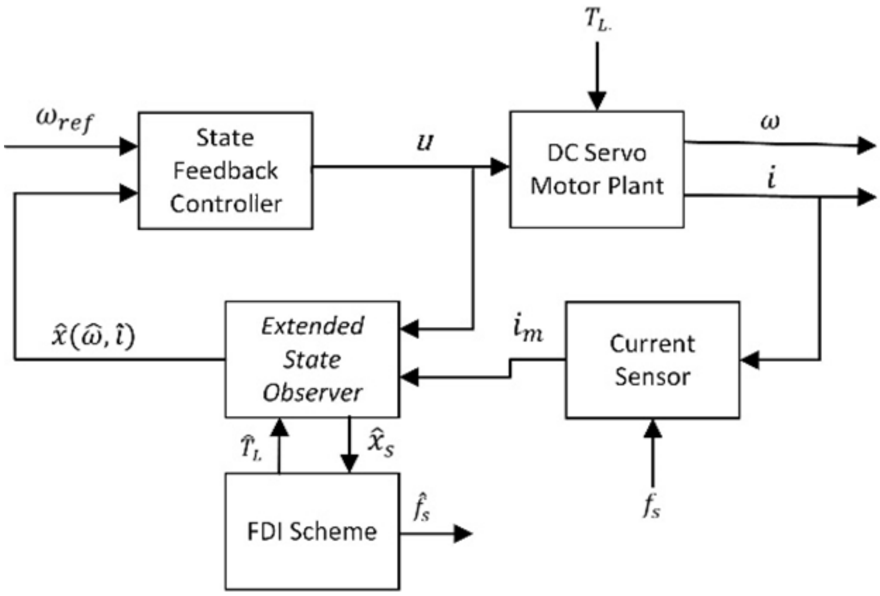

Fig. 4. Block diagram of the proposed speed sensorless FTC in DC servo motor.

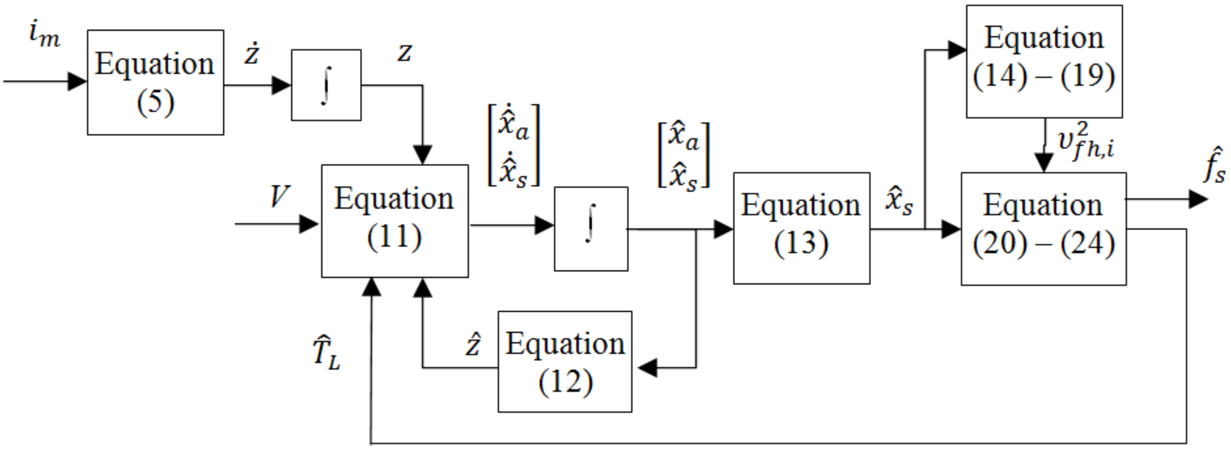

Fig. 5. The modified ESO Algorithm

Then the signal $\hat{x}_{sh}$ is filtered using the following equation:

$$x_{s_{f,i}} = \lambda_1 \hat{x}_{sh} + (1-\lambda_1) x_{s_{f,i-1}} \tag{16}$$

where $x_{s_{f,i}}$ is the filter result at the time sampling index i and $x_{s_{f,i-1}}$ is the filter result at the previous time sampling index (i–1). Finally, R-statistic test is conducted based on exponentially weighted moving "variance" scheme, with these following equations:

$$R = \frac{(2-\lambda_1) v_{f,i}^2}{\delta_{f,i}^2} \tag{17}$$

$$v_{f,i}^2 = \lambda_2 \left(\hat{x}_{s_i} - x_{s_{f,i-1}}\right)^2 + (1-\lambda_2) v_{f,i-1}^2 \tag{18}$$

$$\delta_{f,i}^2 = \lambda_3 \left(\hat{x}_{s_i} - \hat{x}_{s_{i-1}}\right)^2 + (1-\lambda_3) \delta_{f,i-1}^2 \tag{19}$$

where λ_1, λ_2, and λ_3 are the filter parameters whose values are between 0 and 1 ($0 < \lambda_{1,2,3} \le 1$). The parameter λ_1 affects the value of the R signal where the greater the value of λ_1 is, the smaller the value of the R signal is. The parameter λ_2 affects the magnitude of the R value when there is a steady state change. On the other hand, the parameter λ_3 affects the phenomenon of the occurrence of an infinite impulse value that occurs due to division by zero. The smaller the value of λ_1 is, the smaller this impulse value will be. The proposed FDI algorithm works using R value, and v_f^2 value which is hold when a new steady state condition detected, v_{fh}^2. A new condition will be detected when $R \ge R_{cr}$, in which R_{cr} is a threshold value of R for detecting a new steady state condition. On the other hand, a load change will be identified when $v_{fh}^2 \le c$, otherwise a sensor fault identified. c is a threshold value of v_{fh}^2 for identifying the occurred disturbance type, whether the current sensor fault or the load torque change. Each time the type of disturbance is identified, the value of the disturbance is estimated. Thus, the proposed FDI algorithm is written as follows:

if $R < R_{cr}$
then $\upsilon_{fh,i}^2 = \upsilon_{f,i}^2$
$\hat{f}_s(t) = 0,$
$\hat{T}_L(t) = 0$
else $\upsilon_{fh,i}^2 = \upsilon_{fh,i-1}^2$
if $\upsilon_{fh}^2 > c$
then

$$\hat{f}_s(t) = \hat{x}_s(t - T_s) \quad (20)$$

$$\hat{T}_L(t) = \hat{T}_L(t - T_s)$$

else

$$\hat{f}_s(t) = \hat{f}_s(t - T_s) \quad (21)$$

$$\hat{T}_L(t) = \int \mu\, \hat{x}_{\mu h}\, dt \quad (22)$$

end
end

where:

$$\hat{x}_{\mu h}(t) = \sum_{n=-\infty}^{\infty} \hat{x}_\mu[n] rect\left(\frac{t - T_s - 2nT_s}{2T_s}\right) \quad (23)$$

$$x_\mu(t) = [\hat{x}_s(t) - \hat{f}_s(t)] \quad (24)$$

μ is a multiplier constant in order to get the correct value of the load torque. Here the observer's normal approach as proposed in [32] is used in (22).

IV. Results and Discussion

The DC servo model (1) with the parameters listed in Table I has been simulated in order to get the performance of the proposed method. Other parameter values including the controller and the observer gain values and filter parameters of FDI are also listed in this table. Both types of gain are obtained by using the LQR approach. For the three FDI parameters: two threshold parameters and one multiplier parameter are selected by trial and error to obtain the best results. The current sensor fault, which is simulated as a bias, has a value range of 10 to 100 mA. The load torque given to the motor has a range of 0.01 to 0.1 Nm. Two simulation scenarios are carried out, namely the simulation of the FTC speed sensorless system equipped with ESO, and the FTC speed sensorless system equipped with modified ESO. The simulation results for the system with ESO are shown in Figures 6-9. When there is no load change, ESO can estimate the speed and the current values correctly as shown in Figure 6 and Figure 7.

TABLE I
PARAMETER VALUES OF THE SYSTEM

Parameter	Symbol	Value
Moment of inertia of the rotor	J	0.01 kg m^2
Motor viscous friction constant	b	0.1 N m s
Electromotive force constant	K_e	0.01 V/rad/s
Motor torque constant	K_t	0.01 N m/Amp
Electric resistance	r	1 Ω
Electric inductance	L	0.5 H
Controller gains	K_p	[0.6359 0.6235]
	K_i	6.3246
Observer gains	L_x	$\begin{bmatrix} 0.0006 \\ 0.0704 \\ 1 \end{bmatrix} \times 10^6$
	L_f	2.5350×10^6
Filter parameters	λ_1	0.8
	λ_2	0.1
	λ_3	0.01
Threshold of R	R_{cr}	9
Threshold of υ_{fh}^2	c	10^{-6}
Multiplier constant	μ	3

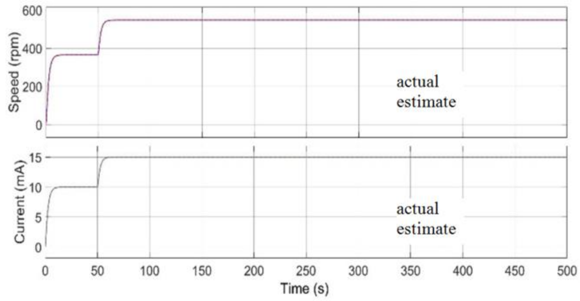

Fig. 6. Current and speed estimates of the ESO in normal condition (no disturbance)

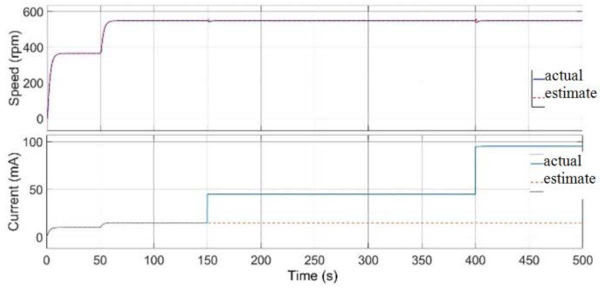

Fig. 7. Current and speed estimates of the ESO in sensor fault case

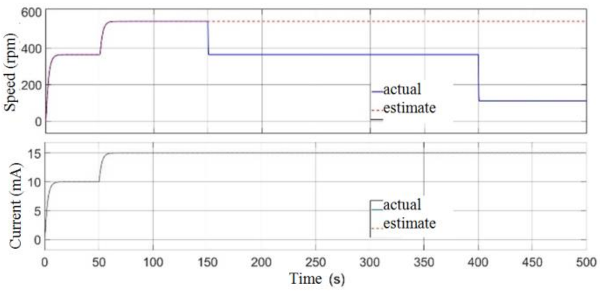

Fig. 8. Current and speed estimates of the ESO in load change case

Incorrect measurement of the current values at the 150th and 400th seconds in Figure 7 does not make the current estimation result wrong so that the actual speed is the same as the estimated speed. At steady state, the actual speed value is equal to the setpoint.

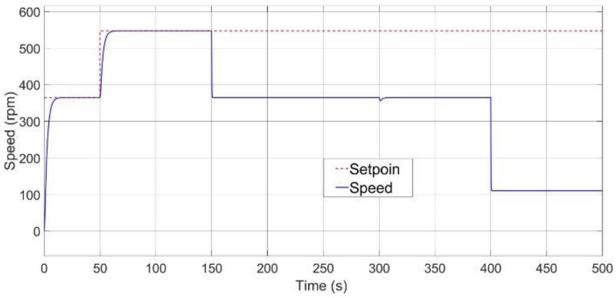

Fig. 9. Speed response of the system with ESO in load change case

Only a slight overshoot occurs briefly when there is a sensor fault. Meanwhile, when there is a change in load at the 150th and 400th seconds, the control system with ESO no longer tracks the setpoint value even though the current estimation result is correct as shown in Figure 9. This is because the undetected torque change causes the speed estimation results to be not the same as the actual conditions, as shown in Figure 8. The *R* value of the FDI scheme is shown in Figure 10. It can be seen here that there is a high overshoot when there is a current fault at the 150th and 350th seconds as well as changes in load torque at the 300th and 450th seconds. Based on these results, the R_{cr} value is determined so that disturbance detection can be carried out correctly. The results of the modified ESO are shown in Figure 11. The response of the estimated current fault looks faster than the response of the estimated load torque. However, both are tracking with the actual value. This causes the control system with modified ESO to keep following the setpoint even though there are sensor faults or change in load torque, as shown in Figure 12. It can be seen here that the estimated response affects the speed response. The current fault only causes a small overshoot compared to the load change, referring to the current estimate being faster than the load estimate (Figure 11). In addition, the greater the load change is, the greater the undershoot that occurs is.

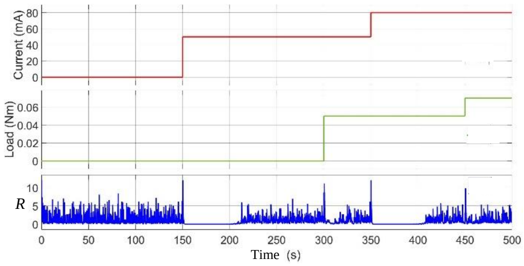

Fig. 10. *R* value of the system with ESO in load change case

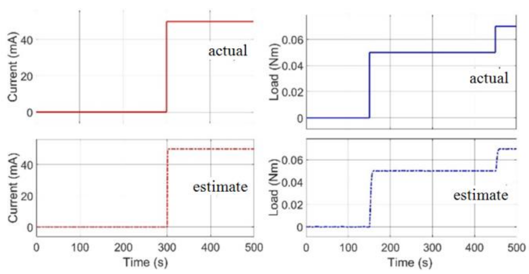

Fig. 11. Sensor fault and load estimates of the modified ESO

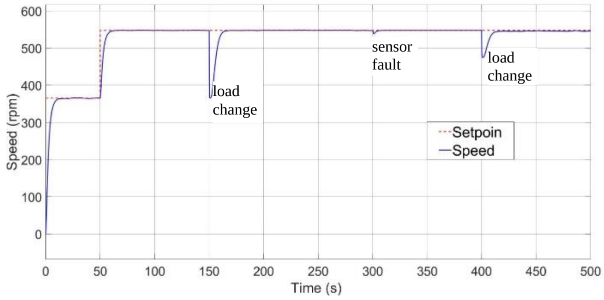

Fig. 12. Speed response of the system with modified ESO

V. Conclusion

This paper studies the fault tolerant control scheme for sensorless speed control of a dc motor. There are two features offered by the proposed method, it tolerates current sensor faults as the only sensor used and accommodates changes in load torque. The novelty of this speed sensorless FTC system is to overcome the unobservability problem that is commonly encountered in the application of Extended State Observer (ESO).

Here, the proposed modified ESO succeeded in using the residual/disturbance state as an identifying variable for the type of fault. Through an R-test-based FDI mechanism, fault is detected and identified using two threshold constants determined by trial and error.

The simulation results show that the proposed method is able to overcome steady state error that arise as a result of sensor fault and load change. The overshoot caused by sensor fault is smaller than the overshoot due to load change. This is because the response from the sensor fault estimate is faster than the response from the load change estimate. For further research, this method needs to be developed to reduce the effort required to determine the threshold values for the FDI section. In addition, the application of the speed sensorless FTC method in real plant cases can also be a challenge to research.

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