MAIN CHARACTERISTICS OF STATIONARY REGIME FOR A SYNCHRONOUS MACHINE

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ABSTRACT

In this paper, we study synchronous machine properties in stationary electromagnetic processes. During the analysis of stationary regimes of functioning, we assume that the voltage that supplies the synchronous machine rotor excitation winding is constant. The three phase voltages system that supplies the stator winding is sinusoidal and symmetrical.

Keywords: *characteristics, stationary regime, synchronous machine.*

1. INTRODUCTION

Pump units which belong to the class of mechanisms with a fan characteristic are widely used in many branches of the economy. The large scale utilization and high power capacity of these units call for the introduction of the most feasible and economical electric drive systems[1-3]. There are also prerequisites of a general nature which substantiate the engineering and economicfeasibility of using controlled drives:

a) In most cases the performance of a pumping station is basically interminable and at the stage of designing this factor hampers optimum selection of the power and number of operating units ;

b) In the process of operation the performance of a unit may change substantially and it is difficult to predict these variations.

Under these circumstances it is possible to ensure the optimum operation of a pump unit only through controlled rotation of the runner. Pumps are often driven by synchronous motors (SM) whose rotor rotation velocity is adjusted by varying the feed voltage frequency. Controlled electric drives applying rectifierfrequency converters (RFC) are best adapted to these requirements. This brought forth the pressing problem of developing synchronous controlled electric drives[4-5].

The following are the basic peculiarities in the performance of a pump unit in terms of the electric drive operating conditions:

a) Dependence of the load moment and SM shaft power on the rotation velocity ;

b) Lengthy performance ;

c) Absence of reversing gear ;

d) Absence of overloads ;

e) Limited range of rotation velocity control.

Besides the above – mentioned peculiarities the specific features of the start and damping regimes of the pump unit and also the method of starting and damping the synchronous motor play an important role in the choice of frequency converter.

At presentsynchronous motors are started directly through the power circuit which has a bad effect on both the electric drive and the circuit. Energy for motor excitation is supplied from the exciter located on the SM rotor shaft. The exciter utilizes the principle of self-excitation. During the start, the exciter is disconnected from the field winding and the latter is connected to the start resistance with the aim of reducing overvoltage. The use of a RFC considerably improves the start and damping regimes of the pump unit synchronous electric drive[6-7].

In this paper, we study synchronous machine properties in stationary electromagnetic processes.

- The constant voltage $u_f = U_{mf}$;
- The three phase voltages system :

$$U_s = \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = U_{m1} \begin{bmatrix} \cos(\omega_1 t + \alpha) \\ \cos(\omega_1 t + (\alpha - \rho)) \\ \cos(\omega_1 t + (\alpha + \rho)) \end{bmatrix}$$

Where

$$\rho = \frac{2\pi}{3};\ \alpha - initialphase;\ U_{m1} - amplitude;$$

$$\omega_1 = Statorvoltageangle\ \text{frecuency that is equal to}\omega, \text{the rotor rotation speed.}$$

The stator winding voltages vector in coordinate axes d,q :

$$U_1 = \frac{2}{3}.\nabla.(\omega_1.t)^T.D_S.U_S = U_{m1}.\begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = \begin{bmatrix} U_{md} \\ U_{mq} \end{bmatrix}$$

We should consider that Stator currents in synchronous machine stationary functioning regime will be sinusoidal and voltages equations in d,q axes-constant expressions. The current amplitudes in stationary regime will be represented I_{md}, I_{mq}, I_{mf}, and the active values are notedI_d, I_q, I_f .

We have$I_{md} = \sqrt{2}.I_d;\ I_{mq} = \sqrt{2}.I_q\ ;\ I_{mf} = \sqrt{2}.I_f.$

In stationary functioning synchronous regime, the currents in short closed damping loops are equal to zero $I_{2d} = 0;\ I_{2q} = 0.$ Even the derivatives of currents in stationary regime are also equal to zero.

Considering the former factors, the synchronous machine equations in stationary regime are:

$$U_d = R_1.I_d - \omega L_q.I_q;$$

$$U_q = R_1.I_q + \omega L_d.I_d + E_f; \quad (1)$$

$$U_f = R_f.I_f$$

Where

$$L_d = L_1 + L_{dd} and L_q = L_1 + L_{qq} - totalWindinginductancesofstatorind,qaxes.$$

$$E_f = \omega L_{dd}.I_f - rotatione.m.f.$$

If we solve the system (1), the active values of stator and rotor currents are expressed as follows:

$$I_d = \frac{R_1.U_d + \omega.L_q.(U_q - E_f)}{R_1^2 + \omega^2.L_d.L_q} \quad (2)$$

$$I_q = \frac{R_1.\left(U_d - E_f\right) - \omega.L_d.U_d}{R_1^2 + \omega^2.L_d.L_q}$$

Very often the analysis of stationary electromagnetic processes is done with$\omega_1^* = \omega^* = 1$. In that case the resistance R_1 does not considerably influence the currents values. That is why in (2) we take $R_1 = 0$.

$$I_d = \frac{U_q - E_f}{\omega.L_d} = \frac{U_1.(\cos(\theta) - \mu)}{\omega.L_d}; \quad (3)$$

$$I_q = \frac{U_d}{\omega . L_q} = \frac{U_1 . \sin(\theta)}{\omega . L_q}$$

With $\theta = \alpha - \pi/2$; $\mu = E_f/U_1 - excitationcoefficient$:

Considering (3), the stator current can be expressed as follows:

$$I_1 = \sqrt{I_d^2 + I_q^2} = U_1/(\omega . L_d) . \sqrt{[\cos(\theta) - \mu]^2 + sin(\theta)^2/\xi^2}$$

Where

$\xi = L_q/L_d - thecoefficientthatcharacterisestheasymetryofmagneticsystem.$

If we multiply the second equation of (1) by imaginary complex j and after addition with first equation (1), then we obtain the voltage equation of stator in complex variables:

$$U_1 = R_1 I_1 + j.\omega . L_0 . I_1 + j\omega . L_m \widetilde{I_1} + jE_f \quad (4)$$

Where $U_1 = U_d + jU_q$;

$$I_1 = I_d + jI_q \text{ ;}$$

$$\tilde{I}_1 = I_d - jI_q;$$

$$L_m = (L_d - L_q)/2;$$

$$L_0 = (L_d + L_q)/2$$

The synchronous machine currents and voltages vector diagram that matches with equation (4) is shown in figure 1.

1- STATIONARY ELECTRIOMAGNETIC TORQUE OF A SYNCHRONOUS MACHINE

We study the main relations for determination of electromagnetic torque established functioning regime. For that purpose we assume that we enrol in stator winding a three phase sinusoidal voltages system with fixed active voltage value U_1 and frequency$\omega = \omega_1$.

For the determination of stationary electromagnetic torque, we assume damping loops currents are equal to zero:

$$M = m.\left[2. L_m . I_d . I_q + L_{dd} . I_q . I_f\right] \quad (5)$$

Where $L_m = (L_{dd} - L_{qq})/2$

From the vector diagram in figure 1,

$$I_d = I_1 . \cos(\beta) \, ; I_q = I_1 \sin(\beta)$$

Where β – deviation angle of stator current vector on longitudinal axis of magnetic symmetry d.

Thus

$$M = m\left[L_m . I_1^2 . \sin(2\beta) + L_{dd} . I_1 . I_f \sin(\beta)\right] \quad (6)$$

Where $I_1^2 = I_d^2 + I_q^2$

Let us express the stationary electromagnetic torque as function of rotor voltage. For that purpose we replace (3) in (5). After transformations, we have

$$M(\theta) = M_{m0} . [\sin(\theta) + \varepsilon \sin(2\theta)] \quad (7)$$

Where $M_{m0} = mU_1^2.\frac{\mu}{\omega^2.L_d}$; $\varepsilon = (1-\xi)/(2\xi.\mu)$;

$$\theta = \alpha - \pi/2 - load\ angle$$

$$\mu = E_f/U_1 - excitation\ coefficient$$

The electromagnetic torque has extremum for load angles

$$\theta_m = \pm arc\ cos(\sqrt{1+32\varepsilon^2} - 1)/(8\varepsilon) \quad (8)$$

For $\theta = \theta_m$, the electromagnetic torque has maximal value $M_m = M(\theta_m) \approx M_{m0}.(1+2\varepsilon^2)$

The quotient of maximal torque over nominal torque for synchronous machine is $1{,}5 \div 3$

2- ANGULAR CHARACTERISTICS OF SYNCHRONOUS MACHINE POWER

The dependence of electromagnetic torque on load angle θ is called angular characteristic of electromagnetic torque. The angular characteristic (7) for little angles θ can be approximated by a sinusoidal function:

$$M(\theta) = M_m.\sin(\pi\theta/(2\theta_m)).$$

For the construction of angular characteristic we assume that the rotationspeedω, the stator voltage active value U_1 and the excitation coefficient μ are fixed.

The aspect of angular characteristic of synchronous machine electromagnetic torque is shown on figure 2.

We have two stationary points A and B for resistance torqueM_C^*. The point A is stable and B unstable.

The synchronous machine active power is defined by the electromagnetic torque M and angularspeedω.

$$P(\theta,\mu) = \omega.M = \frac{m.U_1^2}{\omega.L_d}\left[\mu.\sin(\theta) + \frac{1-\xi}{2\xi}\sin(2.\theta)\right],$$

Where $\xi = \frac{L_q}{L_d}$

For the constant voltage on stator windings U_1 and constant rotation speedω, the active power depends on load angle θ and excitation coefficientμ. The dependence of active power $P(\theta,\mu)$ on load angle θ is called ''angular characteristic of active power. It corresponds to angular characteristic of electromagnetic torque (Fig. 2) with precision up to a factor of ω.

For angle θ_m defined by (8), the active power will reach the maximal value$P(\theta_m,\mu)$. For $\theta > 0$ the active power is positive. This means the motor functioning regime of synchronous machine and the consumption of active power from the sector. For$\theta < 0$, the active power is negative. This means the generator functionning regime and the transformation of the mechanical energy into electrical.

The total power of synchronous machine is

$$S(\theta,\mu) = m.U_1.I_1 = \frac{mU_1^2}{\omega.L_d\xi}.\sqrt{\xi^2.(\cos(\theta)-\mu)^2 + \sin(\theta)^2}$$

For constant voltage in stator windings $U_1^* = 1$ and constant rotation speed$\omega^* = 1$, the total power depends on load angle θ and excitation coefficientμ.

The angular characteristics of total power for various values of μ is shown on figure 3.

The reactive power of synchronous machine is

$$Q(\theta,\mu)=\sqrt{S^2-P^2}=\frac{mU_1^2}{\omega.L_d\xi}.[\sin(\theta)^2+\xi\cos(\theta).(\cos(\theta)-\mu)]$$

For constant voltage in stator windings U_1 and constant rotation speed, the total power depends on load angle θ and excitation coefficient μ.The relation $Q(\theta,\mu)$ is the angular characteristic of reactive power. The figure 4 shows its aspect for various values of μ.

For$\theta=0$, the reactive power has minimal value $Q(\theta,\mu)=\frac{mU_1^2.(1-\mu)}{\omega.L_d}$

The synchronous machine can function as a regulator (compensator) of reactive power consumed from network.

If excitation coefficient$\mu<1$, then the reactive power is positive. For positive reactive power I_1 vector is behind the voltage U_1vector. And the synchronous machine is an inductive load for the network.

If $\mu>1$,the reactive power is negative and the synchronous machine is a capacitive load for the network.

The regulation of reactive power consumption through μ is possible under load $(\theta\neq 0)$ when the synchronous machine functions as a motor or as a generator. If we assume that the load is constant and the consumption of reactive power Q is regulated through action on excitation winding current, then load angle θ will not remain constant.

For a fixed active power P and a givenμ, the load angle can be found from the condition

$$P=\frac{mU_1^2}{\omega.L_d}.\left[\mu\sin(\theta)+\frac{1-\xi}{2.\xi}.\sin(2\theta)\right]\approx P(\theta_m,\mu)sin\left(\frac{\pi.\theta}{2.\theta_m}\right)$$

From the latter expression we can find the load angle as a function of active power and excitation coefficient.

$\theta(P,\mu)\approx\frac{2\theta_m}{\pi}arcsin\left(\frac{P}{P(\theta_m,\mu)}\right)$(9)

The total power for a fixed active power$P$will be

$$S(\theta(P,\mu),\mu)=\frac{m.U_1^2}{\omega.L_d\xi}.\sqrt{\xi^2.[cos[\theta(P,\mu)]-\mu]^2+\sin[\theta(P,\mu)]^2}$$

Where$\theta(P,\mu)$ is defined by (9);$\xi=\frac{L_q}{L_d}$; $\mu=\frac{E_F}{U_1}-excitationcoefficient$

The representation of total power on μ for a fixed load P is shown on figure 5.

It reaches the minimum for reactive power equal to zero$Q(\theta_0,\mu)=0$

This matches with load angle

$$\theta_0(\mu)=arc\cos(\sqrt{4.(1-\xi)+(\xi\mu)^2}-\xi.\mu/(2.(1-\xi))$$

The total power as function of μ for a fixed P and with $Q(\theta,\mu)=0$ is determined by:

$$S_0(\mu)=S(\theta_0(\mu),\mu)=\frac{mU_1^2}{\omega.L_d}.\sqrt{\frac{\mu^2}{2.\xi}+\sqrt{\frac{\mu^2}{4}+\frac{1-\xi}{\xi}}-\frac{1}{\xi}}$$

The plot of dependence of total power on μ for a fixed P and $Q(\theta,\mu)=0$ is shown by the trajectory M-N

The value of total power for which the machine will be out of synchronous regime is:

$$S_m(\mu) = S(\theta_m, \mu) = \frac{mU_1^2}{\omega.L_d}.\sqrt{\frac{\mu^2.(7-5\xi)}{8.(1-\xi)} + \frac{\mu(1-3\xi)}{8.\xi}.\sqrt{\frac{\xi^2.\mu^2}{(1-\xi)^2} + 8 + \frac{1+\xi^2}{2.\xi^2}}}$$

This matches with the trajectory A-B on figure 5.

3- ENERGY LOSSES IN STATIONARY FUNCTIONING REGIME FOR A SYNCHRONOUS MACHINE

The electrical losses appear in stator windings and in excitation winding when circulation of currents.

In a stationary functioning regime the total electrical losses in stator winding and rotor excitation winding

$$\Delta P_E = m.\left(R_1.I_1^2 + R_f.I_f^2\right),$$

Where $I_1 = \frac{U_1}{\omega.L_d}.\sqrt{(\cos(\theta-\mu)^2 + sin(\theta)^2/\xi^2}$; $I_f = \frac{U_f}{R_f}$.

The plots of power losses in windings on load angle θ for a constant excitation coefficient μ are shown on figure 6.

The ratio of electromagnetic torque over power losses in windings:

$$E = \frac{M}{\Delta P_E} = \frac{L_m.I_1^2.\sin(2\beta) + L_{dd}.I_1.I_f.\sin(\beta)}{R_1.I_1^2 + R_f.I_f^2}$$

It reaches the maximal value for:

$$\beta = arc\tan\left[\sqrt{1 + \frac{R_1 L_{dd}^2}{4R_f.L_m^2}}\right] \ and \ \frac{I_1}{I_f} = \sqrt{\frac{R_F}{R_1}.\left[1 + \frac{8R_f.L_m^2}{R_1 L_{dd}^2}\right]}$$

4- CONCLUSIONS

For synchronous machine stationary rotor movement, currents in damping winding do not exist. Currents in rotor excitation winding are defined only by rotor voltage. To characterize the rotor excitation current, it is important to introduce the notion of excitation coefficient.

For constant stator voltage and constant current in excitation winding, currents in stator winding are defined by load angle and excitation coefficient. For a fixed excitation coefficient, total, active and reactive powers and also electromagnetic torque are functions of load angle and they have a U-form character.

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FIGURES

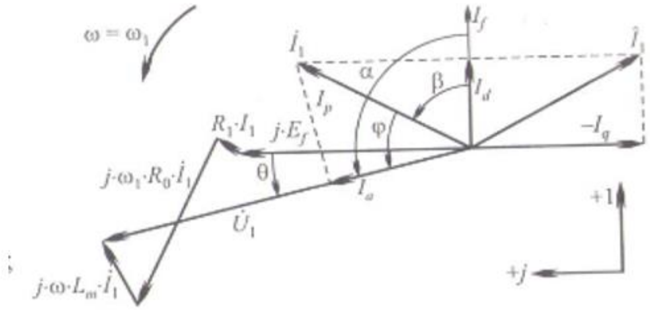

Figure 1: *Vector diagram of synchronous machine currents and voltages.*

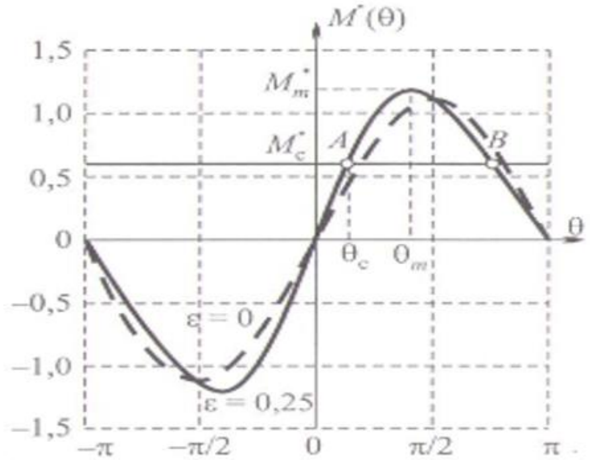

Figure 2: *Angular characteristics of electromagnetic torque.*

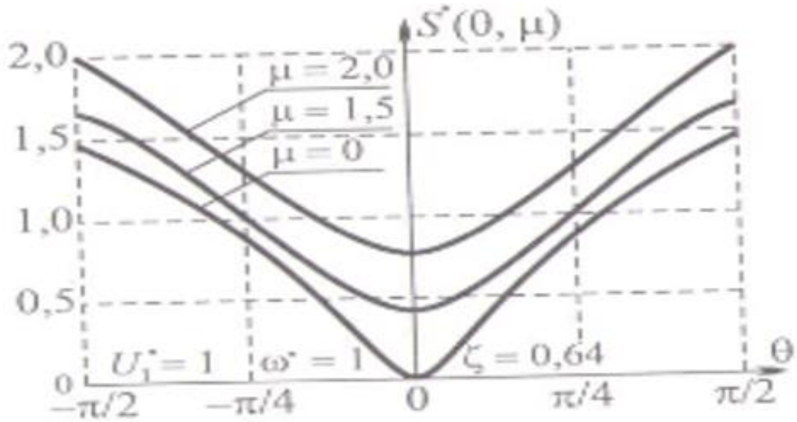

Figure 3: *Angular characteristics of total power.*

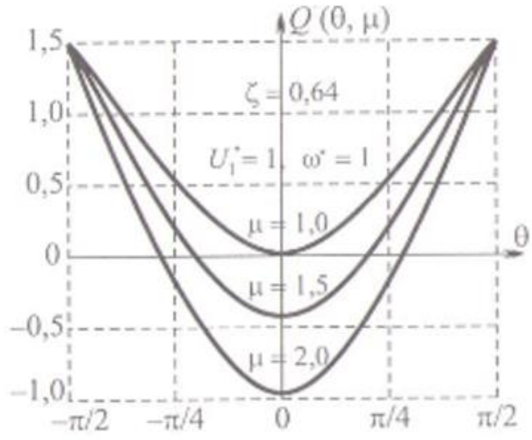

Figure 4: *Angular characteristics of reactive power.*

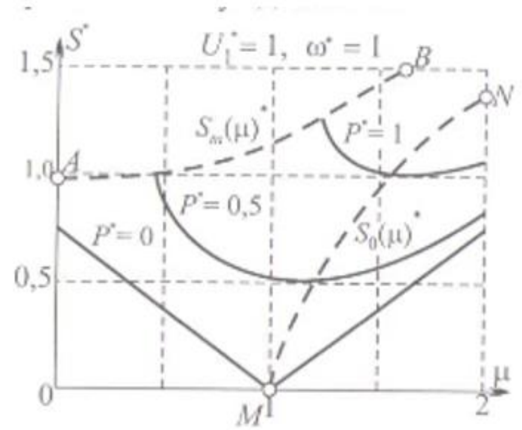

Figure 5: *Dependence of total power on excitation coefficient with constant active power.*

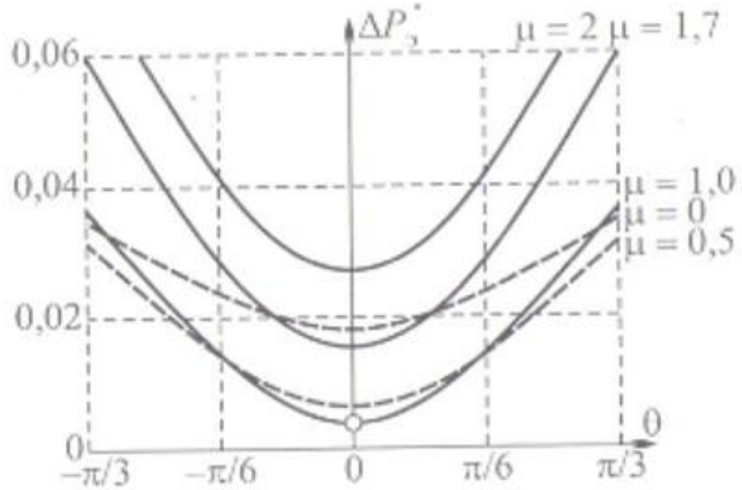

Figure 6: *Dependence of power losses in windings on load angle with constant excitation coefficient.*