Research of static and dynamic characteristics of a process system 'electric drive-fluid-handling machine-pipeline'

Ayman Y. Al-Rawashdeh[1], Vlademer E. Pavlov[2], Khalaf Y. Al Zyoud[1], Mohammad S. Khrisat[3]
[1]Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Amman, Jordan
[2]Department of Mechatronics Engineering, Irkutsk National Research Technical University, Irkutsk, Russia
[3]Department of Mechatronics Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Amman, Jordan

Article Info

Article history:

Received Jun 30, 2023
Revised Jan 9, 2024
Accepted Jan 11, 2024

Keywords:

Asynchronous motor
Fluid-handling machines
Frequency method
Head and flow
Model of electric drive
Pipeline
Throttling control methods

ABSTRACT

The paper offers the obtained quantitative assessment of the performance and energy parameters of a process system composed of an asynchronous motor, a fluid-handling machine and a pipeline when using two methods of performance control, in particular, throttling and speed control methods. Taking into account nonlinearity of mathematical representation of fluid-handling machines and asynchronous drive motors, the starting conditions were analysed using nonlinear differential calculus. The calculations for the models were performed using the MATLAB software package. Transient profiles of flow and head, stator current, angular frequency and torque of an asynchronous motor were obtained at pump startup and control of pump capacity. It has been found that the developed mathematical model of a process system composed of an asynchronous motor, a fluid-handling machine and a pipeline allows obtaining quantitative estimation of the performance and energy parameters of the unit when using two methods of the pump capacity control. The use of frequency method allows to decrease the pump rotation speed and significantly reduce the power consumed by the unit and provide energy-saving mode of operation, the economic efficiency of which depends on the range of feed control.

Corresponding Author:

Ayman Y. Al-Rawashdeh
Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University
Marka, Amman, 11134, Jordan
Email: dr.ayman.rawashdeh@bau.edu.jo

1. INTRODUCTION

The regulation of liquid and gas flows conveyed by pipelines is highly significant. During the term of applications, the fluids being transported are contained within tanks, equipment, and pipelines. Simultaneously, it is acknowledged that pipelines, valves, and other apparatuses generate resistance to the movement of fluids. The presence of mass in flowing liquids or gasses results in the resistance of friction and inertia against the forces driving the motion. The dynamic mathematical models of fluid flows in pipelines should consider the inertial properties of the fluid.

The transient performances, in terms of duration, processing accuracy of control actions, overregulation, and other factors, should satisfy certain requirements while considering two different pumping capacity values. Preventing water hammer and vibrations is a crucial concern in liquid flows. Hence, a dynamic mathematical portrayal of fluids is essential for the advancement of effective flow control systems for pipelines. These models should accurately represent the correlation between external pressure, characteristics of the transported fluid, pipeline and control equipment parameters, and the flow rate.

Fluid-handling machines, also known as turbo-mechanisms, are responsible for efficiently moving enormous quantities of liquid and gas via pipelines. This equipment includes pumps, fans, pressure blowers, and compressors. Researchers are now studying issues connected to the transportation of material media through pipelines. This is important since choosing the right capacity control strategy for these systems can lead to significant energy savings. The mechanical energy exerted on a fluid-handling machine during its operation is transformed into both potential and kinetic energy of the transported material. Energy losses are present in every component of the drive-fluid-handling machine-pipeline process chain.

Various calculations suggest that the electric drives used in fluid-handling devices account for around 25% to 30% of the total global electricity generation [1], [2]. Hence, it is economically justifiable to develop a dependable and sufficient mathematical model for the processes taking place in electric drives of fluid-handling equipment. The authors in [3]–[9] discuss the problems associated with energy efficient capacity control of fluid-handling equipment. Implementation details of a special nature are also taken into account in the range of references [10]–[17]. We will employ the methodologies described in [18] to construct mathematical models of the components involved in the electric drive - fluid-handling equipment pipeline process flow.

2. METHOD AND MODEL OF A PROCESS SYSTEM 'ASYNCHRONOUS MOTOR-FLUID-HANDLING MACHINE-PIPELINE'

The main process parameters of fluid-handling machine are flow and head. These parameters depend on the rotation speed of the machine and the resistance of the pipeline through which the liquid or gas flows. In steady-state mode, the operating point of a pump or fan is defined as the point of intersection of the Q-H characteristic of the machine and the characteristic of the pipeline. When regulating the performance of the fluid-handling machine by throttling method, the position of the pipeline characteristic changes, and when controlling the speed of the drive motor, the Q-H characteristic of the machine changes its position. When the speed is reduced, the Q-H characteristic of the machine moves downwards, while the flow and head values at the operating point decrease. The useful power consumed by the fluid-handling machine is proportional to the product of flow and head. Therefore, when the rotation speed is reduced, the power consumed from the mains decreases, and when using the throttling method, this power increases in proportion to the increase in head. To quantify these methods of pump capacity control, mathematical models have been developed, which take into account the dynamic characteristics of the elements of the process system. Equation of liquid or gas flow in a pipeline [19]–[21]:

$$H - H_{Mag} = \frac{1}{H1}\frac{dQ}{dt} \tag{1}$$

where H is the head (pressure) at the inlet of the machine, Pa; H_{Mag} is the characteristic of the pipeline, Pa; $\frac{1}{A_1}\frac{dQ}{dt}$ is the dynamic head in the pipeline.
Characteristic of the pipeline taking into account the static head is as (2):

$$H_{Mag} = (H_C + \frac{A_2}{A_1})Q^2 \tag{2}$$

where Hc is the static head in the pipeline. Design and process parameter A1 is determined from (3):

$$A_1 = \frac{S}{L\gamma} \tag{3}$$

where $S=\pi d^2/4$ is the equivalent cross-sectional area of the pipeline, m^2; d is the equivalent diameter of the pipeline, m; L is the equivalent length of the pipeline, m; γ is the density of the pumped liquid or gas, kg/m^3.

The resistance factor of the pipeline A2 may be calculated from the datasheet specifications of the fluid-handling machine for the operating point $H=H_H$ and $Q=Q_H$.

$$A_2 = \frac{A_1(H_H - H_C)}{Q_H^2} \tag{4}$$

Laplace transformation of (1) followed by the use of (1) to (4) allow to obtain the fluid-handling machine model shown in Figure 1. Let us use parameter values of the existing pump and pipeline. Technical and design data of the pump and pipeline: pump type SA075T; Q_H=4,680 m^3/h, H_H=9.8 m, H_C=0 m, ω_H=293 1/s, d=50 mm =0.05 m, L=10 m, S=0.0019625 m^2, К=177.5147 Pa·s^2/m^6, K_1=1.4543 Pa·s^2, A1=19.625 10-8 m^3/kg, A2=11522.574 Pa·s^2/kg·m^3. The block model of the regulated electric drive of the pump unit, containing frequency converter (FC), pump and drive motor (asynchronous motor) is shown in Figure 2. The flow diagram contains flow setting device SQ, FC PH, asynchronous motor ad, pump, and measuring unit B.

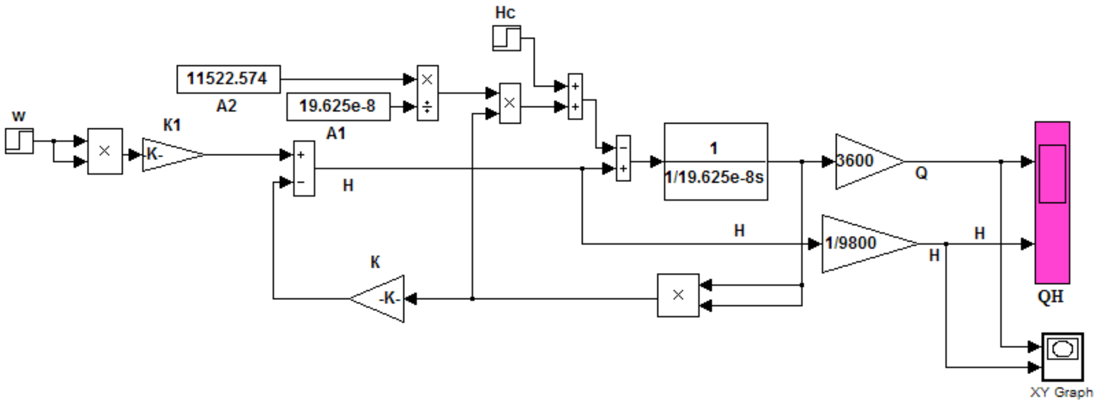


Figure 1. Model of the fluid-handling machine and pipeline

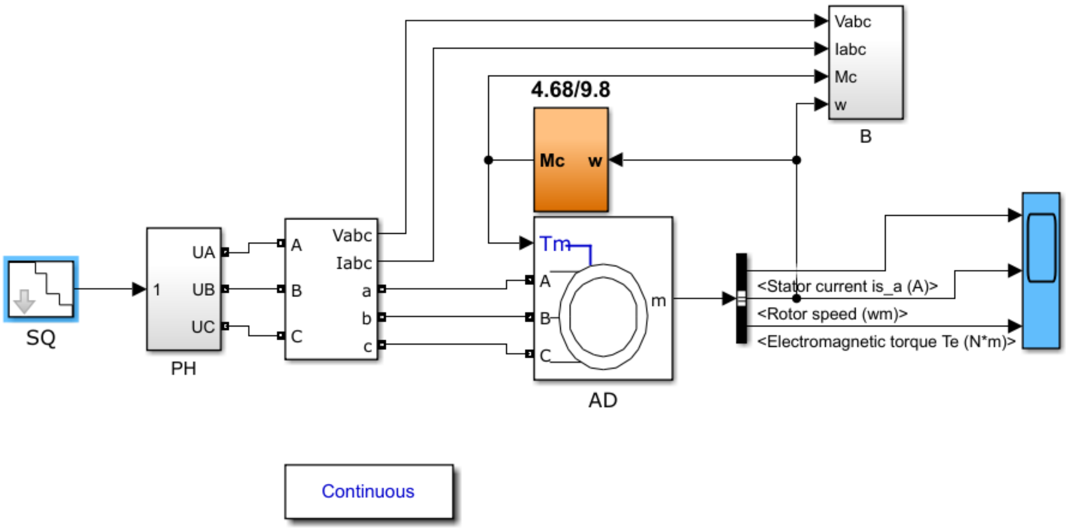


Figure 2. Block model of the process system and FC

Modern FCs are produced using microprocessor-based control system and contain transistorized power part. Such converter as a link of the control system can be represented by instantaneous element with two control channels: voltage and frequency [22]–[25]. At scalar control of such converter for the fan type loads, a nonlinear control law between voltage and frequency is chosen. Such law is chosen in the FC model shown in Figure 3.

The FC model consists of a voltage setting device, which includes two blocks of factors Kd=0.6 and Kq=0.8 determining the amplitude and initial phase of the voltage; a frequency setting device, which includes a time block and a block for setting the angular frequency of the stator field $\omega_1=2\pi f_1$; coordinate converter unit (PK) for converting rotating coordinates x and y into stationary coordinates α and β; phase converter unit (PF) for converting two-phase coordinate system α, β into three-phase A, B, C. The reference signal from the flow valve is fed to the input of the frequency setting device. Therefore, the current frequency at the PF output will be proportional to the reference signal. A multiplier unit is installed at the input of the voltage setting device, so the torque developed by the motor will correspond to the fan load. The model of process system with FC for pump SA075T is shown in Figure 4. The model contains an asynchronous motor (type 4A63B293) with the following nominal data: P_H=0.55 kW; U_H=230/400 V; I_H=3/1.5 A; n_H=2850 rev/min; η_H=0.73%; $\cos\varnothing_H$=0.98; Rs=19.066 Ohm; R_R=14.079 Ohm.

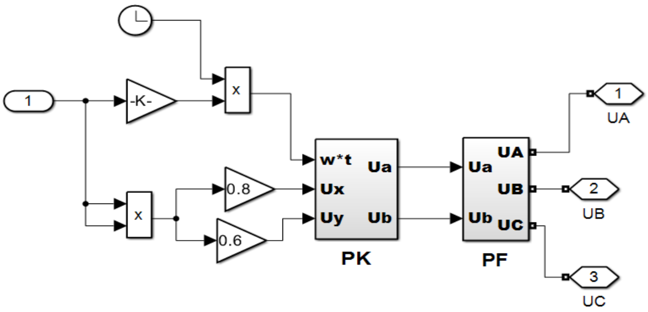


Figure 3. FC model

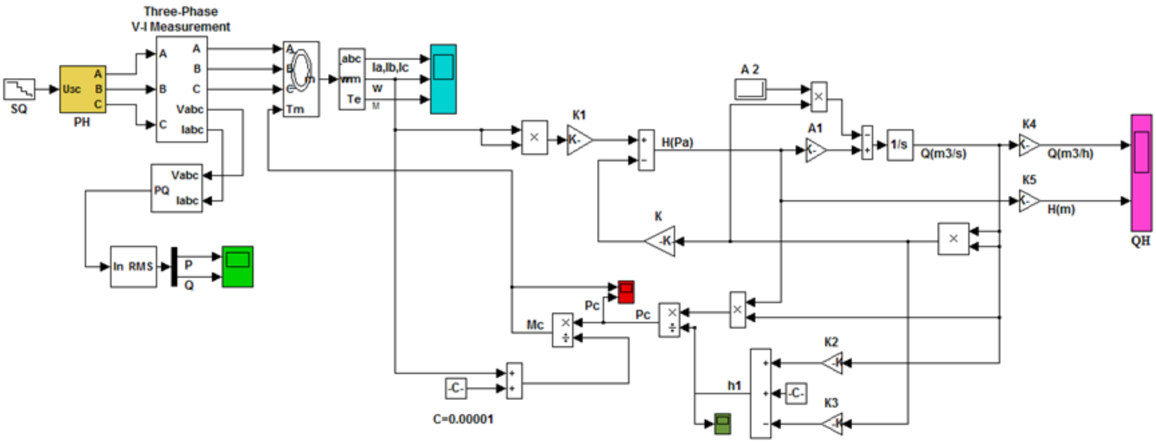


Figure 4. Model of a process system and FC

The model is build according to the block structure shown in Figure 2. The pump model is built using multiplier unit, multiplier-division blocks, adder units, transfer factor units K1...K5, constant value units A1, A2 and C, units of measuring instruments. The pump model takes into account the change in the efficiency of the mechanism during flow control. For this purpose, the factors K2 and K3 are used. The pump model at capacity control by throttling method contained an adjustable factor A2, and at frequency control this factor remains unchanged: A2=11152.574=const.

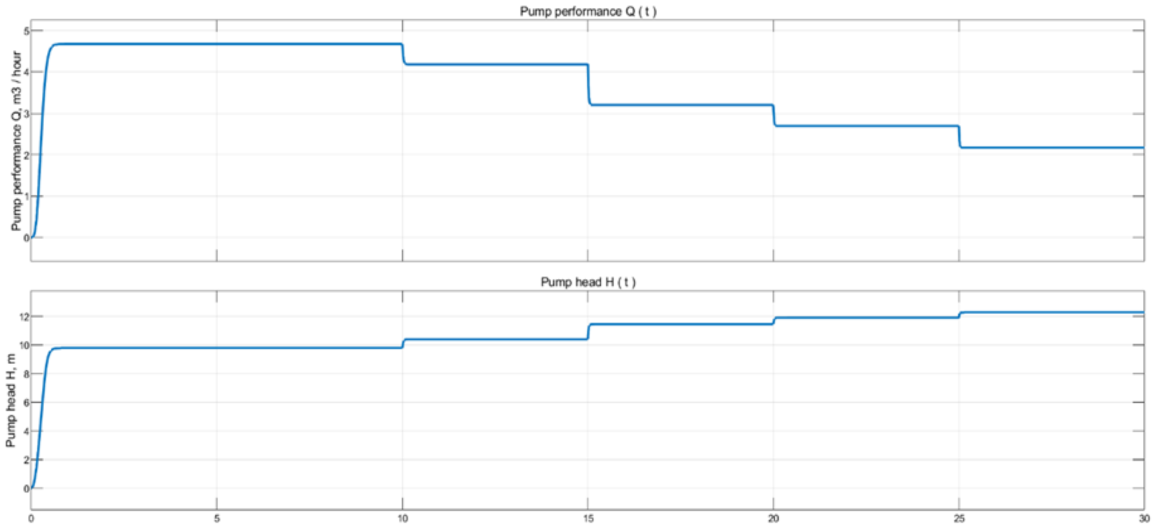
3. RESULTS AND DISCUSSION

Transients (oscillograms) for various parameters of the electric drive and pump when controlling the pump capacity by throttling method and by frequency speed control method were compared. Figure 5 shows the transients of pump head and flow rate at start-up and pump capacity control as shown in Figure 5(a) by throttling method and Figure 5(b) by frequency control. Obtained oscillograms shows that at control of the pump capacity by both methods the flow rate in a steady-state mode is identical and varies within the limits from nominal value of 4.7 m^3/h to minimum value of 2.17 m^3/h. when using throttling method for control, the pump head increases 1.26 times and when using frequency control method, the pump head decreases 4.6 time.

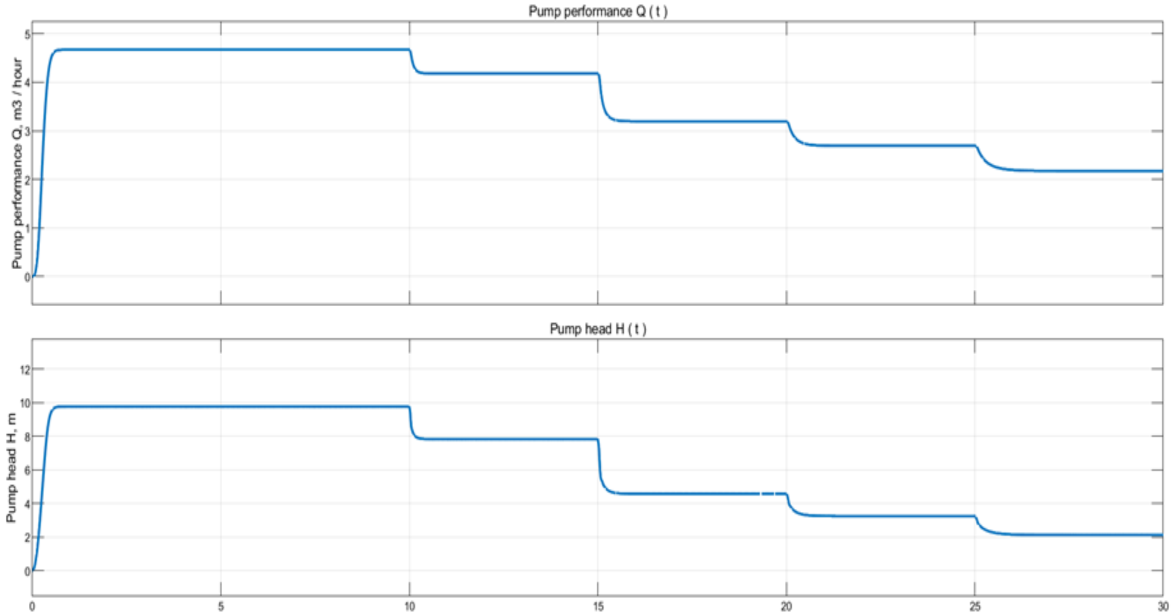
Analysis of the received oscillograms allows to determine that at control of the pump capacity by both methods the flow rate in a steady-state mode is identical and varies within the limits from nominal value of 4.7 m^3/h to minimum value of 2.17 m^3/h; however, the head varies in a different way:

– When using throttling method for control, the pump head increases 1.26 times from 9.73 m to 12.23 m;

– When using frequency control method for control, the pump head decreases 4.6 time from 9.73 m to 2.11 m.



(a)



(b)

Figure 5. Pump head and flow transient at start-up and capacity control (a) by throttling method and (b) by frequency control methods

Figure 6 shows transients on stator current, angular rotation speed and motor torques at start-up and control of the pump capacity as shown in Figure 6(a) by throttling and Figure 6(b) frequency control methods. Obtained oscillograms shows that at control of the pump capacity within the limits from nominal value of 4.7 m^3/h to minimum value of 2.17 m^3/h, the stator current and motor torque are decreased but the speed of the motor remains constant by using throttling method of control, whereas by using the frequency control method the torque and current are more decreased than by using throttling method.

Analysis of the received oscillograms allows to determine that at control of the pump capacity within the limits from nominal value of 4.7 m^3/h to minimum value of 2.17 m^3/h:

– By throttling method, the stator current of asynchronous motor decreases from 0.755 A to 0.734 A; pump speed almost does not change; asynchronous motor torque decreases from 0.732 and to 0.646 Nm;
– By frequency control method, the stator current of asynchronous motor decreases from 0.755 A to 0.43 A; asynchronous motor torque decreases 0.732 to 0.25 Nm.

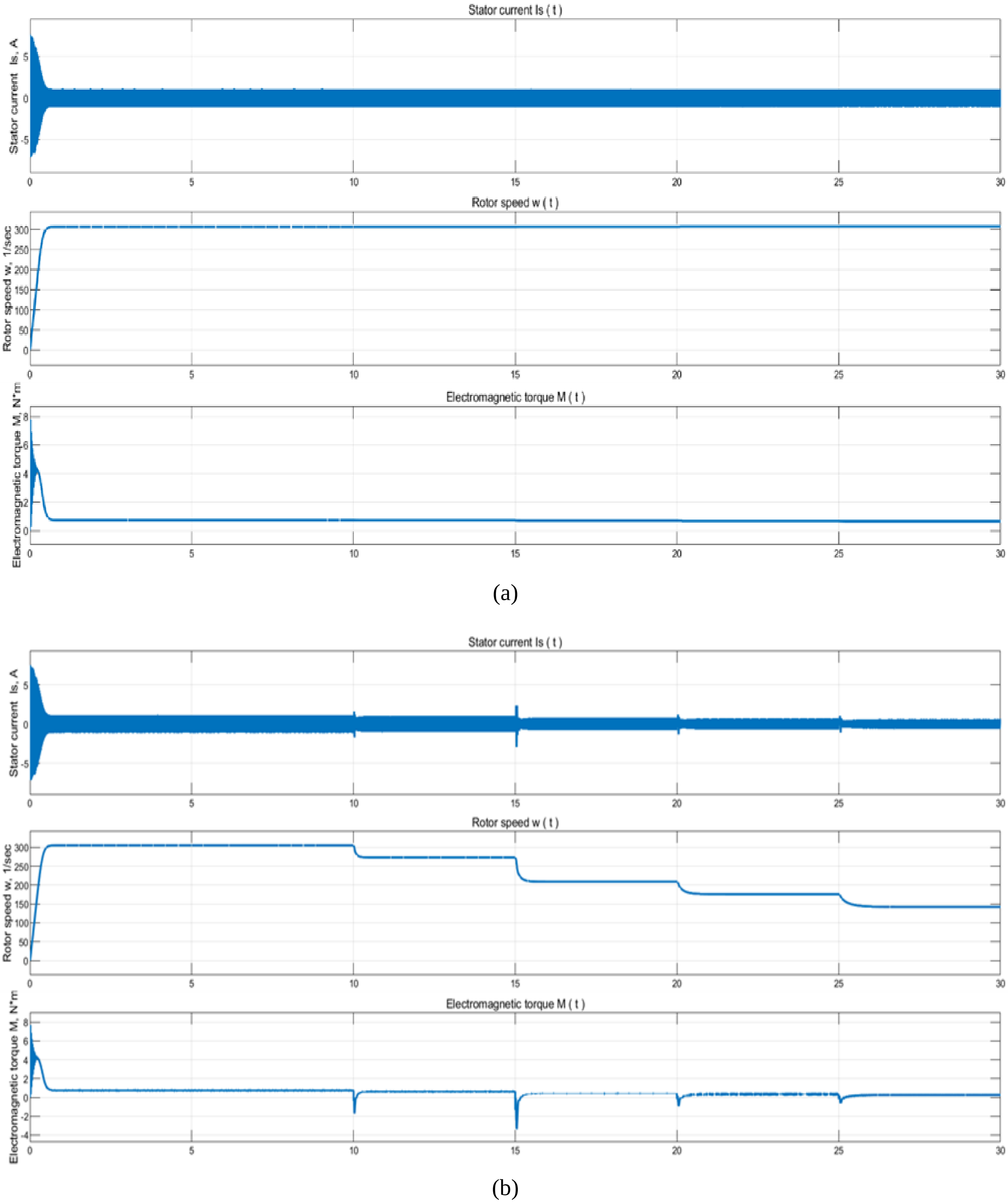
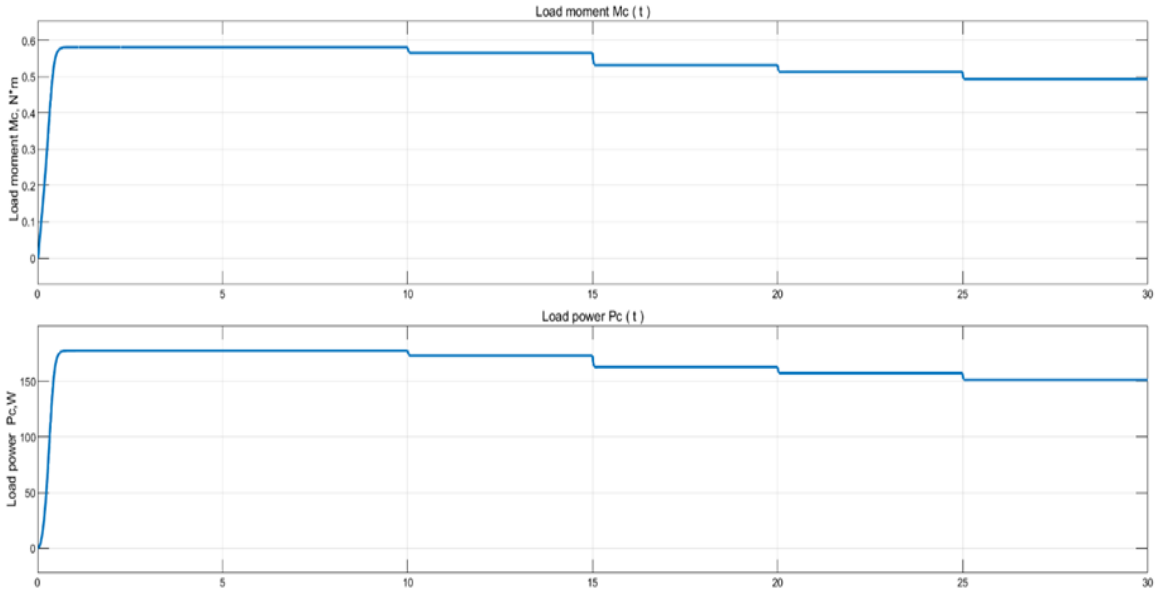


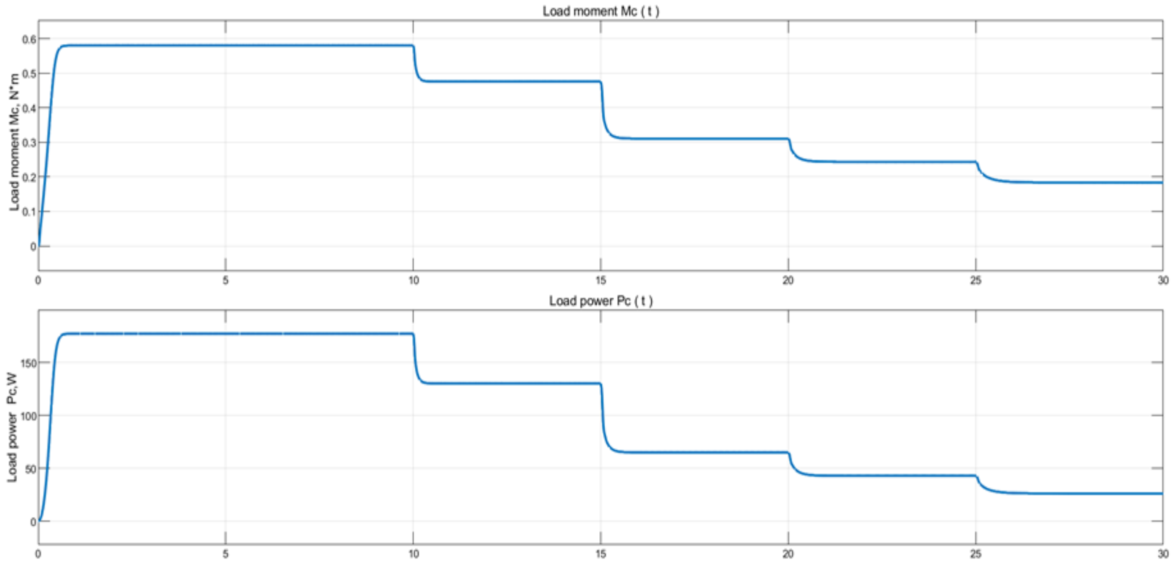
Figure 6. Transients on starter current, angular rotation frequency ω and torque of asynchronous motor M at start-up and control of the pump capacity (a) by throttling and (b) frequency control methods

Figure 7 shows the time variation of torque and power of resistance forces on the shaft of asynchronous motor start-up and pump capacity control as shown in Figure 7(a) by throttling and Figure 7(b) frequency control methods. Obtained oscillograms shows that at control of the pump capacity within the limits from nominal value of 4.7 m^3/h to minimum value of 2.17 m^3/h, the torque of resistance on the shaft of the asynchronous motor reduces, and power of resistance forces also reduces, but by using the frequency control method the torque of resistance on the shaft of the asynchronous motor reduces, and power of resistance forces are more decreased than by the using throttling method. Analysis of the received oscillograms allows to determine that at control of the pump capacity within the limits from nominal value of 4.7 m^3/h to minimum value of 2.7 m^3/h:

- By throttling method, the torque of resistance on the shaft of asynchronous motor reduces from 0.579 to 0.4925 Nm; power of resistance forces reduces from 176.7 to 150.8 J;
- By frequency control method, the torque of resistance on the shaft of asynchronous motor reduces from 0.579 to 0.1834 Nm; power of resistance forces reduces from 176.7 to 26 J.



(a)



(b)

Figure 7. Oscillograms of the torque and power of resistance forces on the shaft of asynchronous motor at start-up and control of the pump capacity (a) by throttling and (b) frequency control methods

4. CONCLUSION

Two methods for control of the performance of the process system composed of an electric drive, a pump and a pipeline were compared. The research has shown that when the pump flow rate decreases by 2.17 times: i) head increases 1.26 times when controlling by the throttling method, and 4.6 times when controlling by frequency method; ii) stator current, torque and speed of asynchronous motor at throttling almost do not change, and at frequency method they decrease: current –1.77 times, torque –2.93 times, speed –2.15 times; iii) torque and power of resistance forces on the shaft of the asynchronous motor at throttling decreases 1.17 times, and at frequency method the moment of resistance forces decreases 3.15 times, and power 6.79 times. Thus, the developed mathematical model of the process system composed of an asynchronous motor, a fluid-handling machine and pipeline allows to obtain quantitative assessment of the performance and energy parameters of the unit using two methods of pump capacity control. Deployment of the frequency method allows to reduce the pump rotation speed, and significantly decrease the power consumed by the unit and provide for energy-saving mode of operation, the economic efficiency of which depends on the range of feed control.

REFERENCES

[1] V. R. Babu, T. Maity, and G. Ramesh, “Speed control and optimum efficiency of induction motor driven ventilation fan in mines,” in *2019 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Feb. 2019, doi: 10.1109/ICECCT.2019.8869355.

[2] V. Kazakbaev, V. Prakht, V. Dmitrievskii, M. N. Ibrahim, S. Oshurbekov, and S. Sarapulov, “Efficiency analysis of low electric power drives employing induction and synchronous reluctance motors in pump applications,” *Energies*, vol. 12, no. 6, p. 1144, Mar. 2019, doi: 10.3390/en12061144.

[3] L. Gevorkov, A. Rassolkin, A. Kallaste, and T. Vaimann, “Simulink based model of electric drive for throttle valve in pumping application,” in *2018 19th International Scientific Conference on Electric Power Engineering, EPE 2018 - Proceedings*, May 2018, pp. 1–4, doi: 10.1109/EPE.2018.8395996.

[4] K. T. Tergemes, D. S. Amanbek, B. M. Maratova, and A. Zhauyt, “Control system improvement of the electric drive of the pumping unit for oil production,” *XVIII International Scientific Technical Conference Alternating Current Electric Drives (ACED)*, May 2021, doi: 10.1109/ACED50605.2021.9462275.

[5] O. A. Klokov and A. A. Pushkina, “Modernization of the electric drive and automation system of the sewage pumping station,” in *International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon)*, Oct. 2020, doi: 10.1109/FarEastCon50210.2020.9271382.

[6] C. Schmehl, M. McKinley, W. McBride, J. Kavanaugh, and R. Paes, “Adjustable speed drive selection for electric submersible pumps,” in *Record of Conference Papers-Annual Petroleum and Chemical Industry Conference*, Sep. 2014, pp. 201–216, doi: 10.1109/PCICon.2014.6961885.

[7] X. Liang, O. Ilochonwu, and R. Adedun, “Dynamic response of variable frequency drives in electrical submersible pump systems,” in *48th IEEE Industrial & Commercial Power Systems Conference*, May 2012, doi: 10.1109/ICPS.2012.6229603.

[8] S. Rachev, G. Ivanova, and D. Koeva, “Vector control of pump unit electric drive with medium voltage induction motor,” in *12th Electrical Engineering Faculty Conference (BulEF)*, Sep. 2020, doi: 10.1109/BulEF51036.2020.9326032.

[9] B. Siro, A. Savulescu, and C. Ianache, “The simulation of crude oil extraction in Canadian pumping with the DTC electric drive in a wide range of operating frequencies,” in *10th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, Jun. 2018, doi: 10.1109/ECAI.2018.8678975.

[10] I. I. Artyukhov, S. F. Stepanov, E. K. Pylskaya, and A. I. Zemtsov, “Dynamics of compressed gas temperature stabilization system with variable-frequency drive of fans in a gas air-cooling unit,” in *International Conference on Electrotechnical Complexes and Systems (ICOECS)*, Oct. 2020, doi: 10.1109/ICOECS50468.2020.9278459.

[11] D. Antipin, D. Bondarenko, and V. Vorobiev, “Study of frequency controlled drive of locomotive power plant cooling fan,” in *International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, May 2020, doi: 10.1109/ICIEAM48468.2020.9111936.

[12] S. Bambiso and K. Kusakana, “Life cycle cost comparison between motors equipped with variable speed drives and dampers for pumps and fans,” in *2018 IEEE PES/IAS PowerAfrica, PowerAfrica 2018*, Jun. 2018, pp. 931–936, doi: 10.1109/PowerAfrica.2018.8521165.

[13] Q. Zhang, G. Lu, Y. Xu, and C. Zhang, “Torsional vibration analysis of shaft in an induced draft fan due to variable frequency drive,” *IEEE Access*, vol. 8, pp. 174723–174735, 2020, doi: 10.1109/ACCESS.2020.3026325.

[14] I. I. Artyukhov, S. F. Stepanov, E. E. Mirgorodskaya, N. P. Mityashin, and A. I. Zemtsov, “Transient processes with starting of a multi-pole asynchronous motor with a fan on the shaft,” in *17th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Jul. 2021, doi: 10.1109/ELMA52514.2021.9503069.

[15] P. Tomov, B. Aprahamyan, K. Petrov, P. Andreev, and P. Petkov, “Experimental survey and analysis on the impact of the commutation process on a positive displacement pump driven by an asynchronous electric motor,” in *16th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Jun. 2019, doi: 10.1109/ELMA.2019.8771523.

[16] A. Savulescu, B. Siro, C. Ianache, and L. Georgescu, “Simulation of the electric drive of a beam pumping unit and its comparative analysis for different operating frequencies,” in *6th International Symposium on Electrical and Electronics Engineering (ISEEE)*, Oct. 2019, doi: 10.1109/ISEEE48094.2019.9136112.

[17] P. H. Wang and T. Y. Wen, “Effects of electrical driving mode on pressure and flow rate of wire-rod electrohydrodynamic pumps,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 10, no. 4, pp. 621–625, Apr. 2020, doi: 10.1109/TCPMT.2020.2978305.

[18] G. G. Goppe and V. E. Pavlov, “Dynamic process mathematical models for a technological complex “electric drive-turbo-mechanism-Pipeline" when controlling its performance by changing electric drive rotation speed,” *News of IrGTU*, vol. 1, no. 72, pp. 121–125, 2013.

[19] G. G. Goppe and V. E. Pavlov, "Studying conditions of process plant electric drive self-starting under disturbances in electrical networks," *News of IrGTU*, vol. 12, no. 83, pp. 252–257, 2013.
[20] V. E. Pavlov and I. G. Peregudova, "Study of conditions for group self- starting electric drives of turbo mechanisms," in *Proceedings - 2019 International Ural Conference on Electrical Power Engineering, UralCon 2019*, Oct. 2019, pp. 404–409, doi: 10.1109/URALCON.2019.8877660.
[21] A. Y. Al-Rawashdeh, "Losses reduction of induction motors operating below the nominal load," *International Journal of Electrical and Computer Sciences IJECS-IJENS*, vol. 2, no. 04, pp. 1–5, 2017.
[22] O. Albarbarawi, A. Al-Rawashdeh, and G. Qaryouti, "Simulink modelling of the transient cases of three phase induction motors," *International Journal of Electrical and Computer Sciences*, vol. 17, no. 4, pp. 6–15, 2017.
[23] A. Y. Al-Rawashdeh, "Investigation of an induction wound rotor motor to work as a synchronous generator," *Engineering, Technology and Applied Science Research*, vol. 9, no. 2, pp. 4071–4074, Apr. 2019, doi: 10.48084/etasr.2606.
[24] I. G. Odnokopylov, Y. N. Dementev, I. V. Usachev, D. Y. Lyapunov, and A. S. Petrusev, "Load balancing of two-motor asynchronous electric drive," in *International Siberian Conference on Control and Communications (SIBCON)*, May 2015, doi: 10.1109/SIBCON.2015.7147249.
[25] P. F. Le Roux and M. K. Ngwenyama, "Static and dynamic simulation of an induction motor using MATLAB/Simulink," *Energies*, vol. 15, no. 10, p. 3564, May 2022, doi: 10.3390/en15103564.

BIOGRAPHIES OF AUTHORS

Ayman Y. Al-Rawashdeh Mechatronics Engineering was born on 01 January 1970 in Jordan. He obtained his Diploma degree in 1995 and Ph.D. degree in 2008 in the field of Mechatronics Engineering. Currently, he is an Associate Professor at the Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Jordan. His main research interests include renewable energy, drive system analysis, and simulations. He can be contacted at email: dr.ayman.rawashdeh@bau.edu.jo.

Vlademer E. Pavlov is as Associate Professor in the Department of Mechatronics Engineering, Irkutsk National Research Technical University, Russia. He was born on 1952. His main research interests include power converter technology, expert systems for setting up electrical equipment, automation and process control. He has published more than 140 journal papers in the fields of electric drives and its applications. He can be contacted at email: pvew52@mail.ru.

Khalaf Y. Al Zyoud High Voltage Engineering and Transformers. He graduated in 1998 from Technical University of Lodz-Poland. He is currently an Associate Professor at the Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Jordan. His main researches interests include power transformers and high voltage engineering and their Diagnoses. He can be contacted at email: kalaf.zyoud@bau.edu.jo.

Mohammad S. Khrisat associate professor in Faculty of Engineering Technology Balqa applied University Amman Jordan received the Ph.D. in the mechatronics engineering from People Friendship University of Russia in 2017 and get the master's degree in computer engineering from NYIT and B.Sc. in Electronic Engineering from Yarmouk University Irbid Jordan. He can be contacted at email: mkhrisat@bau.edu.jo.