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Estimate and Control speed of a DC motor using Different Power Circuits

***Abstract**: In this work, sensorless control speed/torque of a separately-excited DC motor (SDCM) utilizing transfer function characteristics is used with two suggested power drive systems. The first system is a PWM DC/DC converter that only operates in a forward motoring mode. The second proposed power system is a three-phase bridge controlled-rectifier to control the speed of a SDCM. The transfer function of a SDCM is built for estimating speed/torque during steady-state and dynamic operation by sensing terminal voltage and armature current as inputs. The speed is estimated to overcome sensor speed problems. Artificial neural network and/or PI controller is trained to get the required magnitude of firing angle or duty cycle to trig thyristors or tranasistor to control the speed of the SDCM at the wanted values. Therefor based on transfer function characteristics, speed and torque are estimated using direct output current and voltage of the converter circuit. The both proposed circuits and controllers are built and modeled in Matlab program. The systems are simulated under different speed and torque conditions in steady state and transient cases. The modeling results explain the efficiency of the designed controller system. The two systems has quick dynamic responding and suitanble coincidence among the refference, estimated and actual values.*

Streszczenie**: W niniejszej pracy zastosowano bezczujnikowe sterowanie prędkością/momentem obrotowym silnika prądu stałego z obcym wzbudzeniem (SDCM) wykorzystujące charakterystykę funkcji przenoszenia z dwoma sugerowanymi układami napędowymi. Pierwszy system to przetwornica PWM DC/DC, która działa tylko w trybie jazdy do przodu. Drugim proponowanym systemem zasilania jest trójfazowy prostownik sterowany mostkiem do sterowania prędkością SDCM. Funkcja przenoszenia SDCM została stworzona do szacowania prędkości/momentu obrotowego podczas pracy w stanie ustalonym i dynamicznym poprzez wykrywanie napięcia na zaciskach i prądu twornika jako danych wejściowych. Szacuje się, że prędkość pozwala przezwyciężyć problemy z szybkością czujnika. Sztuczna sieć neuronowa i/lub kontroler PI są szkolone, aby uzyskać wymaganą wielkość kąta zapłonu lub cyklu pracy, aby wyzwolić tyrystory lub tranzystory w celu kontrolowania prędkości SDCM przy żądanych wartościach. W związku z tym na podstawie charakterystyk funkcji przenoszenia prędkość i moment obrotowy są szacowane na podstawie stałego prądu wyjściowego i napięcia obwodu przekształtnika. Oba proponowane układy i sterowniki zostały zbudowane i zamodelowane w programie Matlab. Systemy są symulowane w różnych warunkach prędkości i momentu obrotowego w stanach ustalonych i przejściowych. Wyniki modelowania wyjaśniają efektywność zaprojektowanego układu regulatora. Oba systemy charakteryzują się szybkim dynamicznym reagowaniem i odpowiednią koincydencją między wartościami odniesienia, wartościami szacunkowymi i rzeczywistymi. (**Oszacowanie i kontrola prędkość silnika prądu stałego przy użyciu różnych obwodów mocy)

Keywords: Sensorless speed/torque, DC motor, three phase controlled rectifier, dc chopper, and transfer function.
Słowa kluczowe: Bezczujnikowa prędkość/moment obrotowy, silnik prądu stałego, prostownik sterowany trójfazowy, chopper prądu stałego, funkcja przenoszenia.

Introduction

DC machines are commonly used for industrial power uses because of their great reliability and flexibility with low cost. High-performance motor drives are crucial for reliable operation. The power electronic converters are implemented into DC drive applications in modern control systems, particularly in speed and torque control, as well as frequent starting and braking operating modes [1-2]. These requirements can be made through tracking high-quality torque and speed responses [3]. The DC motor (DCM) speed control is introduced depending on proportional-integral-derivative-controller (PID), artificial neural network (ANN), genetic algorithm, fuzzy logic controller, neuro-fuzzy controller, etc [3-9]. The accurate control speed/torque of the DCM is necessary for various applications. A speed sensor of the DCM is employed to obtain speed information. Its performance is changed with the atmospheric conditions, which disturb stability of the closed-loop system. To deal with this issue, sensorless speed control of the DCM is introduced in the following section.

In 2013 [10], neuro-fuzzy controller was suggested to evaluate a DCM speed under different actions depending on measuring the armature current and terminal voltage, which regards steady-state and dynamic operation. Whereas the speed reached to reference value at 0.67 sec. In 2014 [11], a sensorless DCM speed control was achieved using the ANN. The measuring armature current and reconstructed terminal voltage are taken into account for designing of the control system. The actual and estimated speeds are corresponding to desired value within 0.6 sec. The estimated torque and speed of the DCM based on the ANN based on measuring DCM voltage and current were presented in 2016 [12]. The estimated and actual speeds catch suggestion value within 0.87 sec. In 2018 [13], the torque and speed of the DCM were estimated in four-quadrant operation modes. The control system here was designed using the transfer function characteristics. The DC/DC converters are used as a drive circuit. The system is tested through different operating conditions of torque and speed. The speed control of the DCM employing a chopper circuit was presented and simulated by MATLAB as introduced in 2018 [14]. The armature voltage and field flux control methods are used to control speed below and above the rated value. In 2019 [15] presented a new model to control speed of the DCM. A PID controller was optimized to speed the control system. Performance of the PID controller was archived to maintain the transient overshoot response below 0.2048 %, it skilled fast settling of no more than 0.1577s. In 2019 [16] fuzzy logic and PID controllers were built to control speed of the DCM. The results obtained by fuzzy logic controller illustrate that peak time, overshoot, control performance, and settling time have been enhanced prominently compared with a conventional controller. In 2019 [17] the DCM speed and current were regulated effectively based on PI-Petri nets controller. The DC chopper was built to drive the DCM. The Petri nets controller gives good results compared with the PI controller. The DCM current follows its reference value successfully, and the DC voltage is contolled, so a sure operation of the converter with minimum losses is achieved. The output energy quality is improved with the life of the DCM. In 2019 [18] a speed-sensorless control system was introduced for separately-excited DCM (SDCM). A Hybrid Fuzzy-PI Controller is proposed to improve the performance of the DCM.

In 2019 [19] a fuzzy, auto-tuning-PID, and ANFIS controllers were tested at the same conditions to estimate rise and settling times, absorbing different loads, overshoot, and steady-state error, to define the efficiency. The ANFIS control has a fast dynamic performance of DCM speed, with non-oscillating response, less overshoot, and high efficiency. In 2020 [20] the control of DCM Speed was simulated using MATLAB/Simulink. The suggested method used PI controller and speed of the motor controlled that considers an influence of load variation. PI Controller is done to keep the constant speed values at a reduced overshoot and rise time. In 2020 [21], the sensorless speed control of DCM was proposed as an observer method. The designed sensorless illustrates that the observer method is based on current without using the speed sensor. The simulated results are compared and matched to those of actual results. In 2021 [22] a suggested model for servo DCM speed control using different PID controllers was done. However, the PID controller illustrated that the output response tracks the input with error steady state zero.

In this paper,two power circuits used sensorless speed/torque control based on the transfer function characteristics are suggesteded for the SDCM . The estimated speed and torque during the steady-state and transient operation are achieved by measuring terminal voltage and armature current as inputs to develop the suggested control system, as depicted in Fig.1. and Fig.2.

DC Drive circuit

The SDCM is generally used as a variable speed drives. To run SDCM at wanted speed, the suggested power systems are controlled by regulating the armature voltage, which is utilized by varying either duty cycle D of the switching transistor for the first power circuit or select the required value of firing angle (α) to trig thyristors of the second power circuit. The duty cycle D is defined as t_{on}/T_s. Thus, the average output voltage V_a is given as:

(1) $$V_a = \frac{t_{on}}{T_S} * V_{dc}$$

Where T_S =1/F_{sw}, t_{on} is the ON-time period, anf F_{sw} is the switching frequency. The DCM speed is estimated depending on the DCM transfer function as illustrated in Fig.3. Expressions of estimated speed w_{est}, current $I_{arm-est}$, electrical developed T_{e-est} and load T_{L-est} torques using Laplace Transform are written as follows:

(2) $$I_{arm-est}(s) = \frac{V_a(s) - K_m * w_{est}(s)}{(R_a + sL_a)}$$

(3) $$T_{e-est}(s) = K_m * I_{arm-est}(s)$$

(4) $$w_{est}(s) = \frac{T_{e-est}(s) - T_{L-est}(s)}{(B_m + sJ)}$$

(5) $$T_{L-est}(s) = (K_p + \frac{K_i}{s}) * (I_{arm}(s) - I_{arm-est}(s))$$

Where L_a, R_a, K_m, J, B_m, K_i, and K_p are armature inductance, armature resistance, machine constant, moment of inertia, friction coefficient, integral controller gain, and proportional controller gain respectively. To evaluate the DCM speed properly, load and developed torques are estimated, that is to obtain high speed response and adequate match among the desired, estimated and actual values.

Modeling of the Estimation System

The estimation system is built to sense and control the SDCM torque and speed. The estimated speed and torque of the SDCM with the first circuit (chopper circuit) is built as illustrated in Fig.4. The controller circuit is designed with two PI-controllers. The first one is a current controller and the output of this controller is compared with the estimated armature current. The resultant is fed to a second PI-controller to have the modulation index, which is getting by comparing with a triangular signal to get the PWM-pulses of the DCM circuit as explained in Fig.4. The two controllers of the DCM circuit are combined with each other to obtain fast response and to prevent extreme current flowing in the DCM circuit. As a consequnce, the constructed controller during load changing has a good dynamic response to achieve the steady state responses as quick as possible. This controller is very simple with low complexity compared with the other techniques designed in the forward-motoring-mode.

The controller estimation circuit of the second suggested circuit is shown in Fig. 5. The estimation part is the same as in the first circuit. The speed and torque are controlled using ANN and PI controller, which are learned to choose the required value of firing angle to turn ON thyristors of the converter and run SDCM at the wanted speed. A closed loop PI regulator is utilized to get the best value of (α) inserted to the values chosen by ANN to enhance the step reaction performance, Fig.5.

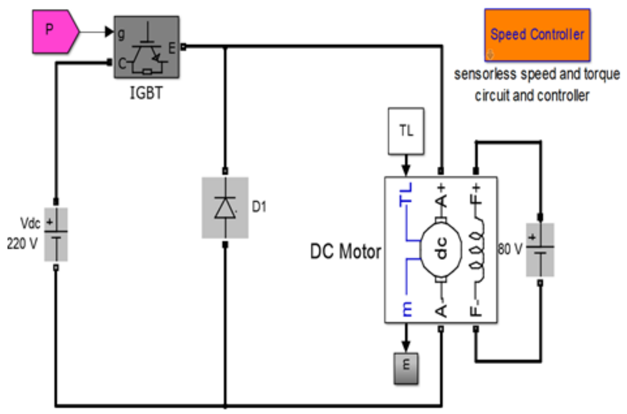


Fig. 1. The first proposed power system of the DCM drive circuit.

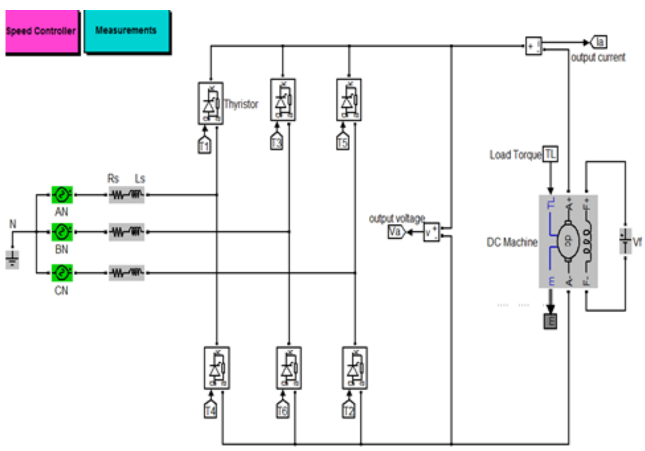


Fig. 2. The second proposed power system of the DCM drive circuit

Simulation Results

The two suggested circuits illustrated in Fig.1and Fig.2 are simulated and modeled by Matlab/Simulink. The DCM specifications under this study are listed in the table(1). The modeling and simulation of the DCM drive circuits are performed upon various speed/torque operating conditions to sense the dynamic response of the SDCM . The speed and load torque reactions of the SDCM at load torque (T_L=10 N.m) for the first and second suggested circuits are explained in Fig.6 and Fig.7, repectively. The actual and estimated (sensorless) speed results are stable and arrived the reference value of (600 rpm) in 0.3 sec. Figures 8 and 9 illustrate the estimated developed torque for the first and second suggested circuit respectively that follows the constant load torque (10 N.m) and remain stable during speed changing. The terminal armature voltage V_a and current I_a responses of the DCM driver circuits are demonstrated in Fig.10 and Fig.11. These waveforms reach steady-state with a certain overshoot during changing speed point because of the nature of the designed sensorless system. Fig.12 explains the effectivity of the controller system capability to control the DCM at certain speed (1000 rpm) and various load torques (5, 7 and 10 N.m) for the first model. Fig.13 explains the speed/torque response for the second model. The sensorless and actual speed/load-torque responses remain about the required level with about zero steady state error. The estimated and actual speed results reach the desired speed within 0.4 second. The electrical developed torque for the two proposed models are illustrated in Figs.14 and 15, respectively. Figures 16 and 17 explain current, and voltage waveforms for the two models. The overshooting illustrated in this waveform appears at start running of the SDCM only. These waveforms explain the power of the designed control circuit to estimate speed/torque of the SDCM without sensors. The designed controller has excellent speed response and reachs steady state as fast as possible which demonstrates the success of the sensorless system controller to follow the wanted speeds and torques.

Table (1). **Drive System Specifications.**

DC armature voltage	240V
Field Voltage (Vf)	189V
Armature Current (Ia)	12A
Electrical Power	2kw
Mechanical Torque	13N.m
Rate Speed	1400rpm
Moment of Inertia (J)	0.012Kg.m^2
Friction Coefficient (B)	0.0204N.m.s
Armature Resistance (Ra)	5.79Ω
Armature Inductance (La)	60mH
Field Resistance (Rf)	246.7Ω
Field Inductance (Lf)	52H
Mutual Inductance (Laf)	1.6H
Pole pairs	1

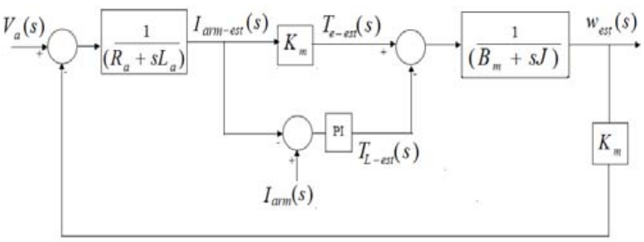


Fig. 3. Block diagram of SDCM

After presenting all results during different casese, the first circuit repsonses are better than the second type and this is due to harmonics in the dc side of the three-phase controlled rectifier which can be improved by filtering the output side. The two suggested circuits give good results with the proprties of sensorless speed and torque.

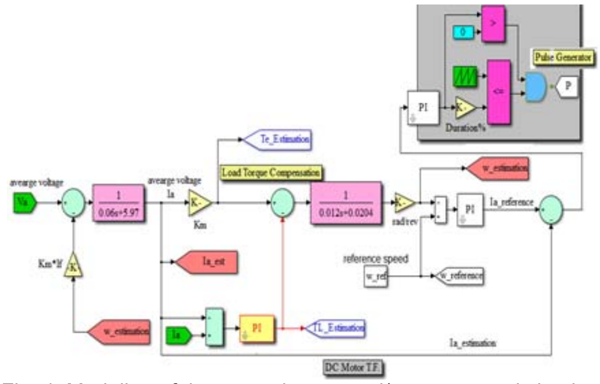


Fig. 4. Modeling of the sensorless speed/torque control circuit of the first suggested system.

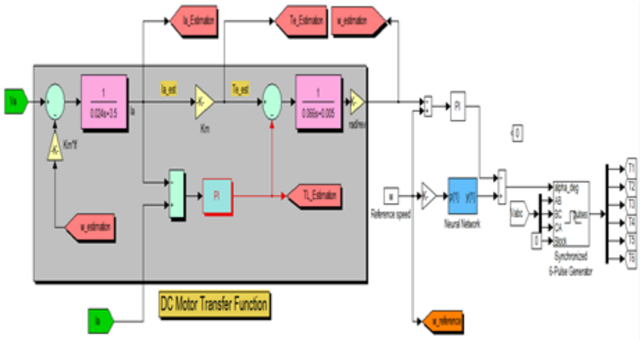


Fig.5. Modeling of the sensorless speed/torque control circuit of the second suggested system.

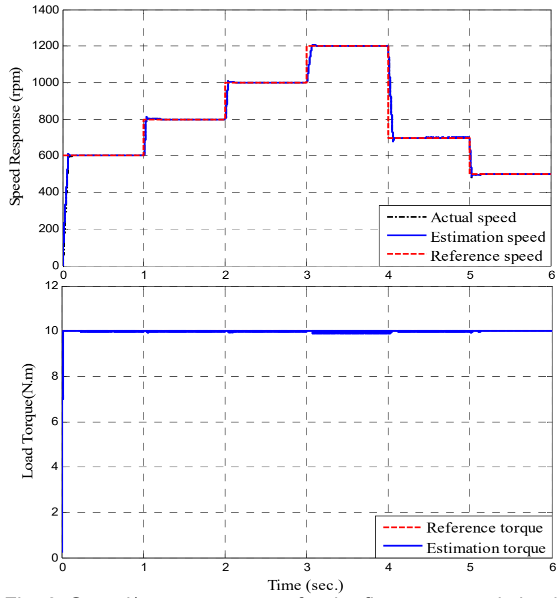
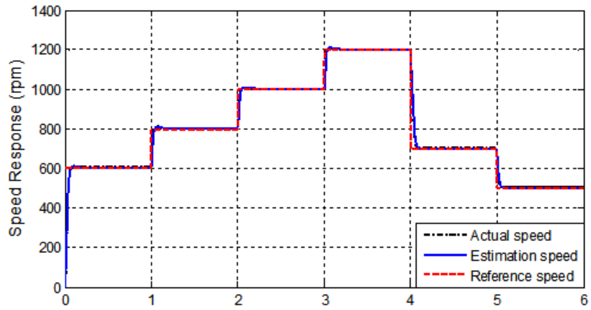


Fig. 6. Speed/torque response for the first suggested circuit



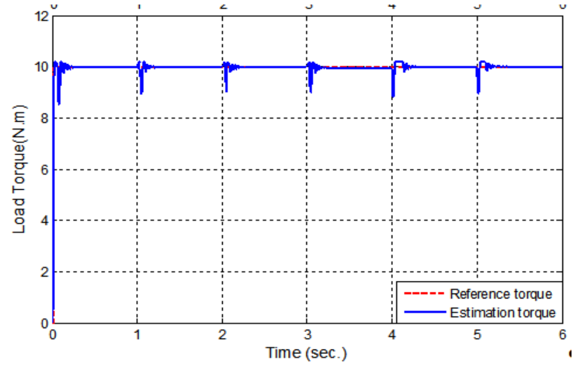


Fig. 7. Speed/torque response for the srcond suggested circuit

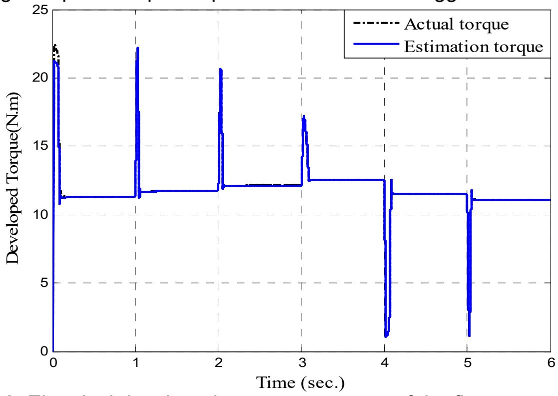


Fig. 8. Electrical developed torque responses of the first suggested circuit at different speed and constant load torque.

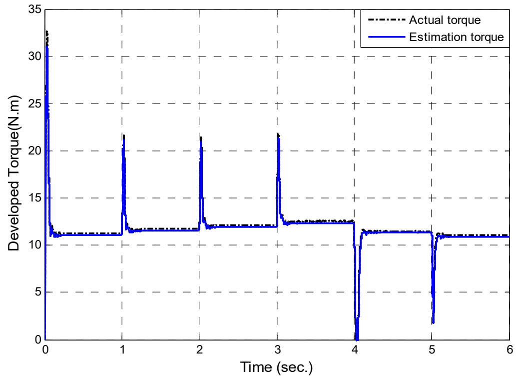


Fig. 9. Electrical developed torque responses of the second suggested circuit at different speed and constant load torque.

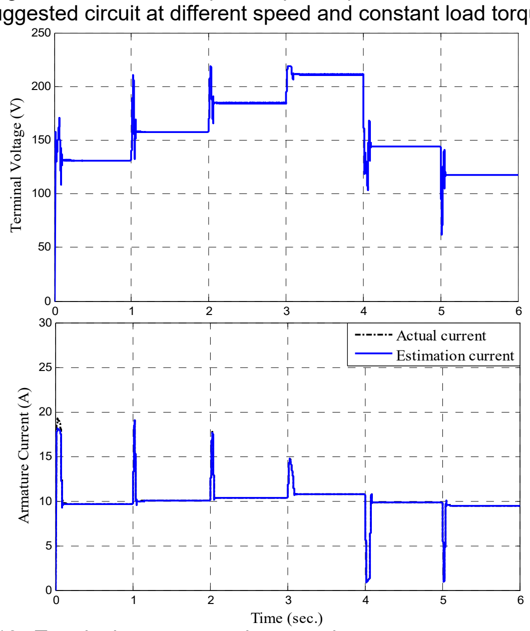


Fig. 10. Terminal armature voltage and current responses of the SDCM for the first suggested circuit

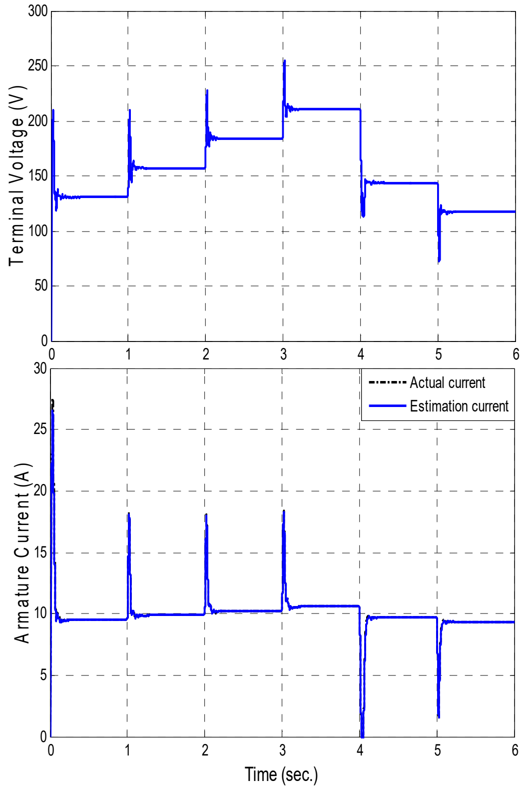


Fig. 11. Terminal armature voltage and current responses of the SDCM for the second suggested circuit

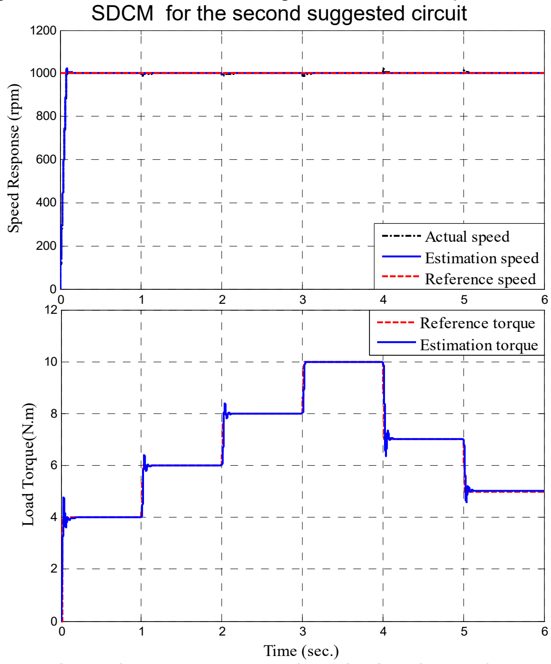
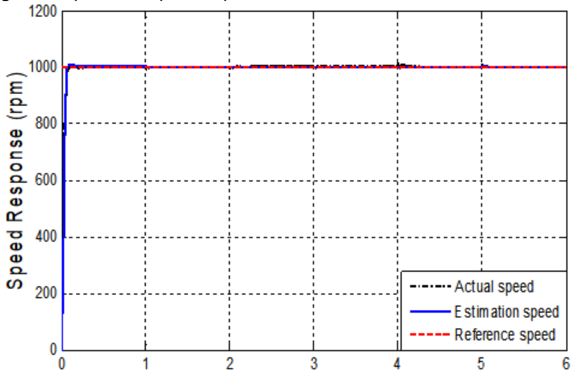


Fig. 12. Speed/torque response of the SDCM for the first model



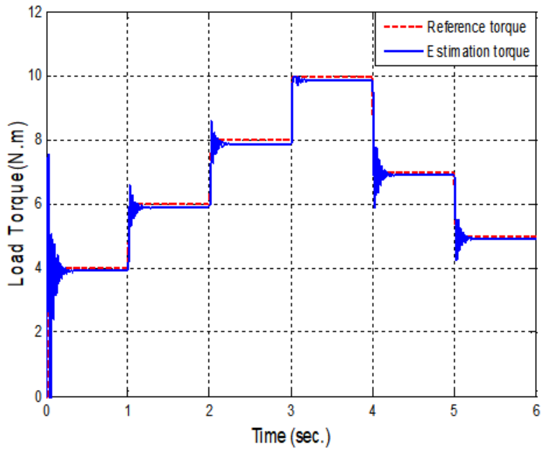


Fig. 13. Speed/torque response of the SDCM for the second model

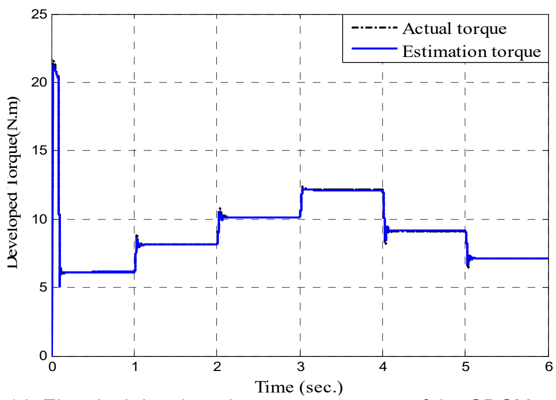


Fig. 14. Electrical developed torque responses of the SDCM under various load torque and constant speed for the first circuit

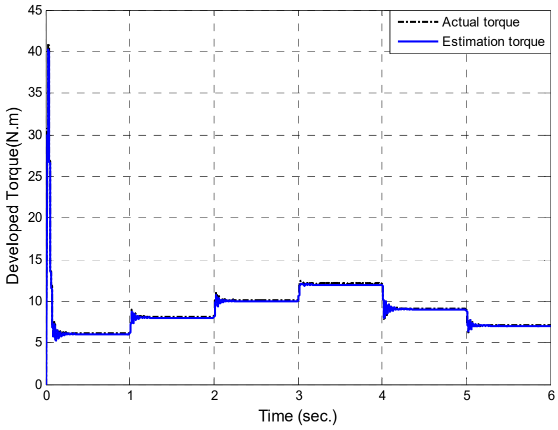
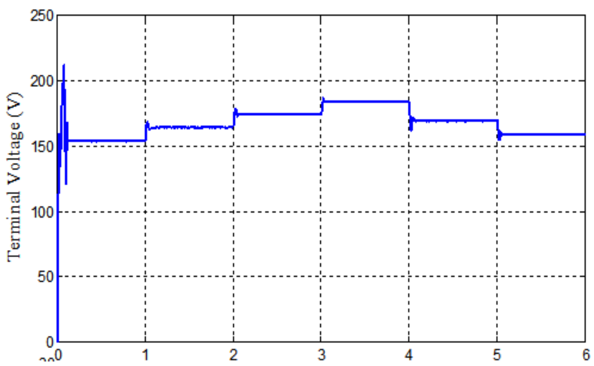


Fig. 15. Electrical developed torque responses of the SDCM under various load torque and constant speed for the second circuit



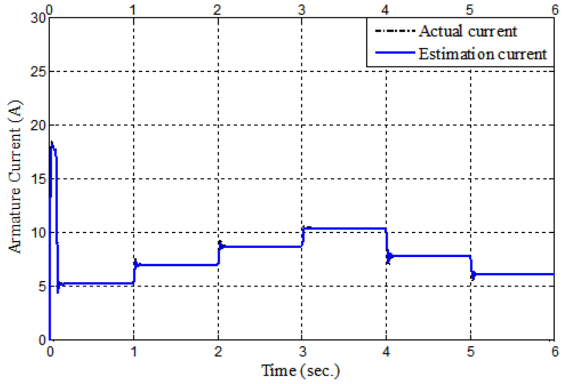


Fig. 16. Armature voltage and current responses of the SDCM .

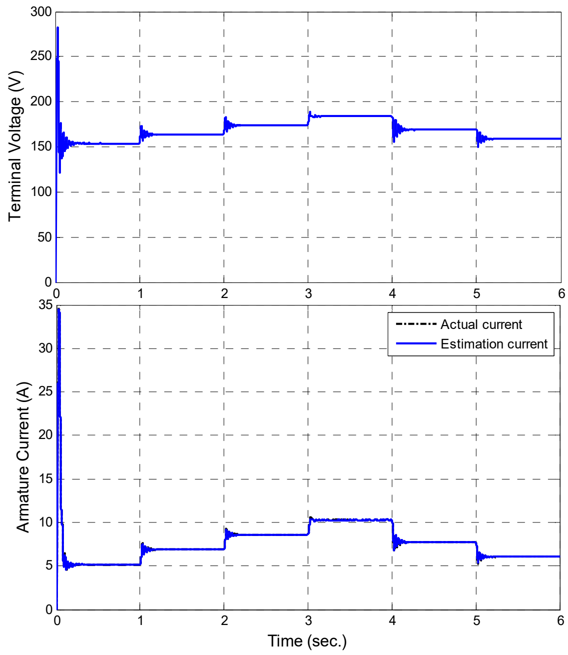


Fig. 17. Armature voltage and current responses of the SDCM .

Conclusions

In this study, sensorless control of the speed/torque of the SDCM depending on transfer function characteristics has been proposed. Measuring of terminal voltage and armature current is taken into consideration as inputs to develop the proposed control system. The transfer function of the SDCM has built to estimate speed/torque during steady-state and dynamic operations. The differences between the estimated and reference speed is implemented at the PI-controller to give intensive control. This SDCM with two power circuits is tested. The first circuit is chopper circuit and the second type is a three-phase bridge controlled rectifier. The simulation results illustrated that the designed controller system is capable of estimating SDCM speed and torque at certain and different load torques. The estimated speed and torque depending on the transfer function characteristics has a well responding and robust to the variation of the speed/torque. Furthermore, the controller system is simple with less complexity. It minimizes computing time and producing lower errors compared with the other techniques.

REFERENCES

[1] Rajnikant Sinha, Prabir Ranjan Kasari, Abanishwar Chakrabarti, Bikram Das and Arindam Das, "Speed Regulation of DC Motor by Buck Converter", International Conference on Power Electronic Drives and Energy Systems for Industrial Growth **(PEDES)**, IEEE 2018.

[2] Nashwan Sultan, Rakan Khalil ANTAR, Bashar FADHEEL, “A Comparative Control Study of A Separately Excited DC Motor Using Intelligent Controllers”, Journal of Engineering and Applied Sciences, Vol. 13, No. 22, pp. 9799-9805, 2018.
[3] M.M. Sankar and G.Sailaja, “Four Quadrant Chopper Control of DC Motor using AT89S52 Microcontroller”, National Conference on Electrical sciences, page: 161-165, 2012.
[4] Hameed, W. I. and Mohamad, K. A., “Speed Control of Separately Excited DC Motor using Fuzzy Neural Model Reference Controller”, International Journal of Instrumentation and Control Systems, vol.2, No.4, page: 27-39, October, 2012.
[5] Hashmia, A. L. and Dakheel, SH. “Speed Control of Separately Exited DC Motor using Artificial Neural Network”, Journal of Engineering and Development, Vol. 16, No.4, pages: 349-362, December 2012.
[6] R. kushwah, S. Wadhwani, “Speed Control of Separately Excited DC Motor Using Fuzzy Logic Controller”, International Journal of Engineering Trends and Technology (IJETT), Vol. 4, Issue 6, pages: 2518-2523, June 2013.
[7] G. Y. Mustafa, A. T. Ali, E. Bashier and M. F. Elrahman, “ Neuro-Fuzzy Controller Design for a DC Motor Drive”, University of Khartoum Engineering Journal (UofKEJ), Vol. 3, Issue 1, pages:7-11, February 2013.
[8] Y. I. Al-Mashhadany, “Modeling and simulation of Adaptive Neuro- Fuzzy controller for Chopper-Fed DC Motor Drive”, Applied Power Electronics Colloquium (IAPEC) conference, pages: 110–115, IEEE April 2011.
[9] P. Cepeda, P. Ponce and A. Molina, “A Novel Speed Control for DC Motors: Sliding Mode Control, Fuzzy Inference System, Neural Networks and Genetic Algorithms”, 11th Mexican International Conference on Artificial Intelligence (MICAI), pages: 116-121, 2012.
[10] Rakan Khalil Antar, Ahmed A. Allu, Ahmed J. Ali, “Sensorless Speed Control of Separately Excited DC Motor Using Neuro-Fuzzy Controller”, 1st International Conference of Electrical, Communication, Computer, Power and Control Engineering ICECCPCE'13, IEEE2013, pages: 37-41, 2013. Mosul, Iraq.
[11] Ahmed A. Allu and Rakan Khalil Antar, “Design and Modeling of Speed Sensorless Control of DC Motor Drive System”, Al-Rafidain Engineering Journal, University of Mosul, College of Engineering, Vol. 22, No. 5, pages: 89-100, 2014.
[12] Rakan Khalil Antar, Ahmed A. Allu, “Sensorless Speed/Torque Control of DC Machine Using Artificial Neural Network Technique”, Tikrit Journal of Engineering Sciences, Vol.23, No.3, pages: 55-62, 2016.
[13] Rakan Khalil ANTAR, “Speed/Torque Estimation and Control of a DC Machine in Four Quadrants Operation Modes”, Al-Nahrain Journal for Engineering Science (NJES), Vol.21, No.2, pp. 238-247, 2018.
[14] M.Gokulkannan, T.Dinesh, S.Murugesan, M.Naveenprasanth and R.Nagarajan, "Performance Improvement in Separately Excited DC Motor Using PI Controller", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Volume 6, Issue 07, 2018.
[15] Sarah N. Al-Bargothi, Ghazi M. Qaryouti, Qazem M. Jaber, "Speed control of DC motor using conventional and adaptive PID controllers", Indonesian Journal of Electrical Engineering and Computer Science, vol.16, No.3, pp.1221-1228, 2019.
[16] R.Nagarajan, M. Gokulkannan, T. Dinesh, S. Murugesan and M. Naveenprasanth, “Performance Improvements of Separately Excited DC Motor Using Fuzzy Logic Control", ISSN: 2454-1907, Vol.6 (Iss.2): February 2019].
[17] Mohamed Lamine Hamida, Hakim Denoun, Arezki Fekik, and Sundarapandian Vaidyanathan, "Control of separately excited DC motor with series multi-cells chopper using PI - Petri nets controller",https://doi.org/10.1515/nleng-2017-0174; pp. 32–38 , Nonlinear Engineering 2019.
[18] Anil Gunde, G. Devadasu and M.Vijayasaanthi, "Design of Hybrid Fuzzy-PI Controller for Sensorless Speed Control of Separately Excited DC Motor Drive", International Journal of Recent Technology and Engineering (IJRTE), ISSN: 2277-3878, Volume-8 Issue-2S8, August 2019.
[19]Mohamed Elhaj Ahmed Mohamed and Yanling Guo," Separately Excited DC Motor Speed Tracking Control Using Adaptive Neuro-Fuzzy Inference System Based on Genetic Algorithm Particle Swarm Optimization and Fuzzy Auto-Tuning PID", doi:10.1088/1755-1315/300/4/042114 IOP Conf. Series: Earth and Environmental Science REES2019.
[20] Oti Stephen Ejiofor, Agada Stephen C., Obe Chinedu, Salihu Ahmed and Ogbuefi Uche C., "Dynamics of Speed Control of Dc Motor using Combine Armature and Field Control with Pi Controller", International Journal of Engineering and Advanced Technology (IJEAT), Vol.9 Issue-3, February 2020.
[21] Diyajeng Luluk Karlina and Katherin Indriawati, " Fault Tolerant Control for Speed Sensorless of DC Motor ", 2020 International Conference on Smart Technology and Applications (ICoSTA) ,IEEE 10.1109/ICoSTA48221.2020.1570615272.
[22] Liqaa Saadi Mezher, "Speed Control for Servo DC Motor with Different Tuning PID Controller with LABVIEW", Journal of Mechanical Engineering Research and Developments, ISSN: 1024-1752, Vol. 44, No. 1, pp. 294-303, 2021.