Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 55 (2021) 911–918

Transportation Research Procedia

www.elsevier.com/locate/procedia

14th International scientific conference on sustainable, modern and safe transport

Comparison between model based and non-model based sensorless methods of brushed DC motor

Michal Vidlak[a,*], Pavol Makys[b], Michal Stano[c]

[a,b,c]*Department of Power Systems and Electric Drives, Faculty of Electrical Engineering and Information Technology, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovakia*

Abstract

This paper presents a comparison between sensorless techniques for estimating speed of brushed DC motor. These techniques can be classified into two groups: model based methods, non-model based methods. The model based methods use a dynamic model of DC motor, where a sliding mode observer, pseudo-sliding mode observer and observer with PI controller are presented. The non-model based methods use a ripple component of DC motor current, where the motor speed is estimated by applying a novel approach. This approach uses a discrete bandpass filter with a floating bandwidth to extract information about the motor speed from the measured motor current. The results obtained from the experimental verification indicate that the novel approach estimates the motor speed correctly in a wide range of speeds.

Keywords: sensorless control; brushed DC motor; bandpass filter; current ripple;

1. Introduction

The advancement of technology and automation has led to a widespread use of electric motors in many applications. Brushed DC motors are used in different industrial sectors and in wide range of consumer products such as pumps, air fans, etc. These drives are also commonly used in the automotive industry, for example, as automobile starters, window lifters, windshield wipers and so on. However, brushed DC motors require more attention to maintenance due to commutator and brushes. The mechanical commutator is the most vulnerable component and the main practical

* Corresponding author. Tel.: +041-513-2270.
E-mail address: michal.vidlak@feit.uniza.sk

10.1016/j.trpro.2021.07.059

problem of these motors. This component may also limit the maximum speed of DC motor due to its mechanical endurance.

A mechanical sensor coupled to a motor shaft is required to obtain information about the speed or position of the motor. Sensors such as resolver, encoder, Hall effect sensor and tachometer are commonly used. However, the overall cost of DC drive system increases significantly with the addition of such sensor, which is prone to failure in the industrial environments. The sensor reliability is significantly affected by environmental conditions, which the sensor is exposed to, such as dust, pollution, vibrations and temperature. A sensorless speed/position estimation can be used to minimize the cost and issues associated with the sensors in a DC drive system. The main advantages of removal of such sensor, and using a sensorless algorithm instead are as follows: decreased maintenance, decreased volume of drive, reduced number of connections, reduced cost of the final system. The sensorless algorithms are also used as redundant solution in case of a sudden failure of the mechanical sensor. These algorithms can be divided into two groups: those based on the dynamic model of DC motor and those based on the ripple component of motor current.

The methods based on the dynamic model of DC motor depend on the parameters of brushed DC motor such as resistance, inductance and back-emf constant. However, these parameters are not constant and they vary under the different operational conditions. Varying parameters for example with temperature then lead to uncertainty into speed estimation. Nevertheless, these parameters can be estimated dynamically, as proposed by Bowes et al. (2004), but this approach usually leads to a nonlinear model, which is more difficult and increased computational time is required. There are also techniques that indirectly model a motor with the use of neural networks, proposed by Weerasooriya and El-Sharkawi (1991) or the Kalman filter by Razi and Monfared (2015). Castaneda et al. (2012) used the combination of Neural networks and Sliding mode control. Sensorless speed control for very small brushed DC motors with an adaptive estimator was presented by Scott et al. (2009).

The methods based on the ripple component of motor current do not require any knowledge of motor parameters to obtain the information about the estimated speed, because the motor current already contains the information about the motor speed. The measured motor current is mainly composed of two components: a DC component and AC component also known as the ripple component. The DC component is responsible for providing torque to the motor and its amplitude depends on a motor load. The AC component is created by converting DC current supplied by a stationary source into AC current in an armature coil by the commutator and brushes. It should be noted that the AC component contains a ripple, which is directly proportional to the motor speed. According to the fact that number of ripples in the measured motor current per one rotation is constant, the motor speed can be estimated. There are some methods which are using the ripple component of brushed DC motor to estimate the motor speed. Ramli et al. (2010) used an adaptive filter to estimate the rotational speed. Vazquez-Sanchez et al. (2012) used the support vector machines, where the motor speed was estimated by using the inverse distance between the detected pulses, and the position was estimated by counting all detected pulses. Radcliffe and Kumar (2015) proposed the method based on measuring the inductive spikes generated when the motor is turned off. Another approach by Vazquez-Sanchez et al. (2016) used spectral components of motor current. This method is useful also for the brushed DC motors with a large number of coils where the ripple component is almost negligible. There are also application notes made by Texas Instruments (2018) and Microchip (2019) where a ripple counting technique was proposed. These approaches estimate the rotor position in form of pulses, while the motor is controlled in an open-loop by an applied voltage.

2. Methods based on the dynamic model of DC motor

The model based methods use the dynamic model of DC motor to estimate the motor speed. These methods are very simple to implement but they require the knowledge of the motor parameters such as armature resistance, armature inductance and back-emf constant. As was mentioned, these parameters are not constant but they vary under different operational conditions. In this paper, three types of sensorless observers will be presented: sliding mode observer, pseudo-sliding mode observer and observer with PI controller. These observers are derived from the Luenberger observer and use the same principle to estimate the motor speed. The main purpose of this principle is to subtract two state variables of the motor, where the first variable is the measured motor current $\boldsymbol{i_a}$ and the second variable is the estimated current from the observer $\boldsymbol{\hat{\imath}_a}$. By subtraction of these two variables, an error of the currents $\boldsymbol{e_i = i_a - \hat{\imath}_a}$ will be presented. This error has to be forced down in order to obtain a value of estimated back-emf and therefore the estimated speed. A block, whose purpose is to force down the error $\boldsymbol{e_i}$ is called a correction block. This block forms a correction loop, which is an important part of the observer. It is necessary to express a differential equation of the electrical part of DC motor to define a differential equation of the observer:

$$\frac{di_a}{dt} = \frac{1}{L_a}(u_a - R_a i_a - e_a) \tag{1}$$

where u_a is the armature voltage, L_a is the armature inductance, R_a is the armature resistance and e_a is the back-emf, which is equal to:

$$e_a = k_E \omega_m \tag{2}$$

where $\boldsymbol{k_E}$ is the back-emf constant and $\boldsymbol{\omega_m}$ is the rotor angular velocity. By performing the following substitutions $\boldsymbol{i_a} = \boldsymbol{\hat{\imath}_a}$, $\boldsymbol{e_a} = \boldsymbol{\hat{e}_a}$ the differential equation of the observer will be expressed as:

$$\frac{d\hat{\imath}_a}{dt} = \frac{1}{L_a}(u_a - R_a \hat{\imath}_a - \hat{e}_a) \tag{3}$$

where $\hat{e}_a$ is the estimated back-emf. A signum function is used as the correction block in the sliding mode observer, which yields the following equation of the estimated back-emf:

$$\hat{e}_a = -U_{max} sgn(i_a - \hat{\imath}_a) \tag{4}$$

where U_{max} is the maximum motor voltage. The block diagram of sliding mode observer is illustrated in Fig. 1(a).

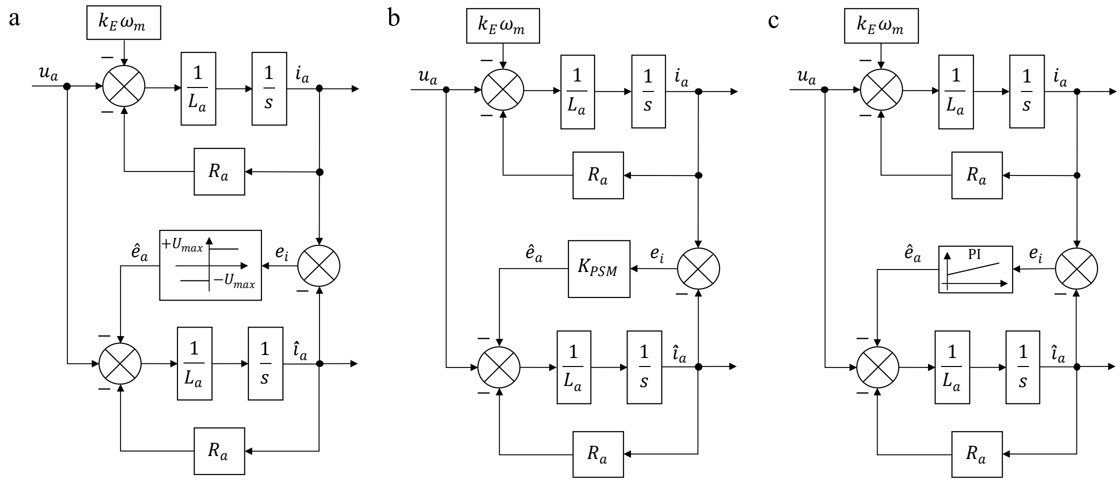

Fig. 1. Block diagram of the: (a) sliding mode observer; (b) pseudo-sliding mode observer; (c) observer with PI controller.

However, the signum function will cause a fast switching between two values $+U_{max}$ and $-U_{max}$ and the output of this block will be the pulsating value of estimated back-emf. Appropriate processing is required in order to use this value as a reliable feedback reference. The processing can be performed either by filtering or mathematically. One of the easiest solutions is to replace the signum function with a high proportional gain, which leads to a structure called the pseudo-sliding mode observer illustrated in Fig. 1(b). The proportional gain of the pseudo-sliding mode observer K_{PSM}, has to be chosen as high as possible within the limits of stability.

$$\hat{e}_a = -K_{PSM}(i_a - \hat{\imath}_a) \tag{5}$$

However, the error between the measured motor current and the estimated current will be forced to a non-zero value, which may cause inaccuracies of speed estimation. By using the PI controller as the correction block, shown in Fig.

1(c), the error between the measured and estimated current will be forced to exactly zero value and therefore more accurate speed estimation will be provided. In this case, the estimated back-emf is defined as follows:

$$\hat{e}_a = -\left(K_P + \frac{K_I}{s}\right)(i_a - \hat{\imath}_a) \tag{6}$$

where K_P and K_I are the proportional and integral gain of the PI controller, respectively. This observer has also some disadvantages such as the more complicated adjustment of the controller gains and the higher order of the system.

3. Methods based on the ripple component of DC motor current

This section presents the non-model based sensorless method used to estimate the speed of brushed DC motor from the measured motor current. The purpose of employing the non-model based method is to have a parameters independent method, which is accurate, simple to implement and does not have a large computational requirements. In this method, it is necessary to know the exact frequency of current ripple to extract the information about the speed from the measured motor current. Fig. 2 shows the measured motor current with a PWM modulation and without a PWM modulation. It is obvious, that the PWM modulation affects the current ripple with higher harmonics.

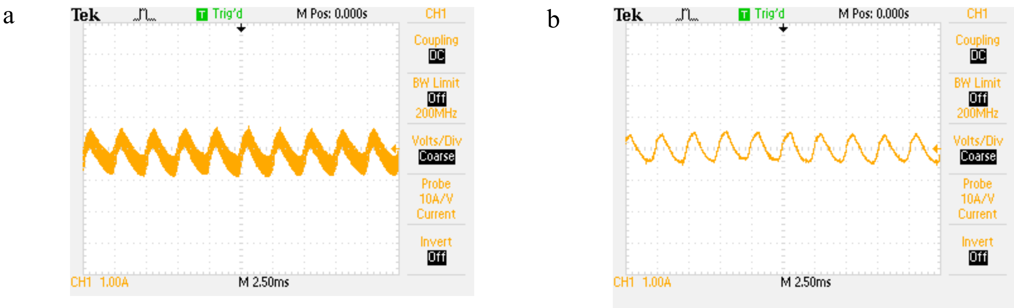

Fig. 2. Brushed DC motor current: (a) with the PWM modulation; (b) without the PWM modulation.

The frequency of current ripple f_r can be calculated by the following equation from Yuan et. al. (2007):

$$f_r = \frac{ckpn_m}{60} \tag{7}$$

where k is the number of commutator segments, p is the number of pole-pairs, n_m is the rotational speed, c is the coefficient contingent to the parity of the number of commutator segments, with $c = 1$ when k is even and $c = 2$ when k is odd. From Equation (7) yields, that for determining an accurate value of the current ripple frequency it is necessary to know the number of commutator segments k and number of pole-pairs p. These parameters are fixed and they depend on the motor construction, thus they are not changing during motor operation. Assuming parameters of the brushed DC motor from Table 1 used to perform an experimental verification and the rotational speed $n_m = 3000\ rpm$, we will obtain the following frequency of current ripple:

$$f_r = \frac{ckpn_m}{60} = \frac{1 \cdot 8 \cdot 1 \cdot 3000}{60} = 400\ Hz \tag{8}$$

By performing Fast Fourier Transform (FFT) of measured motor current at given speed, the frequency of current ripple is presented in a frequency domain as calculated (Fig. 3).

It is obvious from Equation (8), that the frequency of current ripple is proportional to the motor speed and therefore changing in the frequency domain. This frequency can be extracted by applying the bandpass filter, which is used for eliminating the DC component and the other spectral components from the measured current.

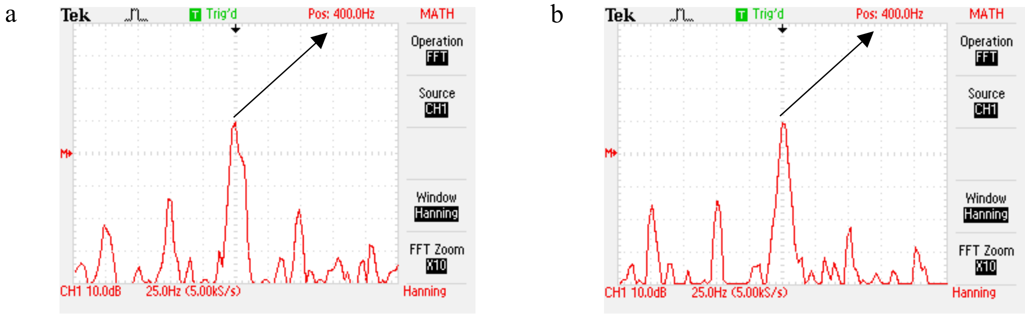

Fig. 3. Frequency of the current ripple at rotational speed $n_m = 3000\ rpm$: (a) with the PWM modulation; (b) without the PWM modulation.

A bandwidth of the bandpass filter has to be chosen appropriately to eliminate frequencies, which are not coupled to the motor speed.

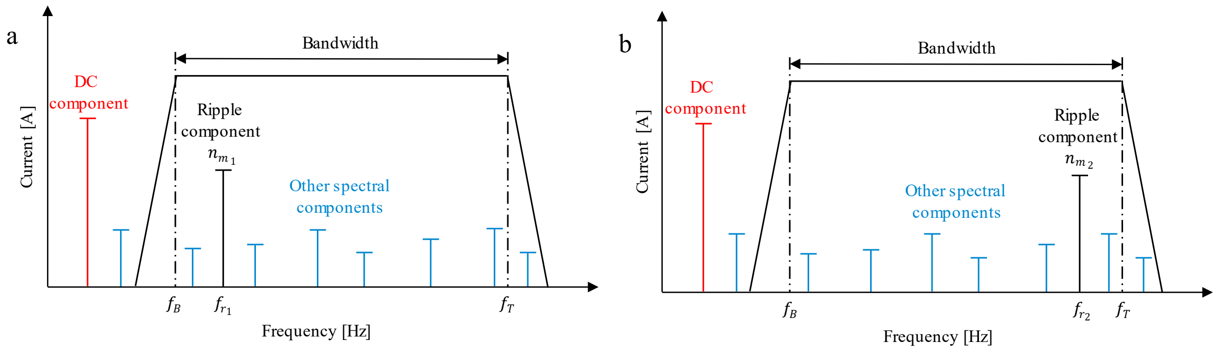

Fig. 4. Bandpass filter with the fixed bandwidth: (a) the lower rotational speed; (b) the higher rotational speed.

The first option is to use large bandwidth, with the bottom and top cut-off frequencies f_B and f_T respectively (Fig. 4). The purpose is to cover an area of the ripple component frequency for the lower rotational speed n_{m1} and the higher rotational speed n_{m2}. However, this may lead to uncertainties into the speed estimation, because the ripple component coupled to the rotational speed is influenced by the other spectral components of motor current as can be seen practically from the FFT in Fig. 3. This approach can be performed either externally with the analogue bandpass filter or internally by the discrete bandpass filter.

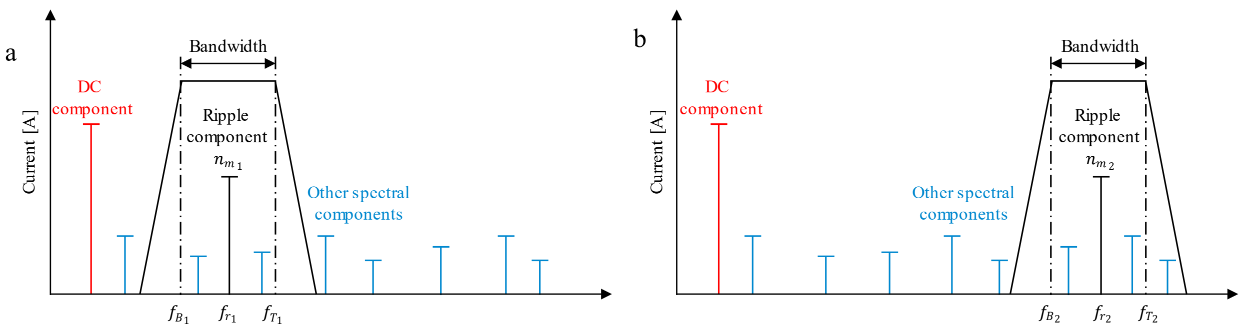

Fig. 5. Bandpass filter with the floating bandwidth: (a) the lower rotational speed; (b) the higher rotational speed.

The second option, is to use smaller bandwidth, whose position is floating in the frequency domain according to the rotational speed of the motor (Fig. 5). Therefore, the ripple component at rotational speed n_{m1} or n_{m2} no longer contains most of the other spectral components, which are not corresponding to the motor speed and the speed can be estimated more precisely. This approach can be performed only by the discrete bandpass filter, which allows appropriate bandwidth variation according to the motor speed. The output of the bandpass filter provides a clean AC signal, which is corresponding to the motor speed. This signal is compared to a reference value in order to convert the ripples to pulses with a frequency equal to the current ripple frequency. The timer peripheral on a microcontroller unit (MCU) is used to measure the length of each pulse and the motor speed can be estimated.

4. Experimental results

This section presents the procedure for measuring accuracy between model based and non-model based methods for the sensorless speed estimation of brushed DC motor. The parameters of tested brushed DC motor are presented in Table 1.

Table 1. Parameters of DC motor.

Parameter	Symbol	Value	Unit
Armature resistance	R_a	0,649	Ω
Armature inductance	L_a	1,130	mH
Back-emf constant	k_E	0,0173	Vs/rad
Moment of inertia	J_M	$9{,}26 \cdot 10^{-6}$	$kg \cdot m^2$
Number of pole pairs	p	1	-
Number of commutator segments	k	8	-

The tests were performed on the 12 V DC/DC converter with MCU from NXP Semiconductors, namely S32K144EVB, which is a low-cost evaluation and development board for general purpose automotive applications. The current was measured on the DC/DC converter by the 5 mΩ shunt resistor and sampling frequency 20 kHz. An incremental encoder was attached to the motor shaft in order to provide reliable information about the actual motor speed.

The results of the experiment were obtained for 6 values of constant speed by changing duty cycle of the PWM modulation up to the nominal motor voltage 12 V. The first experiment was focused on the comparison between the two model based observers from Section 2. Fig.6 shows the comparison between the actual motor speed obtained from the encoder and the estimated speeds obtained from the pseudo-sliding mode observer and observer with PI controller.

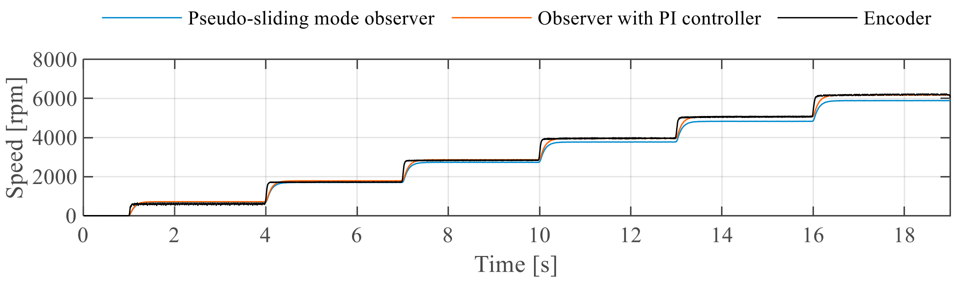

Fig. 6. Comparison between the actual and estimated speed.

Fig. 6 shows, that the observer with PI controller provides more accurate speed estimation than the pseudo-sliding mode observer. The reason can be spotted from Fig. 7, where the error between measured motor current and estimated current of the observer with PI controller is forced down to zero, while the other one has the error with non-zero value.

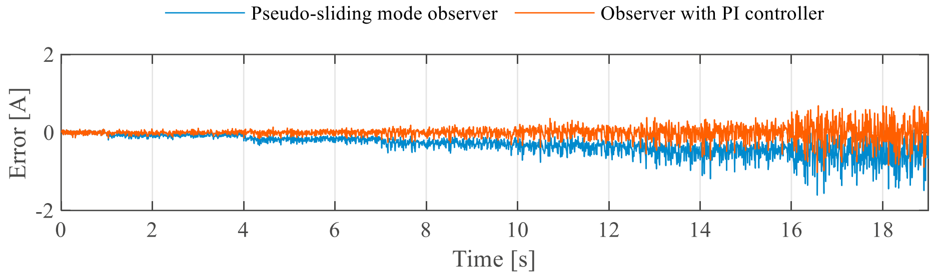

Fig. 7. Error between the measured and estimated current.

Fig. 8 shows the error between the actual and estimated speed for the model based observers. Inaccuracies in the low speeds are caused by the back-emf, which is not distinguishable in this range. Another disadvantage of the model based methods lies on the motor parameters, which tend to change their value for example with temperature. This may cause other inaccuracies in the whole speed range.

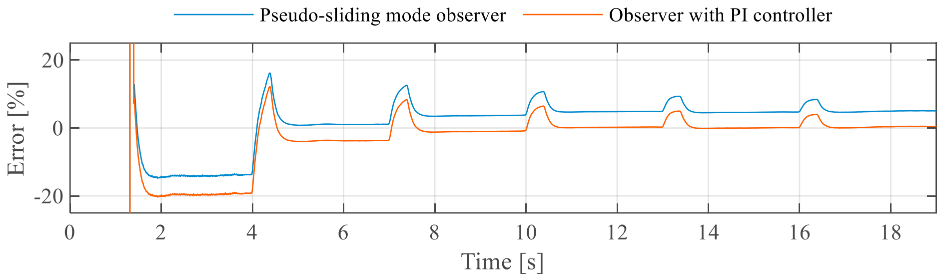

Fig. 8. Error between the actual and estimated speed.

The next experiment was conducted for the non-model based method. The accuracy was tested similarly as in the previous case. Fig. 9 shows the comparison between the actual speed, estimated speed from current ripple and estimated speed from observer with PI controller. The purpose of this figure is to show the differences between model based and non-model based method.

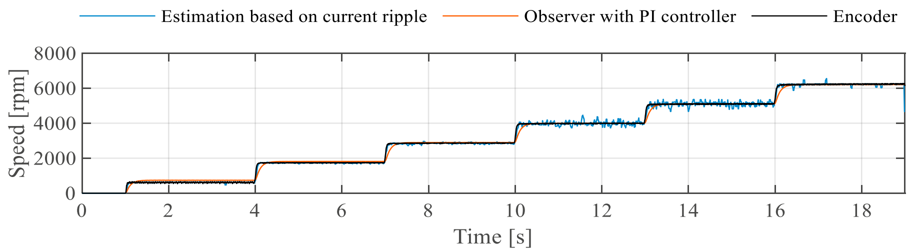

Fig. 9. Comparison between the actual and estimated speed.

It is obvious, that the non-model based method provides better accuracy than model based method and it is copying the actual value obtained from the encoder at low speeds as well. The errors between the actual and estimated speed of both methods are shown in Fig. 10, where the error of non-model based method does not exceed approximately ± 1,5%. The small disadvantage of the non-model based method can be seen at some speeds (see Fig. 9 around 4000 rpm and 5000 rpm), where small noise value is present. This was caused by the other spectral components of measured motor current, which were not filtered out by the bandpass filter. This almost negligible noise may be eliminated by using even smaller bandwidth of the bandpass filter.

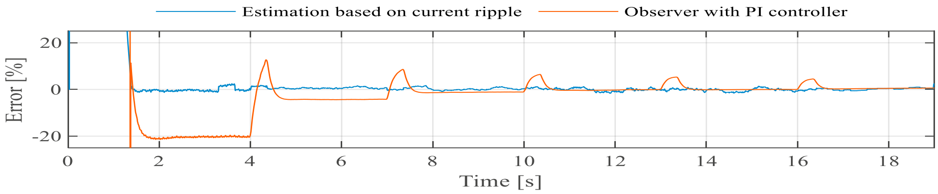

Fig. 10. Error between the actual and estimated speed.

5. Conclusion

This paper has presented the comparison between the model based and non-model based sensorless methods of the brushed DC motor, where both techniques were introduced and experimentally verified. The model based observers specifically the pseudo-sliding mode observer and the observer with PI controller were compared. The observer with PI controller provided more accurate speed estimation than the pseudo-sliding mode observer. The non-model based method used a ripple component of DC motor current, where the motor speed was estimated by applying the novel approach. This approach used the discrete bandpass filter with the floating bandwidth, to extract information about the motor speed from the measured motor current. This method was compared to the model based method in order to clarify the accuracy of both methods. The experimental results showed that the non-model based method is more accurate and the error between the actual and estimated speed did not exceed approximately $\pm$1,5%. This novel approach estimates speed accurately in wide range of speeds and does not require knowledge about the motor parameters such as armature resistance, armature inductance and back-emf constant.

Acknowledgements

This work was supported by Slovak Scientific Grant Agency VEGA No. 1/0615/19, and by projects ITMS:26220120046, cofounded from EU sources and European Regional Development Fund.This publication was realized with support of Operational Program Integrated Infrastructure 2014 – 2020 of the project: Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles, code ITMS 313011V334, co-financed by the European Regional Development Fund.

References

Bowes, S.R., Sevinc, A., Holliday, D., 2004. New natural observer applied to speed-sensorless DC servo and Induction motors. IEEE Transactions on Industrial Electronics, 51, 1025-1032.

Weerasooriya, S., El-Sharkawi, M.A., 1991. Identification and control of a DC motor using back-propagation neural networks. IEEE Transactions on Energy Conversion, 6, 663-669.

Razi, R., Monfared, M., 2015. Simple control scheme for single-phase uninterruptible power supply inverters with Kalman filter-based estimation of the output voltage. IET Power Electronics, 8, 1817-1824.

Castaneda, E.C., Loukianov, G.A., Sanchez, N.E., Castillo-Toledo, B., 2012. Discrete-Time Neural Sliding-Mode Block Control for a DC Motor With Controlled Flux. IEEE Transactions on Industrial Electronics, 59, 1194-1207.

Scott, J., McLeish, J., Round, H., 2009. Speed Control With Low Armature Loss for Very Small Sensorless Brushed DC Motors. IEEE Transactions on Industrial Electronics, 56, 1223-1229.

Yuan, B., Hu, Z., Zhou, Z., 2007. Expression of Sensorless Speed Estimation in Direct Current Motor with Simplex Lap Winding. International Conference on Mechatronics and Automation.

Ramli, R.M., Mikami, N., Takahashi, H., 2010. Adaptive filters for rotational speed estimation of a sensorless DC motor with brushes. 10th International Conference on Information Science, Signal Processing and their Applications (ISSPA 2010).

Vazquez-Sanchez, E., Gomez-Gil, J., Gamazo-Real, J.C., 2012. A New Method for Sensorless Estimation of the Speed and Position in Brushed DC Motors Using Support Vector Machines. IEEE Transactions on Industrial Electronics, 59, 1397-1408.

Radcliffe, P., Kumar, D., 2015. Sensorless speed measurement for brushed DC motors. IET Power Electronics, 8, 2223-2228.

Vazquez-Sanchez, E., Sottile, J., Gomez-Gil, J., 2016. A Novel Method for Sensorless Speed Detection of Brushed DC Motors. Applied Sciences.

Texas Instruments: Automotive Brushed-Motor Ripple Counter Reference Design for Sensorless Position Measurement, 2018.

Microchip Technology Inc: Sensorless Position Control of Brushed DC Motor Using Ripple Counting Technique, 2019.