Evaluation of the behaviour of an induction motor for fan system under various external factors

S Rachev, L Dimitrov

Department of Electrical Engineering, Technical University of Gabrovo, 4 Hadji Dimitar str., Gabrovo 5300, Bulgaria

E-mail: sratchev@mail.com

Abstract. Paper concerns a mathematical model developed for working process observation of a fan system squirrel-cage induction motor electric drive. The electric motor in question is designed for permanent, uninterruptible operation. The system of differential equations is converted and processed with the help of appropriate software. The impact of external factors is assessed – supply voltage deflection and variation of rates of mechanical quantities involved in the motion equation. Electrical power losses in steady-state regime and energy losses at start-up are calculated. The results obtained are practical oriented when considering methods to start and control the rotational frequency to improve energy efficiency.

1. Introduction

According to global studies, the largest consumers of electricity produced in the world are electric motors. The largest share is occupied by induction motors, also called asynchronous. According to expert’s opinion, they represent 80-90% of all electric motors used. It has been found that about 55% of induction motors are used to drive mechanisms such as fans and pumps.

Fan systems are widely used. The term "fans" includes generators for compressed gases, most often for compressed air. Their division into groups depends on the pressure of the exhaust gases and their purpose. The fans create a difference in outlet and inlet pressure from 0.001 to 0.01 MPa. Their purpose is for ventilation of industrial buildings and facilities, for heating systems (air conditioning systems), for cooling motors and rectifiers, for suction of flue gases during central and local ventilation in shafts, for pneumatic transport, for agriculture, etc.

Fans are an inseparable part of different technological processes in the metallurgy, chemical and energy industries. They also serve to creating of technologically clean environment – for production of elements in radio-electronics and computer machinery, in laboratories for tissue cultivation. Practically, there is no branch of every national economy, where fans don’t find application.

By design, fans are divided into centrifugal and axial. Fans are slow-moving and heavy mechanisms. The fans operate with a low degree of compression, and centrifugal fans are used to move lower flow rates at higher pressures than axial fans.

The fans are working hydraulic turbo-mechanisms which convert the mechanical energy into hydraulic – kinetic and potential. The main energy changing component is the impeller, which can be radial, diagonal and axial. Generally the fans with radial and diagonal impellers are called centrifugal fans [1].
Fan motor power ranges from a few tens of watts to several thousand kilowatts. They are usually started without load and the conditions for starting the motors are light. The operating mode is continuous and the number of releases (starts) - small. The productivity, reliability of operation, simplicity of service and automation potential of the mechanisms is in direct dependence on the advanced technical characteristics of electric drives. For this reason, a detailed examination of the electric drive of mechanisms and machines is of essential practical importance. This also applies in full force to the fan drives.

2. Technical considerations

The following should be considered when selecting a fan [2]:

- Type of site – industrial, commercial, residential
- Fluid characteristics – clean air, air with dust or grease, flue gases, operating temperature, etc.
- Type of ventilation system – injection or suction;
- Required flow and pressure;
- Type of power supply – single-phase or three-phase;
- Noise level conditions.

The fans general parameters are:

- Flow rate $Q$ - the volume of air passed through the fan per unit time; measured in [$m^3/s$] or [$m^3/h$];
- Full pressure $P_f [Pa]$ – shows the increase in the specific energy of the air passed through the fan;
- Dynamic pressure $P_d [Pa]$ – characterizes the air kinetic energy after the fan;
- Static pressure $P_{st} [Pa]$ – represents the difference between $P_f$ and $P_d$;
- Power – represents the electric motor full power, providing the fan parameters; measured in [$W$] or [$kW$].

When ordering fan to the manufacturer, the following characteristics should be stated: type of fan; capacity [$m^3/h$]; installed power; rotational frequency per minute [$min^{-1}$]; characteristics of the fluid – temperature, explosiveness, dustiness, adhesiveness of the dust and other specific requirements; fan equipment – frame, vibrated frame, flexible joints and other [1].

Feature of fans such as the so-called turbo-mechanisms is the dependence of the static resistance moment on the angular velocity squared.

In order for a fan to start normally, it is necessary for the starting torque of the drive motor to be greater than the resting moment of the turbo-mechanism, which is determined by the aerodynamic (or hydraulic) drag, but not to exceed 115-120% of the latter one.

Fans rank second among turbo-mechanisms after industrial pumps. Fans operating in production facilities consume significant total electricity.

For powers up to 250 kW, the fans are driven mainly by squirrel cage induction motors, and above this value - by synchronous motors.

Of particular importance for a number of fans is the application of adjustable drive. At present, the trends of the transition to adjustable fan drive have become more than obvious. The accumulated experience from the operation points out that the efficiency of the fans with adjustable electric drive is higher than with non-adjustable motors, on average by 12%.

In direct connection with energy efficiency is the observance of the limits of the so-called indicators of electricity quality. An assessment of the impact of electricity consumers on the overall energy efficiency through an implemented methodology is proposed in [3]. In order to improve energy
efficiency, it is possible to define specific measures. In addition, modern control methods are sources of harmonic distortions that "pollute" the mains and negatively affects the normal operation of other consumers [4].

There is no universal criterion for optimality. Reliability of operation in general and improvement of energy performance are important goals for the electric motors used. In fact, for example, in conventional design methods, minimizing motor mass results in lower energy performance and reduced reliability.

Below are recommended values for different cases – the change of air in a certain space with what frequency for an hour to happen [2]:

For industrial purposes: boiler rooms: 20÷25 times; fabric dyeing rooms: 10÷15 times; powder coating rooms: 10÷15 times; machine rooms: 20÷30 times; factory halls: 3÷6 times; foundries: 30÷40 times; painting rooms: 30÷60 times; welding rooms: 15÷30 times.

For commercial purposes and others: bakeries: 20÷30 times; bank offices: 3÷4 times; coffee bars: 10÷15 times; dining rooms: 5÷10 times; cinemas and theaters: 5÷8 times; conference rooms: 8÷12 times; couloirs: 3÷5 times; garages: 6÷8 times; sports halls: 6÷12 times; hair salon: 10÷15 times; toilets: 8÷15 times; offices: 4÷8 times; libraries: 3÷5 times; recording studios: 10÷12 times; restaurants: 6÷10 times; school rooms: 2÷4 times.

These values are optional and may vary from case to case. The flow rate required is related to the quantity of air needed for one person (these are minimum values): at normal activity: 20÷25 m³/h; during normal activity with smoking allowed: 30÷35 m³/h; for light physical work: 45 m³/h.

The flow rate can be determined by means of the velocity of pull-out:

- For home kitchens: 0.15 up to 0.20 m/s; for industrial kitchens: 0.20 up to 0.25 m/s.
- When degreasing: 0.25 up to 0.50 m/s; When galvanizing: 0.50 up to 1 m/s; For aerosol chambers: 0.70 up to 1 m/s.

The flow rate can also be calculated from the transportation speed: dust: 9 m/s; flour: 13 m/s; sawdust: 15 m/s; metal powder: 15 m/s; shavings: 18 m/s; lead powder: 20÷25 m/s. To calculate the flow, the speed must be multiplied by the cross section of the pipeline.

3. Mathematical model

Centrifugal double-inlet fan VCP-8 intended to complete fan section from air-conditioning chambers has been model studied. It transports air and gases, free from mechanical particles, with a maximum temperature up to 223.16 K (50 °C), by providing a flow rate Q=11000-27000 m³/h and full pressure Pt=300-4000 Pa. It is completed with an electric motor and starting equipment with grade of protection IP44, belts and slide rails for the electric motor.

The mathematical model applied is similar to these ones in [5, 6, 7].

The model voltages of the windings are as follows [5, 6]:

\[
\begin{align*}
    u_{xx} &= r_{xx} i_{xx} + \frac{d\Psi_{xx}}{dt} - \Omega_x \Psi_{xy} ; \\
    u_{xy} &= r_{xy} i_{xy} + \frac{d\Psi_{xy}}{dt} + \Omega_x \Psi_{xx} ; \\
    u_{cx} &= r_{cx} i_{cx} + \frac{d\Psi_{cx}}{dt} - s\Omega_x \Psi_{cy} , \\
    u_{cy} &= r_{cy} i_{cy} + \frac{d\Psi_{cy}}{dt} + s\Omega_x \Psi_{cx} \\
\end{align*}
\]

(1)

where
\[ \Omega_s = \frac{2\pi N}{p} = \frac{\omega}{p} = \frac{\omega_b}{p} \] - field synchronous angular speed; \[ \omega = 2\pi N = \omega_b \] - circular frequency, accepted as a basic one.

\( p \) – number of pole pairs; \( u_{sx}, u_{sy} \) – model stator voltages; \( u_{rx}, u_{ry} \) – model stator voltages; \( r_1, r_2 \) – stator and reduced rotor ohmic resistances; \( i_{sx}, i_{sy}, i_{rx}, i_{ry} \) – model stator and rotor currents

\( \psi_{sx}, \psi_{sy}, \psi_{rx}, \psi_{ry} \) – magnetic fluxes of the stator and rotor; \( s \) – the electric motor slip.

We use the relative units system according to the generally accepted basic values (for example \( \tau = \omega_b t \) - time in relative units). The parameters of the electric motor substitution circuit are determined for a value of the slip \( s = 1 \) by the calculation method [8]. Some technical data and parameters of the electric motor and fan are given in Appendix.

\[
\frac{dl_s^*}{dt} = \frac{L_s^* I_m^*}{L_e} u_{sx} - u_{sy} r_s^* + i_{rx}^* + \ldots \]
\[
\frac{dl_y^*}{dt} = \frac{L_y^* L_m^*}{L_e} s e_{xy}^2 + (1-s) i_{ry}^* \]
\[
\frac{di_x^*}{dt} = \frac{L_x^* L_m^*}{L_e} s e_{xy}^2 - L_y^* i_{xy}^* + (1-s) i_{rx}^* \]
\[
\frac{di_y^*}{dt} = \frac{L_y^* L_m^*}{L_e} s e_{xy}^2 + (1-s) i_{ry}^* \]

where \( u_{sx}^*, l_s^*, l_m^*, l_e^* \) – stator, rotor, mutual and equivalent inductance in relative units, respectively.

The stator voltages \( u_{sx}^* \) and \( u_{sy}^* \) are as follows [5]:

\[
\begin{align*}
\quad u_{sx}^* &= \sqrt{2} k_v \left[ u_s^2 \cos \theta + u_b^2 \cos(\theta - \frac{2\pi}{3}) + u_c^2 \cos(\theta + \frac{2\pi}{3}) \right] \\
\quad u_{sy}^* &= -\sqrt{2} k_v \left[ u_s^2 \sin \theta + u_b^2 \sin(\theta - \frac{2\pi}{3}) + u_c^2 \sin(\theta + \frac{2\pi}{3}) \right]
\end{align*}
\]

where \( u_s^*, u_b^* \) and \( u_c^* \) are the phase voltages in relative units;

\( k_v = V / V_{NOM} \) gives the account of supply voltage value, so called multiplicity of supply voltage [6];

\( V \) – supply voltage value in circulation; \( V_{NOM} \) – supply voltage rated value.

Because of squirrel-cage rotor relevant voltages are \( u_{rx}^* = 0 \) and \( u_{ry}^* = 0 \). The phase stator voltages in relative units are obtained to be:

\[
\begin{align*}
\quad u_A^* &= k_v \cos(\theta + \varphi_0^*) \sin(\theta + \varphi_0^* - \frac{2\pi}{3}) \\
\quad u_B^* &= k_v \cos(\theta + \varphi_0^* - \frac{2\pi}{3}) \\
\quad u_C^* &= k_v \cos(\theta + \varphi_0^* + \frac{2\pi}{3})
\end{align*}
\]

where \( \varphi_0^* \) – initial phase of supply voltage.

It is proved that after substitution of (4) into (3) and transformation the result is:
\[ u^*_{sx} = \frac{2}{\sqrt{3}} k_p \frac{3}{2} \cos\theta; \quad u^*_{sy} = \frac{3}{\sqrt{2}} k_p \left( -\frac{3}{2} \right) \sin\theta = \frac{3}{\sqrt{2}} k_p \sin\theta. \]  

(5)

The phase stator currents are as follows:

\[
\begin{align*}
    i^*_{sx} &= \frac{2}{\sqrt{3}} i^*_{st} \cos \tau - i^*_{sy} \sin \tau \\
    i^*_{sy} &= \frac{2}{\sqrt{3}} i^*_{st} \cos(\tau - \frac{2\pi}{3}) - i^*_{sy} \sin(\tau - \frac{2\pi}{3}) \\
    i^*_{sx} &= \frac{2}{\sqrt{3}} i^*_{st} \cos(\tau + \frac{2\pi}{3}) - i^*_{sy} \sin(\tau + \frac{2\pi}{3})
\end{align*}
\]  

(6)

The induction motor electromagnetic torque is as follows (\( M_N \) - base moment):

\[ M^* = \frac{M}{M_N} = \frac{pL_d^2 I^*_{st} L_m^*}{M_N \omega} \left( i^*_{sy} i^*_{sy} + i^*_{sx} i^*_{rx} \right) = \frac{pu_d^2 L_m^*}{M_N \omega} \left( i^*_{sy} i^*_{sy} + i^*_{sx} i^*_{rx} \right). \]  

(7)

After conversion, the motion equation is as follows [9]:

\[ \frac{ds}{dt} = -\frac{p}{J_S \omega} (M - M_L), \]  

(8)

where \( M_L \) - mechanism resistance moment; \( J_S \) - total inertia moment of the drive system.

The fan blower is a mechanism which characteristics is presented by following equation [9]:

\[ M^*_{L,r} = M^*_{L,r init} + \left( M^*_{L,init} - M^*_{L,r init} \right) (1 - s)^2 \]  

(9)

where \( M^*_{L,r init} \) - initial resistance moment; \( M^*_{L,init} \) - rated resistance moment.

After transformation equation (8) is obtained to be:

\[ \frac{ds}{d\tau} = -\frac{pM_{L,r}}{J_S \omega} \left[ \frac{pu_d^2 L_m^*}{M_N \omega} \left( i^*_{sy} i^*_{sy} + i^*_{sx} i^*_{rx} \right) - M^*_{L,r init} - \left( M^*_{L,init} - M^*_{L,r init} \right) (1 - s)^2 \right] \]  

(10)

The dynamic behaviour of a fan driven by an induction motor has been studied by a system of five differential equations formed by equations (2) and (10) [7, 10]. The four of these equations are for model stator currents and the fifth one is related to torques and it is the motion equation [7, 11]. As mentioned above, the moment of resistance is changed by so-called ‘square-law’ [12]. Let us emphasize that the basic equations of any induction machine are strongly nonlinear.

The electric drive total inertia moment \( J_S \) is presented through factor of inertia \( FI \) and rotor moment of inertia \( J_r \) [10]:

\[ J_S = FI \times J_r \]  

(11)

The variable electrical losses in the stator and rotor, the magnitude of which depends on the values of the flowing currents, are calculated as follows [5, 6, 7]:

\[ \Delta P_y = \Delta P_1 + \Delta P_2 \approx 3I_1^2 \rho_1 + 3I_2^2 \rho_2, \]  

(12)

where

\( I_1 \) - stator current; \( I_2 \) - rotor current reduced to the stator;
\( \Delta P_1 = 3I_1^2r_1 \) – electrical power losses associated with stator windings heating when current flows thereon.
\( \Delta P_2 = 3I_2^2r_2 \) – again such losses, but in rotor windings.

If the induction motor operates in the small slip zone to the nominal one, the equality applies \( I_1^2 \approx I_2^2 + I_0^2 \), where \( I_0 \) – magnetizing current.

The following is therefore in force:
\[
\Delta P_\pi = 3I_2^2 \left( r_1 + r_2 \right). \tag{13}
\]

Since
\[
I_2' = \sqrt{\frac{M\omega_0 s}{3r_2}} \tag{14}
\]

The electrical losses are ultimately represented in such a way:
\[
\Delta P_i = \Delta P_1 + \Delta P_2 = M\omega_0 s (1 + \frac{r_1}{r_2}) \tag{15}
\]
where \( \omega_0 \) – synchronous angular speed.

The differential equations system combining equations (2) and (10) was subsequently treated by the functional calculus Rkadapt with an adaptive approach step size embedded in the Mathcad® software of the PTC® (Parametric Technology Corporation).

4. Results and findings

Through the mathematical model implemented the processes during fan operation have been studied, as the supply voltage and the factor of inertia vary. The combined influence of the two quantities was studied, not separately. Some of the results are presented in tables and graphs.

Table 1 presents the influence of supply voltage and factor of inertia \( FI \) on the emerging impact torques and currents. The starting time is calculated, with the criterion that two immediately following values of angular velocity differ by no more than 1%.

This means that electromechanical transient processes have been completed, and electromagnetic transient processes are known to end long before.

Table 2 presents overall electrical power and energy losses calculated. The speed-time and torque-time characteristics for \( V = 0.9V_N \) and \( FI = 5.5 \) are drawn in Figure 1 and Figure 2, separately. The other figures represent: Figure 3 and Figure 4 – dynamic mechanical characteristics in case of Factor of Inertia \( FI = 1.5 \) and \( FI = 5.5 \) for \( V = 0.9V_N \). The other figures represent: Figure 5 – starting time vs. factor of inertia dependence; Figure 6 – electrical power losses vs. multiplicity of supply voltage; Figure 7 – energy losses vs. factor of inertia dependence; Figure 8 – electrical power losses vs. multiplicity of supply voltage.

Currently, electric motors must meet the recommendations of IEC 60034-30-1: 2014 in terms of efficiency levels (IE codes) or to meet the NEMA MG 1 standards (meet or exceed the recommendations for energy efficiency level Premium Efficiency). From 01.01.2017 in the European Union all electric motors with power from 0.75 \( kW \) to 375 \( kW \) must have an efficiency corresponding to IE3 code, except those designed to operate with an electronic speed controller (VSD), which may be IE2 efficient.

The considered centrifugal double-inlet fan VCP-8 is intended to complete fan section from air-conditioning chambers, which is very different from the application for flue gas extraction, for example. Because of higher number of starts there is a possibility to apply frequency-controlled motor with a quality inverter - the so-called variable speed drive (VSD).
For the European Union, the energy efficiency class of such electric motors must be at least IE2 (which is a cheaper technical solution at competitive prices compared to an IE3 motor). With such a drive, the speed, torque and power output can be adjusted. This improves drive efficiency and saves energy.

The speed control of electric motors with VSD is performed in 2 ranges:
- up to rated speed - a constant torque of the motor shaft is maintained, the voltage frequency varying about in the range from 5 Hz to 50 Hz. The mechanical power of the motor shaft varies from minimum to rated value..
- from rated to maximum speed - constant power is maintained when changing the speed of rotation.

The ratio of maximum torque to rated torque is kept constant.

Table 1. The supply voltage and factor of inertia effects.

| $K_V$ | $F_I$ | $T_{imp}, Nm$ | $i_{imp}^*$ | $t_{st}, s$ |
|-------|-------|----------------|-------------|------------|
| 1.00  | 1.5   | 5.006          | 8.068       | 0.507      |
| 2.5   | 3.5   | 5.257          | 8.244       | 0.482      |
| 4.5   | 5.297 | 8.832          | 0.523       |
| 5.5   | 5.366 | 8.865          | 0.570       |
| 1.5   | 4.563 | 8.597          | 0.582       |
| 2.5   | 4.704 | 8.637          | 0.585       |
| 0.95  | 3.5   | 4.761          | 8.761       | 0.591      |
| 4.5   | 4.791 | 8.703          | 0.607       |
| 5.5   | 4.328 | 8.983          | 0.621       |
| 1.5   | 4.133 | 7.750          | 0.384       |
| 2.5   | 4.242 | 8.125          | 0.407       |
| 0.90  | 3.5   | 4.286          | 8.185       | 0.428      |
| 4.5   | 4.374 | 8.065          | 0.506       |
| 5.5   | 4.489 | 8.218          | 0.523       |
| 1.5   | 5.460 | 9.502          | 0.421       |
| 2.5   | 5.685 | 9.642          | 0.438       |
| 1.05  | 3.5   | 5.774          | 9.020       | 0.457      |
| 4.5   | 5.821 | 9.897          | 0.483       |
| 5.5   | 5.850 | 9.951          | 0.521       |
| 1.5   | 5.293 | 9.886          | 0.553       |
| 2.5   | 6.202 | 9.893          | 0.498       |
| 1.10  | 3.5   | 6.312          | 9.933       | 0.492      |
| 4.5   | 6.370 | 10.195         | 0.418       |
| 5.5   | 6.406 | 10.289         | 0.423       |
| 1.5   | 6.392 | 10.207         | 0.706       |
| 2.5   | 6.775 | 10.361         | 0.382       |
| 1.15  | 3.5   | 6.869          | 10.634      | 0.375      |
| 4.5   | 6.940 | 10.537         | 0.362       |
| 5.5   | 6.984 | 10.599         | 0.438       |
| 1.5   | 6.865 | 10.499         | 0.752       |
| 2.5   | 7.283 | 10.857         | 0.423       |
| 1.20  | 3.5   | 7.446          | 11.100      | 0.384      |
| 4.5   | 7.532 | 10.770         | 0.371       |
| 5.5   | 7.584 | 10.744         | 0.408       |

Table 2. Overall losses of electrical power and energy.

| $K_V$ | $F_I$ | Electrical power losses – steady state regime $\Delta P_1 + \Delta P_2, W$ | Energy losses – starting regime $W_{START}, kWh$ |
|-------|-------|--------------------------------------------------------------------|---------------------------------------------|
| 1.00  | 1.5   | 435                                                                | 334                                         |
| 2.5   | 3.5   | 1.291                                                               | 1.57                                        |
| 4.5   | 5.5   | 1.808                                                               | 2.323                                       |
| 5.5   | 1.5   | 0.894                                                               | 1.495                                       |
| 2.5   | 3.5   | 3.984                                                               | 0.591                                       |
| 0.95  | 3.5   | 482                                                                | 2.113                                       |
| 4.5   | 5.5   | 2.788                                                               | 3.484                                       |
| 5.5   | 1.5   | 1.042                                                               | 3.84                                        |
| 1.05  | 3.5   | 538                                                                | 1.533                                       |
| 4.5   | 5.5   | 2.329                                                               | 2.940                                       |
| 5.5   | 1.5   | 0.638                                                               | 2.99                                        |
| 2.5   | 3.5   | 1.114                                                               | 3.75                                        |
| 1.05  | 3.5   | 394                                                                | 1.626                                       |
| 4.5   | 5.5   | 2.209                                                               | 4.198                                       |
| 5.5   | 1.5   | 2.911                                                               | 4.831                                       |
| 2.5   | 3.5   | 1.036                                                               | 2.65                                        |
| 1.10  | 3.5   | 363                                                                | 1.748                                       |
| 4.5   | 5.5   | 1.909                                                               | 3.248                                       |
| 5.5   | 1.5   | 1.058                                                               | 2.440                                       |
| 2.5   | 3.5   | 0.966                                                               | 2.420                                       |
| 1.15  | 3.5   | 328                                                                | 1.329                                       |
| 4.5   | 5.5   | 1.650                                                               | 2.440                                       |
| 5.5   | 1.5   | 1.420                                                               | 2.270                                       |
| 2.5   | 3.5   | 1.071                                                               | 1.359                                       |
| 1.20  | 3.5   | 301                                                                | 1.689                                       |
| 4.5   | 5.5   | 2.270                                                               | 2.787                                       |
**Figure 1.** Speed-time characteristic for \( U = 0.9U_N \) and \( FI = 5.5 \).

**Figure 2.** Torque-time characteristic for \( U = 0.9U_N \) and \( FI = 5.5 \).

**Figure 3.** Dynamic mechanical characteristic in case of Factor of Inertia \( FI = 1.5 \) for \( V = 0.9V_N \).

**Figure 4.** Dynamic mechanical characteristic in case of Factor of Inertia \( FI = 5.5 \) for \( V = 0.9V_N \).

**Figure 5.** Starting time vs. factor of inertia dependence

**Figure 6.** Electrical power losses vs. multiplicity of supply voltage.
5. Conclusion
With the help of the proposed mathematical model it is possible to analytically study the operation of a fan and in this case to assess the influence of operating voltage and inertial masses on the ongoing electromagnetic and electromechanical processes. Values for the resulting impact torques, currents, angular velocities and accelerations are also obtained.

The stator electrical losses and flowing current are increased in a heavy workload and decreased at low motor load. The share of total electrical losses in relation to the rated power is up to 2.4%.

In addition to theoretical study of electric drives in operation, the developed model can be applied for expedient choice of drive motor and its control, ensuring the behavior of the entire electromechanical system under user-specified requirements and initial conditions.

The results obtained are practical oriented when considering methods to start and control the rotational frequency of induction motors driving turbo-mechanisms.

Appendix
Technical data of the electric motor AT2 180 L4 [14]:

\[
P_N = 22kW \quad V_N = 400V \quad f_N = 50Hz \quad p = 2 \quad n_N = 1450 \text{ min}^{-1};
\]

\[
I_{phN} = 72.3A \quad J = 0.07646kgm^2 \quad J_{ST} / J_N = 7.0 \quad M_{ST} / M_N = 2.2 \quad M_{MAX} / M_N = 2.9;
\]

\[
r_1 = 0.4843\Omega \quad x_1 = 1.154\Omega \quad r_2 = 0.619\Omega \quad x_2 = 1.195\Omega \quad x_m = 51.719\Omega.
\]

Technical data of fan blower VCP-8, made by Spartak JSC, Burgas, BULGARIA [1]:

\[
n_N = 1320 \text{ min}^{-1}; \quad P_N = 22kW; \quad \text{Sound level pressure 93 dB(A).}
\]

6. References
[1] https://www.spartak.bg
[2] http://www.heriks.com
[3] Ivanova G 2020 Specifics in determining the operational energy efficiency index eeoI according to the requirements of the international maritime organization IMO for the period 2020-2025, 12th Electrical Engineering Faculty Conference BulEF 2020, Varna, Bulgaria

[4] Stoyanov I, Iliev T, Evstatiev B and Mihaylov G 2019 Harmonic distortion by single-phase photovoltaic inverter 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE) pp 1-4, doi: 10.1109/ATEE.2019.8725009

[5] Hughes A 2005 Electric Motors Drives Fundamentals, Types and Applications Third edition (Newnes 2005) p 384

[6] Rachev S 2004 Dynamic study of fan blower induction motor electric drive, 4th International Conference RADMI 2004, Zlatibor Serbia and Montenegro 2004, pp 268-273
[7] Rachev S, Dimitrov L, Ivanov I, Karakoulidis K 2017 Study the effects of no nominal conditions on the performance of high efficiency induction motor, 8th International Conference on Energy and Environment CIEM 2017, University Politehnica of Bucharest, Romania IEEE Xplore

[8] Rachev S, Dimitrov L, Karakoulidis K, Ivanov I, Anghel Drugar in C V 2018 Electric power losses of frequency controlled electric drive with high-voltage induction motor, International Conference on Applied and Theoretical Electricity 2018 (ICATE 2018) Craiova Romania (IEEE Xplore® Catalog Number: CFP1899S-ART)

[9] Chapman S J 1985 Electric Machinery Fundamentals (McGraw-Hill, N. Y.)

[10] Kluchev V I 1989 Electric Drive Theory (Tehnika, Sofia) (in Bulgarian)

[11] Rachev S, Koeva D. (eds) 2016 Electromechanical model and operating modes of high-voltage induction motor electric drive – part I: impact torque and currents International Symposium on Fundamentals of Electrical Engineering (ISFEE), University Politehnica of Bucharest, Romania

[12] Crowder R 2006 Electric Drives and Electromechanical Systems Oxford UK pp 35-42

[13] Rizzoni G 1993 Principles and Applications of Electrical Engineering (Illinois, USA Richard D. Irwin) pp 853–855

[14] https://www.elprommotors.com

Acknowledgements

The implementation of this paper is thanks to the support from:

- the University Project 2104E ‘Electric drives for electric vehicles and industrial applications, electrical components and systems – practical and mathematical model studies in terms of energy and economic efficiency’, financed by the Ministry of Education and Science of the Republic of Bulgaria

- the Project BG05M2OP001-1.002-0023 Competence Center ‘Intelligent Mechatronic, Eco- and Energy-Saving Systems and Technologies’ financed by the Operational Program ‘Science and Education for Intelligent Growth’ of the European Regional Development Fund.