Volumetric Flow Observer For A Pumping Unit Without Backpressure With Induction Electric Drive

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Abstract. The article describes the construction of a volumetric fluid supply observer in pumping systems. The electric drive of the pump unit uses an induction motor with a squirrel-cage rotor. The rotation speed of the electric motor is adjustable. A centrifugal pump is used to pressurize a pipeline. Requirements for the automation level of pumping units are growing, so the research topic is relevant. When constructing the observer, the double squirrel cage induction motor model in a fixed coordinate system is used. The impeller rotation speed and the pump resistance moment were estimated based on the Luenberger observer. The observer is used to identify the volume flow. It is based on a centrifugal pump model using approximating coefficients of a Second-Degree Polynomial function. The article provides the dynamic characteristics of the reference model and observer. As a studies result, an error in the steady state operating mode of 1\% was determined.

1. Introduction
The adjustable electric drive of centrifugal pumping units is widely used in industry, production, transportation of liquids \cite{1-3} and medicine \cite{4}. To increase the automation of fluid pumping processes, measurement and determination of a large number pumping unit parameters is required \cite{5}. An important parameter is the instantaneous volumetric flow rate or pumped liquid flow. Direct flow measurement is not always possible for technical, economic and structural reasons. In direct volumetric flow rate measurement of a pumping unit, the following main methods are used:
- Ultrasonic method - the difference measuring in the ultrasonic waves velocity in a moving fluid stream;
- Electromagnetic method - use of the Faraday's law of induction for conductive liquids. EMF in a fluid is directly proportional to the fluid velocity;
- Vortex method - measuring the flow velocity by the turbulence frequency in the fluid flow;
- Mass method - measuring the substance mass that is proportional to the pumping unit volumetric flow.

This article discusses an indirect method for determining the liquid volumetric flow rate in a pumping unit with an induction electric drive. It is determined without backpressure by direct measurement of current and voltage. These values are also measured in frequency-controlled electric drives. They are needed to control power converters in transient and steady-state modes \cite{6,7}.

2. Mathematical description
A centrifugal pump with an induction electric drive is an object with several physical subsystems: electrical, mechanical and hydraulic.
The electrical subsystem is a squirrel-cage induction electric motor. It receives power from a three-phase AC voltage source. A double squirrel cage induction electric motor in a fixed coordinate system can be described by the following system (1):

\[
\begin{align*}
    u_{a1} &= R_1 i_{a1} + k_0 \frac{d i_{a1}}{dt} + k_2 \frac{d \psi_{R1a}}{dt} + k_3 \frac{d \psi_{R2a}}{dt} \\
    u_{a2} &= R_1 i_{a2} + k_0 \frac{d i_{a2}}{dt} + k_2 \frac{d \psi_{R1b}}{dt} + k_3 \frac{d \psi_{R2b}}{dt} \\
    0 &= -k_2 R_1 \frac{d i_{a1}}{dt} + \frac{1}{T} \psi_{R1a} - \frac{R_1 L_m}{\sigma} \psi_{R2a} + p_1 \omega_m \psi_{R1b} \\
    0 &= -k_2 R_1 \frac{d i_{a2}}{dt} + \frac{1}{T} \psi_{R1b} + \frac{R_1 L_m}{\sigma} \psi_{R2b} - p_1 \omega_m \psi_{R1a} \\
    0 &= -k_2 R_1 \frac{d i_{a1}}{dt} + \frac{1}{T} \psi_{R2a} - \frac{R_1 L_m}{\sigma} \psi_{R2a} + p_1 \omega_m \psi_{R2b} \\
    0 &= -k_2 R_1 \frac{d i_{a2}}{dt} + \frac{1}{T} \psi_{R2b} - \frac{R_1 L_m}{\sigma} \psi_{R2a} - p_1 \omega_m \psi_{R2a} \\
    M &= \frac{3}{2} p_1 k_2 (\psi_{R1a} i_{a2} + \psi_{R1b} i_{a1} - \psi_{R2a} i_{a1}) + \frac{3}{2} p_1 k_2 (\psi_{R2a} i_{a2} - \psi_{R2b} i_{a1}) \\
    \frac{d \omega_m}{dt} &= -\frac{M - T_1}{J}
\end{align*}
\]

where \( u_{a1}, u_{a2}, i_{a1}, i_{a2}, \psi_{R1a}, \psi_{R1b}, \psi_{R2a}, \psi_{R2b} \) are the spatial components of the voltage, current and rotor flux linkage vector.

\( \omega_m \) – is the rotor angular velocity;

\( M \) – is the centrifugal pump load torque.

The mechanical subsystem connects the coordinates of the hydraulic and electrical subsystems with each other.

The hydraulic subsystem consists of a pressure-generating pump and a pipeline connected to the discharge pipe. The pump runs on a hydraulic system without back pressure. The centrifugal pump pressure in the hydraulic subsystem can be determined as (2):

\[
\begin{align*}
    h &= \frac{\rho g \omega_m}{\omega} \left[ \left( C_0 - C_2 q \left( \frac{\omega_m}{\omega} \right) \right) - C_1 \left( q \left( \frac{\omega_m}{\omega} \right) \right)^2 \right] \\
    T_1 &= \frac{h q_3}{\omega} + T_0
\end{align*}
\]

where \( h \) is the pump instantaneous head pressure value (m);

\( \rho \) is the fluid density (kg / m³);

\( q \) is the instantaneous pump flow rate (m³ / s);

\( \omega \) is the pump impeller angular velocity (rad / s);

\( C_0, C_1, C_2, C_3 \) – approximation coefficients of a Second-Degree Polynomial function.

A simulation model of the hydraulic and mechanical subsystem is presented in Figure 1.
Equation (2) can be rewritten with respect to the volumetric flow rate of the liquid. An aperiodic link with a time constant $T_q$ (as an interference filter) is added to it. The result is the following expression (3)

$$\dot{q}_l = \frac{1}{T_q p + 1} \left[ \frac{\omega_m}{\dot{\omega}_m} \right]^2 \left( C_0 - C_1 \dot{q}_l + \frac{\omega_m}{\dot{\omega}_m} \right) - C_3 \left( \dot{q}_l + \frac{\omega_m}{\dot{\omega}_m} \right) - C_2 \left( q_{nom} - \dot{q}_l + \frac{\omega_m}{\dot{\omega}_m} \right)^2$$

where $\dot{N}_{hyd}$ is the pump hydraulic power (4).

$$\dot{N}_{hyd} = \dot{\omega}_m (\dot{T}_L - T_0)$$

$\dot{\omega}_m$, $\dot{T}_L$ - estimated values of the pump load torque and rotor speed (pump impeller).

A simulation model that implements equations (3,4) is presented in Figure 2.
To determine the pump load torque and rotor speed, the Luenberger observer [8-10] is applied to the mathematical description of the induction motor (1). The controlled parameters in system (1) are the induction machine stator current and voltage. The rotation speed in operator form is estimated in equation (5):

$$
\begin{align*}
R_s \left( \frac{k_5}{R_s} p + 1 \right) i_{5\alpha} &= u_{5\alpha} - k_{R_1} p \dot{\psi}_{R1\alpha} - k_{R_1} p \dot{\psi}_{R2\alpha} + k_L \Delta i_{5\alpha} \\
R_s \left( \frac{k_5}{R_s} p + 1 \right) i_{5\beta} &= u_{5\beta} - k_{R_1} p \dot{\psi}_{R1\beta} - k_{R_1} p \dot{\psi}_{R2\beta} + k_L \Delta i_{5\beta} \\
\frac{1}{T_{R_1}} \left( T_{R_1} p + 1 \right) \dot{\psi}_{R1\alpha} &= k_{R_1} R_{i\alpha} i_{5\alpha} + \frac{R_{i\alpha} L_m}{\sigma} \dot{\psi}_{R2\alpha} - p R_i \dot{\omega}_m \dot{\psi}_{R1\beta} \\
\frac{1}{T_{R_1}} \left( T_{R_1} p + 1 \right) \dot{\psi}_{R1\beta} &= k_{R_1} R_{i\beta} i_{5\beta} + \frac{R_{i\beta} L_m}{\sigma} \dot{\psi}_{R2\beta} + p R_i \dot{\omega}_m \dot{\psi}_{R1\alpha} \\
\frac{1}{T_{R_2}} \left( T_{R_2} p + 1 \right) \dot{\psi}_{R2\alpha} &= k_{R_2} R_{i\alpha} i_{5\alpha} + \frac{R_{i\alpha} L_m}{\sigma} \dot{\psi}_{R1\alpha} - p R_i \dot{\omega}_m \dot{\psi}_{R2\beta} \\
\frac{1}{T_{R_2}} \left( T_{R_2} p + 1 \right) \dot{\psi}_{R2\beta} &= k_{R_2} R_{i\beta} i_{5\beta} + \frac{R_{i\beta} L_m}{\sigma} \dot{\psi}_{R1\beta} + p R_i \dot{\omega}_m \dot{\psi}_{R2\alpha}
\end{align*}
$$

where $\dot{\omega}_m$ is the angular velocity estimate

$i_{5\alpha}, i_{5\beta}, \dot{\psi}_{R1\alpha}, \dot{\psi}_{R1\beta}, \dot{\psi}_{R2\alpha}, \dot{\psi}_{R2\beta}$ are the estimates of the spatial stator current vectors projections and rotor flux linkages;

$\Delta i_{5\alpha} = i_{5\alpha} - \hat{i}_{5\alpha}, \Delta i_{5\beta} = i_{5\beta} - \hat{i}_{5\beta}$ are the stator current residuals;

$k_L$ is the gain of residual current.

The load torque observer is the algebraic sum of the proportional and integral residual current products components and the rotor flux linkage corresponding components (6).
\[ \dot{M} = \frac{3}{2} p_r k_r \left( \dot{\psi}_{R1} \dot{i}_{SB} - \dot{\psi}_{R1} i_{SU} \right) + \frac{3}{2} p_r k_1 \left( \dot{\psi}_{R2} \dot{i}_{SB} - \dot{\psi}_{R2} i_{SU} \right) + \frac{3}{2} p_r k_r \left( \dot{\psi}_{R1} \dot{i}_{SB} - \dot{\psi}_{R2} \dot{i}_{SU} \right) \]
\[ T_{LP} = k_{TLP} \left[ k_r \left( \dot{\psi}_{R1} \Delta \dot{i}_{SB} - \dot{\psi}_{R1} \Delta i_{SU} \right) + k_1 \left( \dot{\psi}_{R2} \Delta \dot{i}_{SB} - \dot{\psi}_{R2} \Delta i_{SU} \right) \right] \]
\[ T_{LI} = \frac{k_{TLI}}{p} \left[ k_r \left( \dot{\psi}_{R1} \Delta \dot{i}_{SB} - \dot{\psi}_{R1} \Delta i_{SU} \right) + k_1 \left( \dot{\psi}_{R2} \Delta \dot{i}_{SB} - \dot{\psi}_{R2} \Delta i_{SU} \right) \right] \]
\[ \dot{\hat{T}}_L = \frac{3}{2} p_r \left( T_{LP} + T_{LI} + T_{LD} \right) \]
\[ \hat{T}_{PL} = \frac{1}{T_{PL} p + 1} \dot{\hat{T}}_L \]
\[ \dot{\phi}_m = \frac{M - \dot{\hat{T}}_L}{J_p} \]

A simulation model that implements equations (1, 5, 6) is presented in Figure 3.

**Figure 3.** An electromechanical subsystem simulation model of the flow observer.

### 3. Mathematical modelling of the flow observer

To study the observer operating modes in the MatLab / Simulink environment, simulation models were used (Figure 1-3). As an pumping unit example (reference model), a pump with a rated power of 1500 W and a rated flow of 8 m³/h was used. The mathematical description of the models corresponds to systems of differential equations (1-6).

The operation of the observer and the dynamic system was investigated. The voltage frequency and system hydraulic conductivity were variable parameters. Time plots of the voltage frequency and hydraulic conductivity are shown in Figure 4.
Figure 4. Time plots of the voltage frequency and hydraulic conductivity.

Figure 5. Time plot of stator current.

Figure 6. Time plot of the rotor flux linkage.
Figure 7. Time plot of the electromagnetic moment.

Figure 8. Time plot of the induction motor rotor speed.

Figure 9. Time plots of the pump load torque.
4. Conclusion

Analysis of the data presented in Figure 5-10 showed that the proposed volume flow observer is stable in dynamic operating modes. The current curve (Figure 5) shows strong dynamic fluctuations with an external disturbance. The obtained values of the rotor flux linkage and electromagnetic torque practically do not differ from the corresponding values of the induction motor model (Figure 6.7). The rotor angular velocity determined using the observer is slightly different from the reference (Figure 8). The maximum relative error of the resistance torque is in the dynamic mode, 37.2%, in the static mode 0.016% (Figure 9). The error of the volume flow observer in dynamic mode is 125.3%, in steady state 1% (Figure 10). There are some features when regulators are used in a real drive control system. So, for example, disturbing influences are usually less than were simulated. This will positively affect the accuracy of the observer. This issue requires separate studies.

5. References

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