Modeling of an induction motor centrifugal-pump system under variable speed conditions

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Abstract. This study examines the creation and analysis of a virtual model for a water supply system consisting of a centrifugal pump with an asynchronous electric drive. The model was implemented in the Matlab/Simulink/Simscape environment. It is structured through three interconnected subsystems, built using appropriately selected functional blocks. Parameters whose values were determined using a genetic algorithm were used to configure the induction motor block, while catalog data was used for the pump. Simulation studies were conducted at the rated rotational frequency, as well as under three different operating modes. Analysis of the results shows that the flow rate values correspond to the theoretical relationships determined by the similarity equations. This confirms the applicability of the developed virtual model.

1 Introduction

The MATLAB software environment is used for simulation modeling and research of electrical and electromechanical systems. The simulation models in this environment replicate the structure of real-world objects, are developed using standard Simulink/Simscape blocks, and essentially represent virtual laboratory test benches. They allow experiments to be conducted in the same way as with the actual test objects. The blocks in these libraries can be used to simulate the operation of a centrifugal pump driven by an induction motor. A significant challenge in configuring the models is determining the necessary parameters for the various types of electric machines, as information on them is lacking in the reference literature. Many research projects focus on controlling the speed of an induction motor [1 - 4]. To model the drive of a centrifugal pump by an induction motor, it is necessary to have data on the variation of the head and the power consumption of the pump as a function of its flow rate at a specific shaft rotation frequency. The dynamic simulation of the "induction motor–centrifugal pump" system at variable rotational speeds is presented in [5, 6]. A study aimed at optimizing energy consumption in systems for maintaining constant pressure using variable-speed electric pumps has been conducted [7].

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Many studies have addressed the issue of flow control in centrifugal pumps, as well as comparative analyses of combined pressure and flow control systems aimed at optimizing the operation of pumping systems in water supply networks, as well as improving the efficiency of water supply.

The aim of this article is to develop a virtual model of a centrifugal pump with an asynchronous electric drive in the MATLAB/Simulink/Simscape environment and to investigate the system's operation at different rotational frequencies.

2 Mathematical models

On Figure 1 is shown a model in the Matlab/Simulink/Simscape environment for the analysis of a centrifugal pump driven by an induction motor. The model consists of three subsystems constructed using appropriately selected and configured blocks from the Matlab/Simulink/Simscape environment.

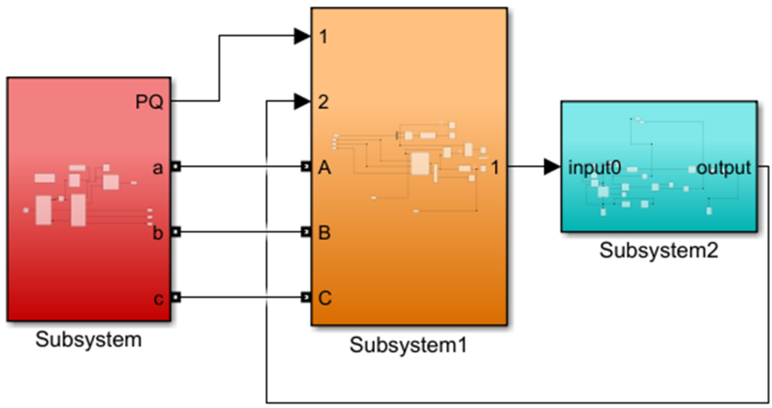


Fig.1. Subsystems of the virtual model for studying a centrifugal pump.

The mathematical model of the IM is described by the following system of differential equations, formulated based on the theory of the generalized two-phase machine [1].

$$U_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega\psi_{sq} \tag{1}$$

$$U_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega\psi_{sd} \tag{2}$$

$$U'_{rd} = R'_r i'_{rd} + \frac{d\psi'_{rd}}{dt} - (\omega - \omega_r)\psi'_{rq} \tag{3}$$

$$U'_{rq} = R'_r i'_{rq} + \frac{d\psi'_{rq}}{dt} + (\omega - \omega_r)\psi'_{rd} \tag{4}$$

The equation for the electromagnetic moment:

$$T_e = 1{,}5p\left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right) \tag{5}$$

and

$$J\frac{d\omega}{dt} = T_e - T_m \tag{6}$$

In the above equations are used the following designations: Rs, R_r' - active resistance of the stator and reduced rotor winding; U_{sd}, i_{sd}, U_{rd}', i_{rd}' and U_{sq}, i_{sq}, U_{rq}', i_{rq}' - the projections of the stator and rotor voltage and current on the axes **d** и **q**; ψ_{sd}, ψ_{sq}, ψ_{rd}', ψ_{rq}'- the projections of the stator and rotor flux linkages on the axes **d** and **q**; ω and ω_r - synchronous and angular speed of the rotor; p - number of pole pairs; J – inertia moment; T_m – the applied to the rotor shaft resistance moment.

The relationship between a pump's head and its flow rate is described by the equation [6]:

$$H = a_3.Q_i^2 + a_2.Q_i + a_1 \tag{7}$$

where a_1, a_2, and a_3 are coefficients.

If the pump's rotational speed (n) differs from the rated speed, the following equation [6] can be used:

$$H = A_1.n^2 + A_2.Q.n + A_3.Q^2; \tag{8}$$

the new coefficients are: $A_1 = \frac{a_1}{n_r^2}$; $A_2 = \frac{a_2}{n_r}$; $A_2 = a_3$.

When determining the constants in Equation (8), the type of pumps used in the water supply system and their operating characteristics are taken into account. The values of the constants are calculated for changes in head near the pump's optimal operating point.

3 Structure of the virtual model for investigate a centrifugal pump

Figure 2 shows the structure of the Subsystem block from Figure 1. The virtual IM is powered by a Three-Phase Programmable Voltage Source. An RMS block has been added to obtain the effective value of the consumed current. The three-phase voltage and current are measured using a Three-Phase V-I Measurement block, and the consumed power is measured using a 3-phase Instantaneous Active & Reactive Power meter.

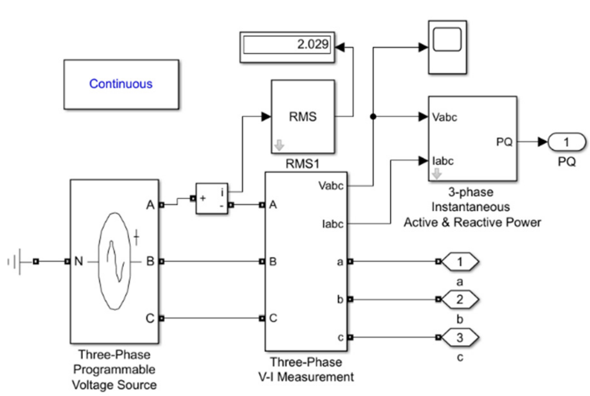


Fig.2. Subsystem Structure.

An induction motor with the following specifications was used in the study: rated power Pr=1.1kW rated voltage Ur=220/380V; rated current Ir=4.4/2.5A; cosφ=0.85; Δ/Y stator winding connection diagram, rated rotational speed n = 2830min^{-1}.

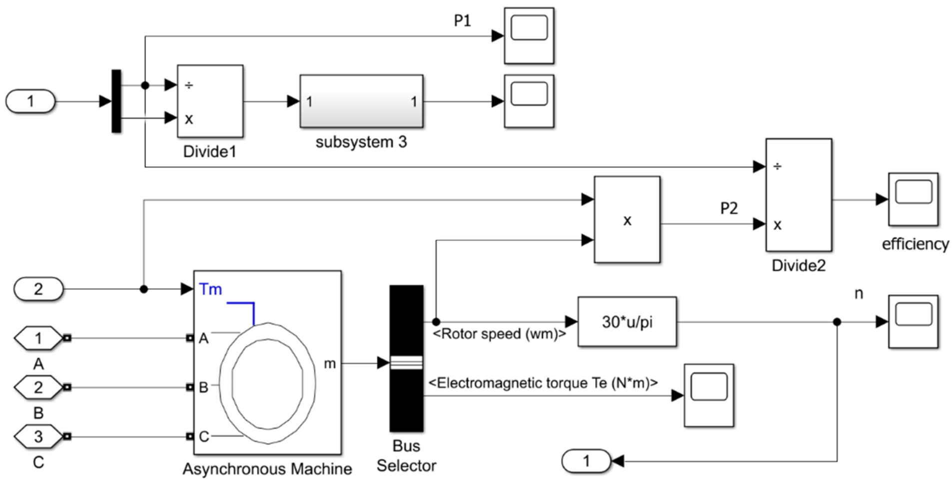


Fig.2. Structure of subsystem 1.

To configure the virtual model of the induction motor shown in Figure 2, the following values must be known: the active and reactive resistances of the stator winding – R_1, X_1 of the shunt winding - R_2', X_2' and the inductive reactance X_μ of the demagnetizing circuit of the actual IM. These were determined using a genetic algorithm. The resulting values are presented in Table 1.

Table 1. IM Parameters.

R_1, Ω	R_2', Ω	X_1, Ω	X_2', Ω	X_μ, Ω
6.07	5.69	5.95	5.95	152.13

To measure the state variables of the induction motor - angular velocity and electromagnetic torque, a Bus Selector block is added. Blocks have been added to the developed model to visualize data for: active power P1 and power factor cosφ, apparent power P2, motor efficiency, electromagnetic torque T_e, and rotational frequency of the asynchronous motor (n). The values of P1 and Q, obtained at the output of the 3-phase Instantaneous Active & Reactive Power block, are fed to the input of the Divide1 block. To calculate, according to Equation (7), two Trigonometric Function blocks are used. The calculations are performed in subsystem 3. The power factor is determined by the expression:

$$\cos\varphi = \cos\left(\operatorname{arctg}\left(\frac{Q}{P}\right)\right) \tag{9}$$

The structure of subsystem 2 is shown in Figure 3. A centrifugal pump with a rated power of Pr=1.1 kW head H=67 m and flow rate Q=2m^3/hr.

The following components were used to build the model: Centrifugal Pump – a centrifugal pump; Ideal Torque Sensor – converts a variable passing through the sensor into a control signal proportional to the torque; Solver Configuration – defines the parameters of the virtual model before starting the simulation; PS-Simulink Converter – converts a physical signal into a Simulink output signal; Hydraulic Fluid – specifies the type of hydraulic fluid used in a circuit consisting of hydraulic blocks, flow and pressure sensors, flow resistance, and water tanks.

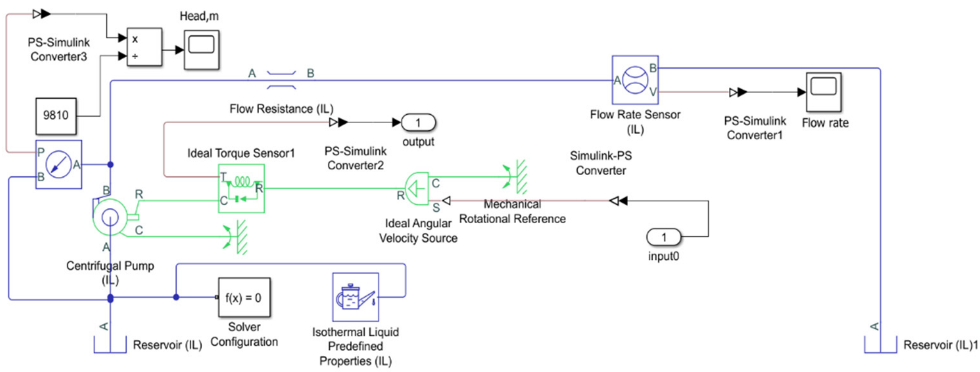


Fig.3. Structure of subsystem 2.

When sizing a centrifugal pump, it is necessary to know how the head and power consumption vary with the pump flow rate at the rated rotational speed. This data can be obtained experimentally or, as in this study, from the pump catalogue. Data on the pump's flow rate and head at frequencies other than the rated frequency are obtained using similarity equations:

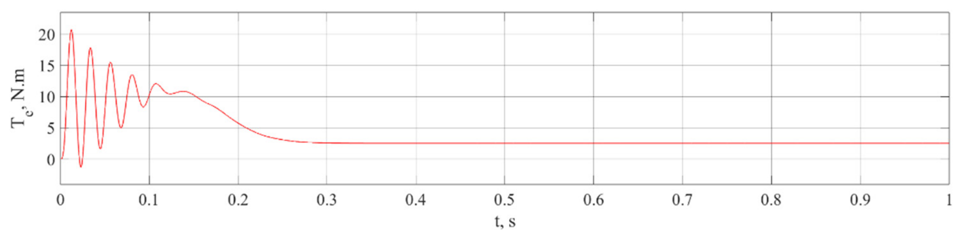
$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \tag{10}$$

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \tag{11}$$

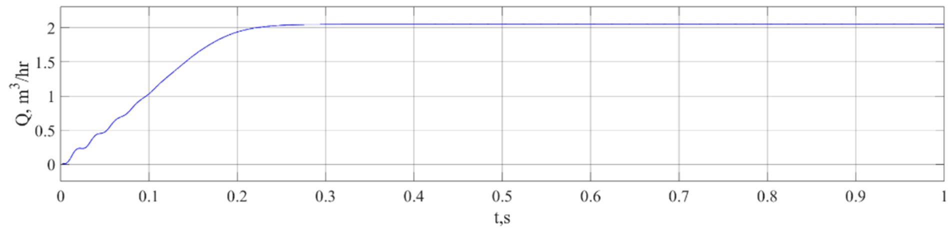
$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \tag{12}$$

4 Simulation results

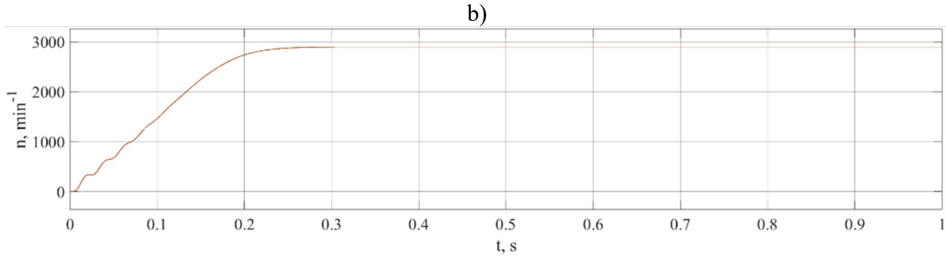
Figure 4 shows the change in the electromagnetic torque when the resistance torque is T_m=2.53 N.m, as well as the rotational speed of the motor shaft. In the simulation shown here, the pump flow rate is Q=2m^3/hr and the head is H=67m.



a)



b)



c)

Fig.4. Electromagnetic torque T_e (a), flow rate Q (b), and rotational speed n (c).

The results shown in Figure 5 are from tests of the centrifugal pump at rotational speeds of n=2348 min^{-1}; 2000 min^{-1};1481 min^{-1}. The resulting relationships show the influence of rotational speed on the dynamic characteristics of the electric drive and the hydraulic system.

Fig. 5a shows that, upon startup of the pump unit, the electromagnetic torque exhibits a pronounced transient process characterized by an initial overshoot above the set value. The maximum torque value is reached at the very start of operation, which is due to the need to overcome the inertial forces of the rotating parts and the increasing hydraulic load. After the transient process subsides, approximately at t = 0.2 s, the electromagnetic torque reaches a practically constant value corresponding to the steady-state operating mode. At higher rotational speeds, an increase in the required torque is observed, which is associated with increased hydraulic losses and the greater power required to maintain a higher flow rate.

Fig. 5b shows the transient flow rate characteristics of the pump at different rotational speeds. It can be observed that an increase in rotational speed leads to an increase in the steady-state flow rate. At the highest speed, the maximum flow rate of approximately Q = 1.65 m^3/h, while at lower speeds the flow rate decreases accordingly to about Q = 1.4 m^3/h and Q=1.05 m^3/h. This confirms the relationship between rotational speed and the performance of the centrifugal pump, in accordance with the laws of similarity for pumping machines.

The transient processes under the various operating modes show a rapid attainment of steady-state values, with a settling time of approximately 0.2 s. The absence of significant fluctuations after this point indicates stable operation of the control system and good dynamic compatibility between the electric motor and the pump unit.

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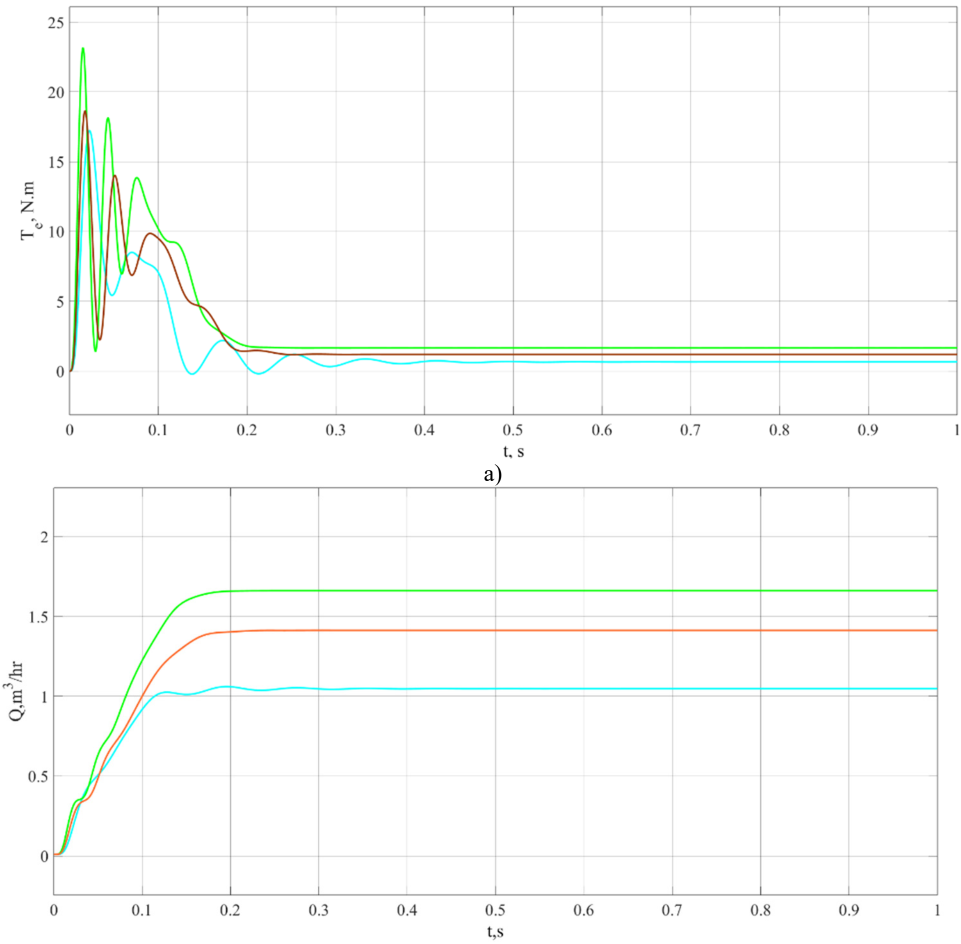

Fig.5. Electromagnetic torque T_e (a) and flow rate Q (b) at different rotational speeds n.

The results confirm that rotational speed control is an effective method for regulating the flow rate in water supply systems, allowing the pump's operating point to be adapted to the system's changing demands.

5 Conclusion

This paper presents a virtual model developed in the Matlab/Simulink/Simscape environment for the analysis of a centrifugal pump driven by an induction motor. Three subsystems describing the operation of the model's components are structured using appropriately selected blocks. The operation of the virtual model is simulated at the pump's rated rotational speed and at three frequencies different from it. The flow rates obtained in these studies are identical to those obtained using similarity equations, which confirms the model's validity. This model can also be used to study various electric motor-driven pumps in practice, provided their parameters are known.

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