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Dynamic Study of Synchronous Machine Electric Drive

The dynamic behaviour of the fan blower synchoronous machine drive have been studied in the paper. The equations for the voltages of the synchoronous machine windings are presented in a coordinate system which rotates at the angular speed of the rotor. The mechanical equipment is presented by means of a single-mass dynamic model. The derived system of differential equations is transformed and solved using suitable software product. The results obtained for rotation frequency and electromagnetic torque motor in the courses of different values of rated supply voltage and of different initial resistant moment of the mechanism have been graphically presented. Conclusions from the results obtained have been done.

1. Introduction

It is known, that synchronous machines work under three different regimes – as a generator, as a motor and as a synchronous condenser [1].

As the special features of machine-working under one or another regime make different demands to the machine construction, industry produces synchronous machines designed only for regimes as a generator or as a motor.

Synchronous motors (SM) are being started more frequently, so they have to hold starting torque, bigger than generators. This influences the rotor construction – the damper (starting) winding of SM is being designed for larger currents and for more continuous work.

Synchronous machines have been widely applied when necessary maintaining constant rotation frequency and for speedly unadjustable electric drives of pumps and fan blowers. The use of synchronous machines has proved to be very sensible in cases when power supply networks have low power factor in consequence of great number reactive power consumers. Using their natural inclination for transmission of reactive energy excess during consuming active one it is possible to compensate insufficiency of reactive energy in networks by regulating the excitation [1]. The character of rated power factor of synchronous machines, as a rule is outstripping.

Starting stator current varies 3÷8 times of rated one depend for the different types of motors, as the motor with higher speed gets larger values.

Asynchronous starting is most often used – by far the most popular way to start a SM is to employ damper winding. Damper winding consists of special bars laid into notches carved in the face of a SM rotor and then shorted out on each end by a large shoting ring) is put short-circuit starting winding.

Direct-on-line starting of SM is applied when the network power is sufficient. Otherwise it is possible to apply low voltage starting, starting by autotransformer or by reactor [1]. Nowadays there is tendency toward production of SM, allowing direct-on-line starting for different values of rated power.

There is a trend for a deep analysis of SM transient processes in asynchronous regimes, in turning over again and in a series of break-down regimes. In such analysis of SM complex processes a lot of assumptions are made, but in that way physical processes are well revealed.

2. Mathematical Model

SM model, driving fan blower mechanism in the coordinate system which rotates at the angular speed of the rotor is shown on Figure 1.

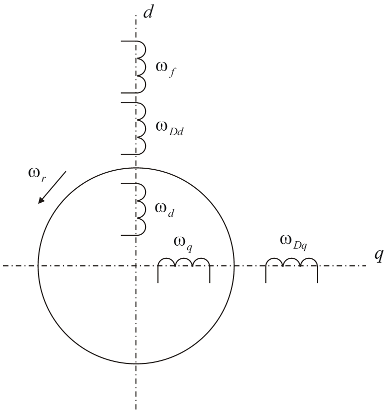

Figure 1. Model of Synchronous Motor.

The per-phase equivalent circuit of SM in the coordinate system which rotates at the angular speed of the rotor is shown on Figure 2.

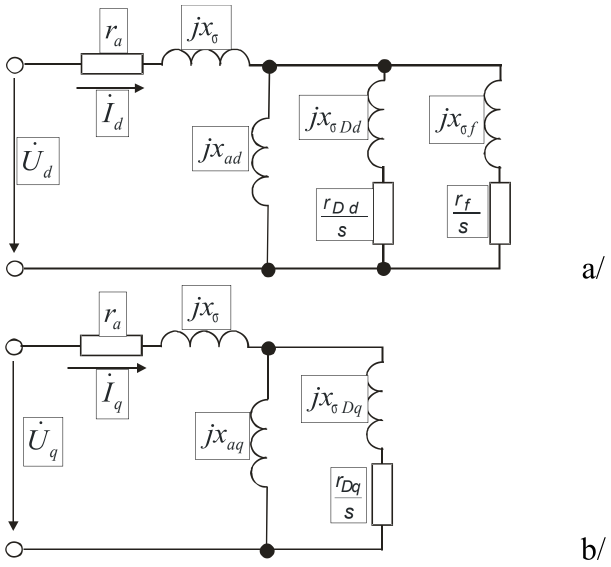

Figure 2. The per-phase equivalent circuit of SM.

The equations for the voltages of the windings of the SM in the coordinate system which rotates at the angular speed of the rotor are [4]:

$$v_d = \frac{d\Psi_d}{dt} - \Psi_q \omega_r + r_a . i_d;$$

$$v_q = \frac{d\Psi_q}{dt} + \Psi_d \omega_r + r_a . i_q;$$

$$v_f = \frac{d\Psi_f}{dt} + r_f . i_f; \qquad (1)$$

$$0 = \frac{d\Psi_{Dd}}{dt} + r_{Dd} . i_{Dd};$$

$$0 = \frac{d\Psi_{Dq}}{dt} + r_{Dq} . i_{Dq}$$

where r_a – ohmic resistance of armature winding;

r_f – ohmic resistance of excitation winding;

r_{Dd}, r_{Dq} – ohmic resistances of damper winding along longitudinal and transverse axises;

i_d, i_q – currents in armature winding along longitudinal and transverse axises;

i_f – current in excitation winding;

i_{Dd}, i_{Dq} – currents in damper winding along longitudinal and transverse axises;

ω_r – electrical angular speed of rotor.

The equations for the magnetic fluxes are [4]:

$$\begin{aligned}
&\Psi_d = i_d x_d + i_f x_{ad} + i_{Dd} . x_{ad};\\
&\Psi_q = i_q x_q + i_{Dq} . x_{aq};\\
&\Psi_f = i_d x_{ad} + i_f x_f + i_{Dd} . x_{ad}; \qquad (2)\\
&\Psi_{Dd} = i_d x_{ad} + i_f x_{ad} + i_{Dd} . x_{Dd};\\
&\Psi_{Dq} = i_d x_{aq} + i_{Dq} . x_{Dq},
\end{aligned}$$

where x_σ – inductive dissipation reactance of stator loop;

$x_{\sigma Dd}$, $x_{\sigma Dq}$ – inductive dissipation reactances of longitudinal and transverse damper loops;

$x_{\sigma f}$ – inductive dissipation reactance of excitation winding;

x_{ad}, x_{aq} – inductive reactances of armature reaction along longitudinal and transverse axises;

$x_d = x_{ad} + x_\sigma$; $x_q = x_{aq} + x_\sigma$; $x_f = x_{ad} + x_{\sigma f}$;

$x_{Dd} = x_{ad} + x_{\sigma Dd}$; $x_{Dq} = x_{aq} + x_{\sigma Dq}$.

After substitution of (2) in (1) we obtain:

$$\begin{aligned}
&v_d = x_d \frac{di_d}{dt} + x_{ad} \frac{di_f}{dt} + x_{ad} \frac{di_{Dd}}{dt} - \Psi_q \omega_r + r_a . i_d;\\
&v_q = x_q \frac{di_q}{dt} + x_{aq} \frac{di_{Dq}}{dt} + \Psi_d \omega_r + r_a . i_q;\\
&v_f = x_{ad} \frac{di_d}{dt} + x_f \frac{di_f}{dt} + x_{ad} \frac{di_{Dd}}{dt} + r_f . i_f; \qquad (3)\\
&0 = x_{ad} \frac{di_d}{dt} + x_{ad} \frac{di_f}{dt} + x_{Dd} \frac{di_{Dd}}{dt} + r_{Dd} . i_{Dd};\\
&0 = x_{aq} \frac{di_q}{dt} + x_{Dq} \frac{di_{Dq}}{dt} + r_{Dq} . i_{Dq}
\end{aligned}$$

After transformation we get system of equations (4) in form of *Cauchy* for electrical part of drive:

$$\begin{aligned}
\frac{di_d}{dt} &= \frac{(x_{ad}^2 - x_f x_{Dd})[-v_d - (i_q x_q + i_{Dq} x_{aq})\omega_r + r_a i_d] + (x_{ad}^2 - x_{Dd} x_{ad})(v_f - r_f i_f) - (x_{ad}^2 - x_{ad} x_f) r_{Dd} i_{Dd}}{2x_{ad}^3 - (x_f + x_d + x_{Dd}) x_{ad}^2 + x_d x_f x_{Dd}};\\
\frac{di_q}{dt} &= \frac{1}{x_{aq}^2 - x_q x_{Dq}} \{ x_{Dq} [-v_q + (i_d x_d + i_f x_{ad} + i_{Dd} x_{ad})\omega_r + r_a i_q] - x_{aq} r_{Dq} i_{Dq} \};\\
\frac{di_f}{dt} &= \frac{(x_{ad}^2 - x_{Dd} x_{ad})[v_d + (i_q x_q + i_{Dq} x_{aq})\omega_r - r_a i_d] + (x_{ad}^2 - x_d x_{Dd})(-v_f + r_f i_f) - (x_{ad}^2 - x_d x_{ad}) r_{Dd} i_{Dd}}{2x_{ad}^3 - (x_f + x_d + x_{Dd}) x_{ad}^2 + x_d x_f x_{Dd}};\\
\frac{di_{Dd}}{dt} &= \frac{(x_{ad}^2 - x_f x_{ad})[v_d + (i_q x_q + i_{Dq} x_{aq})\omega_r - r_a i_d] + (x_{ad}^2 - x_d x_{ad})(v_f - r_f i_f) + (x_{ad}^2 - x_d x_f) r_{Dd} i_{Dd}}{2x_{ad}^3 - (x_f + x_d + x_{Dd}) x_{ad}^2 + x_d x_f x_{Dd}};\\
\frac{di_{Dq}}{dt} &= \frac{1}{x_{aq}^2 - x_q x_{Dq}} \{ x_{aq} [v_q - (i_d x_d + i_f x_{ad} + i_{Dd} x_{ad})\omega_r - r_a i_q] - x_q r_{Dq} i_{Dq} \};
\end{aligned} \qquad (4)$$

The parameters of substitution circuit of SM vary in definite limits [3, 4]. Parameters, used for concrete investigations are given in the Appendix.

The stator voltages V_d and Vq are determined from the expressions:

$$V_d = k_V V_m \cos(1 - \frac{\omega_r}{\omega_o})t \qquad (5)$$

$$V_q = k_V V_m \sin(1 - \frac{\omega_r}{\omega_o})t$$

where $k_V = \frac{V}{V_N}$ – gives the account of supply voltage value;

V_m – amplitude value of phase voltage;

$\omega_0 = 2\pi f_e$ – circular frequency;

f_e – electrical frequency, Hz.

The electromagnetic torque of the SM is obtained to be:

$$T = \Psi_d i_q - \Psi_q i_d; \qquad (6)$$

After substitution of (2) in (6) we get:

$$T = x_d i_d i_q + x_{ad} i_f i_q + x_{ad} i_{Dd} i_q - x_q i_q i_d - x_{aq} i_d i_{Dq}; \qquad (7)$$

The mechanical equipment is presented by means of a single-mass model which is described with total moment of inertia.

Equation of motion is:

$$T - T_L = \frac{J_\Sigma}{p} \frac{d\omega_r}{dt}, \qquad (8)$$

where T_L – resistant moment of the mechanism;

J_Σ – total inertia moment of the motor and of the mechanism, reduced to the motor shaft;

p – number of pole couples of the motor;

Inertial moment of fan blowers is many times lower than driving motor one. That is why it is counted by coefficient, increasing motor one in a few per cent.

For investigation of motor operation in different values of load, supply voltage and network frequency is necessary to know specific mechanism resistant moments.

The fan blower mechanism is presented by following equation [5]:

$$T_L = T_{L_{INIT}} + \left(T_{LN} - T_{L_{INIT}}\right)\left(\frac{\omega_r}{\omega_0}\right)^2 . \qquad (9)$$

After putting (6) and (9) in (8) and transformation we get:

$$\frac{d\omega_r}{dt} = \frac{p}{J_\Sigma}[x_d i_d i_q + x_{ad} i_f i_q + x_{ad} i_{Dd} i_q - x_q i_q i_d - x_{aq} i_d i_{Dq} - T_{L_{INIT}} - (T_{LN} - T_{L_{INIT}})(\frac{\omega_r}{\omega_0})^2] \qquad (10)$$

The full system of differential equations which describe the dynamic behavior of the fan blower SM drive is formed by the equations (4), (5) and (10).

3. Results

For some mechanisms with difficult starting conditions sorting electric motor is carried out according to the obtaining conditions of initial torque with definite value. Also, because of the lack of motors with sought initial torque, it is necessary to increase motor rated power so much to get enough initial torque. On the other hand sometimes initial torque of mechanism driven is increased unreasonably. Therefore we have to be quite critical to references data given for initial torque value.

That is to say it is highly important to make the right motor choice for particular drive. That is the reason for investigating the influence of initial torque on starting processes. Concerning different references this torque varies between 0.05÷0.36 multiplied by rated motor torque or 15÷25 per cent of the same.

Investigations in different values of supply voltage are done, too. It is essential to point that terms like 'increasing' and 'decreasing' of voltage are quite provisional and hold good only in cases of active and inductive loads. In case of capacitive load armature reaction causes increasing the resulting magnetic flux, which leads to voltage increasing, when the load gets larger.

The software product *MathCAD 2001* [2] has been used for solving the system, including equations (4), (5) and (10). Using the proposed mathematical model, the transient processes have been examined when the value of the supply voltage varies. Some of the results obtained are presented in the paper - Figures 3 ÷ 7, Table 1 and Table 2.

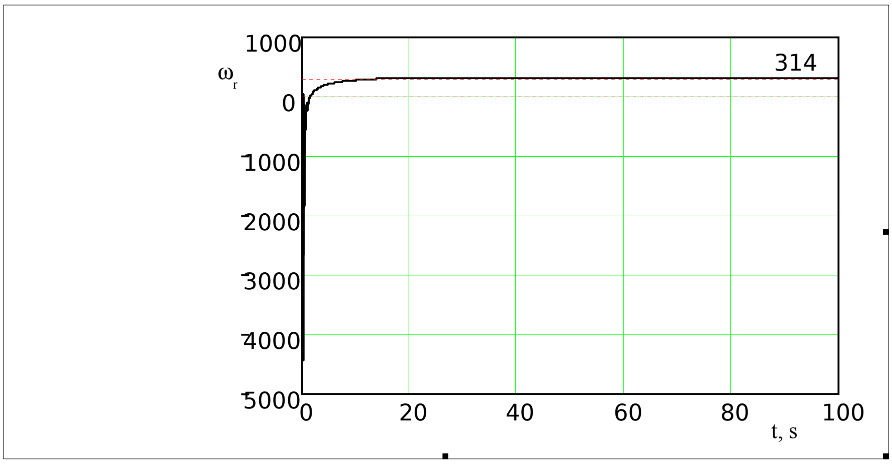

Figure 3. Characteristic ω_r =f(t).

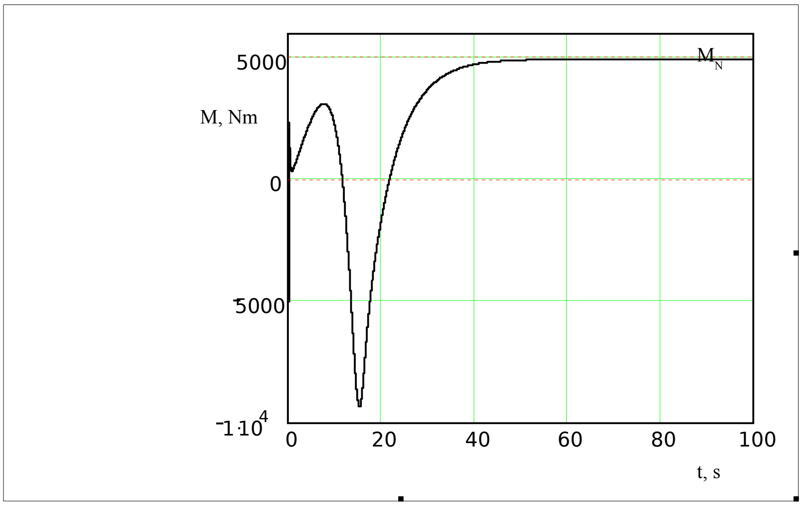

Figure 4. Characteristic M=f(t).

Table 1. Values obtained with different values of supply voltage

k_U	M_{impact}, Nm	$t_{transient\ process}$, s
0.80	7330	12.602
0.90	8339	13.271
1.00	9349	13.881
1.10	10360	14.441

Table 2. Values obtained with different initial resistant moment (k_U =1.0)

$M_{init,}$ %	M_{impact}, Nm	$t_{transient\ process}$, s
0.05	7354	13.867
0.10	9352	13.874
0.15	9349	13.881
0.20	9346	13.887
0.25	9343	13.893
0.30	9341	13.899
0.36	9338	13.906

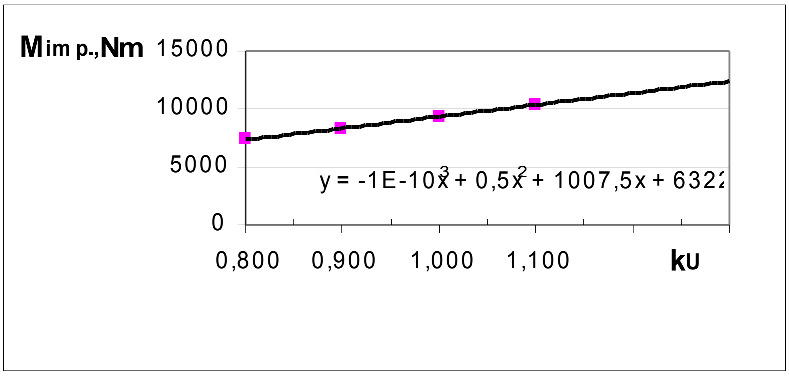

Figure 5. Characteristic M $_{impact}$ =f(k_U).

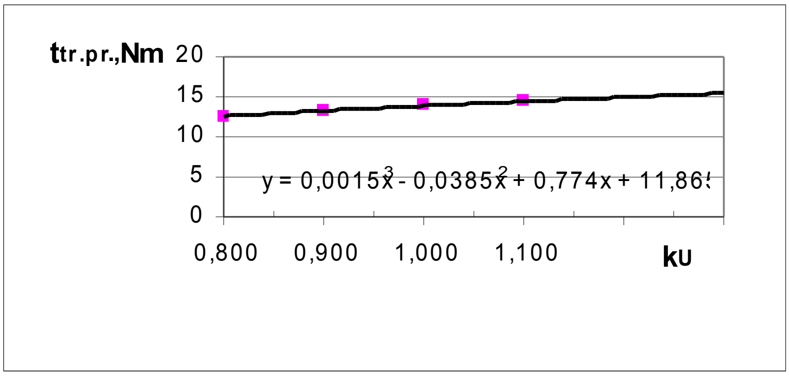

Figure 6. Characteristic t $_{\text{transient process}}$=f(k_U).

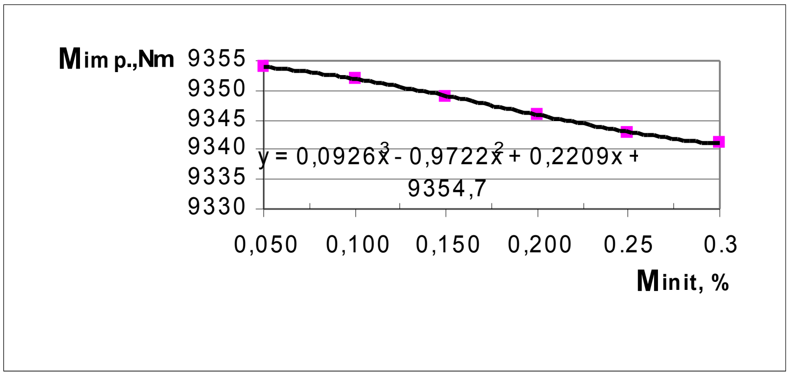

Figure 7. Characteristic M $_{\text{impact}}$ =f(M$_{\text{init}}$).

4. Conclusion

The mathematical model developed in the paper is useful for SM fan blower transient processes investigations. It is possible to determine the influences of supply voltage and initial resistant moment over the operation of the mechanism.

The detailed study of electromagnetic and electromechanical transient processes makes possible the most rational design of SM electric drives.

Appendix

Technical data of synchronous generator SD 85/56-8:

$P_N = 400kW$; $U_N = 6000V$; $f_N = 50Hz$;

$p = 4$; $n_N = 750\min^{-1}$; $I_{1N} = 46A$;

$\eta_N = 93.7\%$; $\dfrac{I_{1ST}}{I_{1N}} = 6.66$; $PF_N = 0.9(cap.)$;

$I_{fN} = 160A$; $U_{fN} = 60V$; $GD^2 = 120kgm^2$;

$r_a = 0.6025\Omega$; $r_f = 0.0602\Omega$; $r_{Dd} = 0.9112\Omega$;
$r_{Dq} = 2.1839\Omega$;
$x_{ad} = 0.3955\Omega$; $x_{aq} = 0.2481\Omega$; $x_{\sigma f} = 0.0719\Omega$;
$x_{\sigma} = 0.0529\Omega$; $x_{\sigma Dd} = 0.0391\Omega$; $x_{\sigma f} = 0.0312\Omega$.

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