Achievement of maximum energy efficiency through vector control of induction motor electric drive

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Abstract. Electric motors are the predominant driving devices globally, consuming electricity. For this reason, research aimed at minimizing their energy consumption is very relevant. The paper concerns an applied energy-saving method - vector control of an induction motor. With regard to this, a necessary condition for achieving maximum efficiency is to choose the optimal value of the magnetizing current. If the magnetizing current is not controlled properly, the result may be higher electricity consumption from a frequency-controlled motor than that of a direct-on-line power supply. In this case, a specific electric drive with certain parameters is analyzed. The research is based on a mathematical model, representing a system of differential equations, which is transformed and solved by appropriate software. The aim is to look for a minimum of electrical power losses. The physical side of the topic is treated exclusively without analyzing the economic benefits of the introduction of energy saving measures.

1. Introduction

Electrical machines come in a vast range of sizes and types. Their torque available on the shaft varies from mNm for micromachines to MNm for large machines [1].

The electric motors work under their own inherent operating characteristics. However, in many applications some desirable characteristics are obtained by use of control equipment. For most electric drives, the static and dynamic characteristics of electric motors can be matched to the load characteristics and so the transition from electrical to mechanical energy is more productive and inexpensive [2].

In turn, three-phase induction motors (IM) cover machines with rated powers from less than 100 W to 20 MW [3].

Indeed quite not large improvements in their efficiency would contribute to measurable energy savings. The criterion for optimizing the electric machine can be to improve its performance. Users have other criteria, such as small initial price.

The synchronous speed of IM depends on the frequency of the supply voltage and the number of poles of the machine [4].

Generally speaking, electric drives regulate the speed of the motor by changing the frequency of the current that supplies the motor. Nowadays, the two most often applicable methods for speed regulation are frequency and flux vector control. The flux vector drive adjusts both the absolute value and the way of the magnetic flux in IM [5].
At the same time, it is clear that the more complex a control is, the higher the cost [4].

The pumps are particularly suitable for possible reduction of electricity consumption - they are not always required to operate at maximum capacity. This means that there is a possibility of energy savings if the speed of the motor can be changed according to the load demand. In other words, there are possible energy savings if the motor speed can be varied under the operating load [6].

It is needed to be explored the electro-mechanical and electro-magnetic processes occurring in the dynamic behaviour of IM in order to get a clearer idea of their work. The specific goal of the study is to obtain the losses of electric power in the IM for the pump unit in cases of direct-on-line (DOL) operation, frequency and indirect vector control and to compare them in terms of savings obtained.

2. Some considerations

The electromagnetic loads of AC electric machines (value of magnetic induction, current density, etc.), energy losses and heating is determined not by the active but by the apparent power, as the value of the magnetic flux in the motor depends on the total voltage and not only on its active component.

IM are suited for DOL operation. DOL drives are not controllable, in the sense that they can be turned on and off only. Such drives stress both network and machinery and may be energy inefficient. An IM direct torque control (DTC) drives are a good solution for many applications [7].

The rotating magnetic field of the stator generated during the supply voltage crosses the rotor windings, and an electro-motive-force is induced in them by mutual induction. To set up the mutual flux, IM draws magnetizing current. The absolute value of this current is very high due to the great reluctance of the air gap of the motor [8].

Complete adjustability of the electric drive can be ensured if electromagnetic torque control is provided. This makes separate coordinate control of the vectors included in the selected equation of the electromagnetic torque imperative. The vector control drive is able to react promptly to variations during operation and to control torque, which distinguishes it from a scalar control controller for various mechanisms. A special feature is that an active motor model for vector control is applied for the inverter switching circuit.

The motor current can be divided into two portions: flux current (as the exciting current of a DC motor) and in-phase current (as the armature current of a DC motor). By changing the voltage supplied to the motor is controlled the flux current. The in-phase current depends in direct proportion to the load. The vector control retains the V/Hz core and adds additional blocks around the core to refinement the electric drive behaviour [5].

With vector control, direct and indirect methods are possible. Vector sensor-less control generally means control without any speed and flux sensor.

It is necessary to emphasize that the changes of the mechanical quantities and the reaching of the established values proceed more slowly than those of the electrical ones [9].

The dynamic mechanical characteristics giving the relationship between the shaft torque and the angular velocity is usually quite different from the static mechanical characteristics.

Typical examples of variable torque mechanisms are pumps. The pumps can be operated quite well with a simple open-loop, i.e. sensor-less inverter-fed IM drive.

The power losses in all windings of an IM in established non-transient mode with mains supply are [10]:

\[
P_{\text{loss}} = i_{sd}^2 R_s + i_{sq}^2 (R_s + R_R),
\]

where \(i_{sd}, i_{sq}\) – stator current components (magnetizing and quadrature one, respectively); \(R_s\) – stator phase resistance; \(R_R\) – rotor resistance in modified inverse equivalent circuit.

The following dependencies must be added

\[
R_R = b^2 R_r
\]

\[
b = L_m / L_r,
\]
where $b$ – factor of proportionality; $R_r$ – rotor resistance in basic $T$-shape equivalent circuit; $L_m$ – mutual inductance; $L_r$ – rotor inductance.

The main feature of vector control is that the magnetizing current determines the magnitude of the flux coupling of the rotor field and is kept invariant. Each resistance moment corresponds to a value of the magnetizing current when the power losses are minimal. In this regard, the minimum power losses will be determined as follows [10]:

$$P_{loss}^* = \frac{T_m}{\mu} \frac{R_S + \gamma^2 R_R + \gamma^2 R_S}{R_M P},$$

(4)

where $\gamma^2 = R_S / (R_R + R_S)$.

The studies are based on the phase basic $T$-shape equivalent circuit with its corresponding parameters, previously implemented in [11], which is subsequently converted as inverse equivalent circuit for frequency/vector control (where motor leakage inductances absent).

3. Results and findings

Applying software simulations, it is useful to observe all quantities and to study the influence of various changing parameters. Simplifying assumptions are used: there is no asymmetry between the phase windings; the interspace between the movable and immovable part of the motor is fixed; the rotor parameters are adjusted to the primary circuit. The nonlinearity of the equations is due to the multiplication of independent variables or their functions. As is known, the differential equations of an AC machine contain variable coefficients. The direct coordinate transformation equations are applied in order to eliminate variable coefficients. The coordinate system used is orthogonal.

The electromechanical system of an electrically driven pump is described by a mathematical model based on a system of five differential equations - four for model stator/rotor currents and fifth equation is the motion equation. The particulars of the electric motor considered are the same used in [11] and can be seen in table 1. The dynamic simulation studies of the IM pump drive have been carried out by means of purposeful software. Three possible cases have been developed: DOL operation, control while maintaining $V/Hz^2 = \text{const.}$ and when applying indirect vector control.

| Description               | Data                  |
|---------------------------|-----------------------|
| Type, Designation         | ATM 100LBH4           |
| Rated power ($P_{\text{rated}}$) | 3.0 kW               |
| Rated stator voltage ($V_{\text{rated}}$) | 400 V              |
| Operating frequency ($f$)    | 50 Hz                |
| Line stator current ($I_1$)    | 6.3 A                |
| Efficiency                | 86.5%             |
| Pole pair number          | 2                   |
| Rotor speed ($N_r$)        | 1450 rpm            |
| Power factor              | 0.79               |
| Rotor torque of inertia ($I_r$) | 0.04 kg m$^2$       |
| Stator resistance $R_s$    | 1.68 $\Omega$       |
| Rotor resistance $R_r'$    | 1.686 $\Omega$      |
| Stator leakage reactance $X_s'$ | 2.564 $\Omega$      |
| Rotor leakage reactance $X_r'$ | 2.559 $\Omega$      |
| Magnetizing reactance $X_m$ | 62.287 $\Omega$    |

Characteristics of total motor electrical power losses and magnetizing current at DOL starting are depicted in figure 1 and figure 2, respectively.
Figure 1. Electrical power losses during DOL starting.

Figure 2. Magnetizing current during DOL starting.

Figure 3 and figure 4 present the electrical power losses while maintaining $V/Hz^2 = \text{const.}$ and when applying indirect vector control respectively.

Some numerical values in model studies are interesting: electrical power losses in the established regime at DOL starting – 351.460 W; electrical power losses in the established mode of operation...
while maintaining $V/Hz^2 = \text{const.} = 251.104$ W; electrical power losses in the established mode of operation when applying indirect vector control = 138.374 W.

4. Conclusion
The possibility of energy saving of the pump drive with adjustable speed has been studied in the research. The results of the studies carried out are obtaining numerical values for the losses of electric power in a specific IM for a pump unit under different ways of control. The simulation results can be validated by performing measurements of operating such pumping systems. Unfortunately, in many cases such pumps operate in places with certain levels of security where access for outsiders is restricted or prohibited in its entirety.

Research and design of such systems as the electric drive based on vector controlled IM represents rather difficult task.

Speed regulation of pump systems IM powered by inverter leads to significant economic benefits due to reduced energy costs. In electromechanical energy conversion, the reduction of electrical power losses when applying frequency / vector control is noticeable.

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