ANALELE UNIVERSITĂȚII
"EFTIMIE MURGU"REȘIȚA
ANUL XXII, NR. 1, 2015, ISSN 1453 - 7397

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Optimisation of the Start-up and Operation Regimes of Cooling Water Pumps of a High-Power Hydro Generator

It is necessary to make sure that the operation of cooling installations of hydro generators could be made in conditions of enhanced security so that the probability of defects occurrence during their exploitation be practically null. The asynchronous regime of direct network start up is accompanied by very high values of the start-up current, associated with important voltage drops on supply cables, which results in the extension of the motor starting time. The present paper shows an efficient method of driving the cooling water pumps by the supply of electric driving motors with variable frequency.

Keywords: *hydro generator, optimisation, asynchronous motor, pumps, variable efficiency.*

1. Introduction

The pumps assuring the cooling water to a high power hydro generator is driven by asynchronous motors with the rotor in short-circuit. The electric installation for driving these motors must assure the following:

- startup in safety conditions of asynchronous motors for driving the pumps supplying the cooling water to the hydro generator
- reduction of the thermal stresses in the stator winding of the asynchronous motor by the optimisation of the startup process
- reduction of the startup current during the asynchronous short circuit regime, in order to diminish the electromagnetic stresses in asynchronous motors
- change of the rotation speed of driving asynchronous motors, depending on the necessary cooling water debit.

2. Theoretic considerations

The economic operation of an electric driving system is closely connected, on the one hand, to the driving system and on the other hand by the indices which characterise the economic regime. [1]

When the electric motor is directly supplied from the electric power network, the main components of an electric driving system are:

- the electric motor M
- the transmission organ OT
- the working machine ML

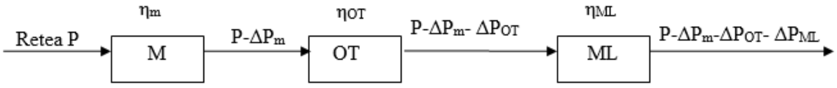

Figure 1. Diagram of direct electric driving

The indices characterising the economic regime of the driving system:

- the electric power P_e consumed by the motor from the network
- the motor efficiency η_m
- the efficiency of the transmission organ η_{OT}
- the efficiency of the working machine η_{ML}

The efficiencies determine the power losses: ΔP_m – in motor, ΔP_{OT} – in the transmission organ, ΔP_{ML} – in the working machine. These power losses determine the useful mechanical power Pm at the exit from the system [2], [3].

As during the operation process the driving system is put to operate in very different conditions, which impose the change of parameters of the electric driving motor, it is necessary that the electric motor operates on another characteristic than the natural one. For this to be possible it is necessary that the motor supply is made through an intermediate device which allows the adaptation of the motor operation characteristic to the requirements of the working process.

In this case, the driving system will be that shown in figure 2 [1]:

Figure 2. Diagram of indirect electric driving

If the electric motor operates at nominal voltage and frequency parameters, it will operate on the natural characteristic.

If the working process imposes operation conditions which the electric motor cannot fulfil on the natural characteristic, it is necessary, through the DA driving device, to proceed to the modification of certain operation parameters so that the motor can pass to the artificial characteristic that may assure the required conditions.

The artificial mechanical characteristics [2], [3] for an asynchronous motor may be obtained by the change of the resistance in the rotor circuit:

- the change of the power voltage U1
- the change of the frequency of the supply voltage f1

An asynchronous machine may be equalled with en electric circuit of a certain impedance, defined through the electric parameters [4-6]:

- stator dispersion impedance

$$\underline{Z_1} = R_1 + jX_{1\sigma} \tag{1}$$

- rotor dispersion impedance reduced to the stator

$$\underline{Z_2'} = R_2' + jX_{2\sigma}' \tag{2}$$

- magnetisation impedance

$$\underline{Z_m = R_m + jX_m} \tag{3}$$

- load impedance

$$\underline{Z_s'} = \frac{1-s}{s} R_2' \tag{4}$$

where: R_m – magnetisation resistance; $X_{1\sigma}$ – dispersion impedance on a stator phase; $X_{2\sigma'}$ – dispersion reactance for a rotor phase reduced to the stator; X_m – magnetisation resistance; s – rotor slide

The equivalent diagram of the asynchronous machine is shown in Figure 3.[2,6] The frequency of the motor rotor current is f_2 and it varies depending on the slide s, resulting:

$$f_2 = s * f_1 \tag{5}$$

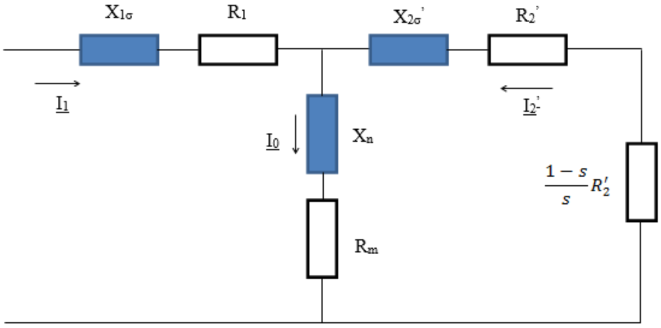

Figure 3. The equivalent diagram of the nominal operation of asynchronous motor

It results that the electromotor voltage U_{e2} and the inductive reactance X_2 of the rotor winding will change too along with the slide s, as it depends on the rotor circuit frequency.

If the rotor is blocked, and thus n=0, the following slide results:

$$s_0 = \frac{n_1 - n}{n_1} = \frac{n_1}{n_1} = 1 \tag{6}$$

The rotor reactance in these conditions is X_{20} and the induced electromotor voltage will be U_{e20}. It results that the operation at a slide $s_0 = \frac{n_1 - n}{n_1}$ we get , for the rotor reactance, the expression : $X_2 = s * X_{20}$, and $U_{e2} = s * U_{e20}$ respectively.

In this situation for describing the connection relations between the stator circuit and the rotor circuit of an asynchronous motor, it is necessary to report the parameters of the rotor circuit to the number of coils of the stator circuit [7,8].

The relationing is made by writing the ratio between electromotor voltage U_{e1} from the stator and from the rotor U_{e20} , more precisely:

$$\frac{U_{e1}}{U_{e20}} = \frac{w_1 * k_1}{w_2 * k_2} = C_U \tag{7}$$

and at the same time one writes also the ratio between the stator currents I_1 and rotor currents I_2:

$$\frac{I_1}{I_2} = \frac{w_1 * m_1 * k_1}{w_2 * m_2 * k_2} = C_i \tag{8}$$

where: m_1, m_2 – number of phases in stator and rotor respectively
w_1, w_2 – number of coils in the stator and rotor respectively
k_1, k_2 – factors of stator and rotor winding.

we thus obtain:

$$U'_{e20} = C_e * U_{e20} = U_{e1} \tag{9}$$

$$I'_2 = \frac{I_2}{C_i} \tag{10}$$

$$r'_2 = C_i^2 * r_2 \qquad \text{and} \qquad X'_2 = C_i^2 * X_2 \tag{11}$$

Like in the case of the asynchronous motor [9,10] the current I_2' has a value close to that of the stator current and thus it cannot be neglected. It results that the variable losses in the stator and rotor wingding are given by the relation:

$$p = 3\left(I_1^2 * r_1 + I_2'^2 * r_2'\right) \tag{12}$$

taking into account the relation

$$\underline{I_1} = \underline{I'_2} + \underline{I_0}, \tag{13}$$

it results:

$$p = 3I_2'^2\left(r_1 + r_2'\right) + 3I_0^2 * r_1 \tag{14}$$

As the losses caused by the magnetisation current I_0 are practically constant, one may consider that the variable losses may be calculated with the relation:

$$p = 3I_2'^2(r_1 + r_2') \tag{15}$$

When the motor operates in nominal regime, the losses will be:

$$p_n = 3I_{2n}'^2(r_1 + r_2') \tag{16}$$

In general in nominal load the variable losses p are related to the nominal ones p_n.

3. Optimisation of the operation regimes on the artificial characteristic of the asynchronous machine

The artificial mechanic characteristic for an asynchronous motor with the rotor in short-circuit may be obtained by the change of the supply voltage U_1 and by the change of the frequency of the supply voltage f_1 [7-10].

The analytical expression of the mechanical characteristic of the asynchronous motor may be written under the form [2]:

$$M = \frac{2 \cdot M_k}{\frac{s}{s_k} + \frac{s_k}{s}} \tag{17}$$

where:

M – is the motor load couple;
M_k – is the critical couple of the motor;
s – motor slide during nominal operation;
s_k – critical slide.

The plot of the mechanic characteristics is given in Figure 4:

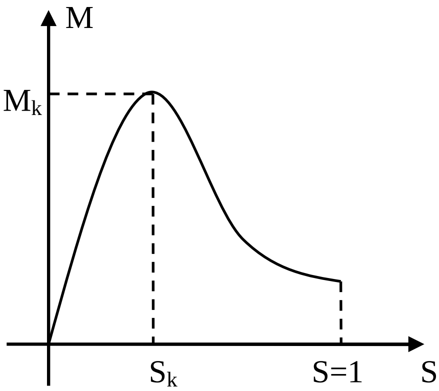

Figure 4. Mechanic characteristic of the asynchronous motor

The critical couple M_k is the maximum value that can be reached by the motor couple during startup when the number of revolutions grows from n=0 to $n=n_1$ and the slide drops from s=1 to s=0.

The value of the critical couple is given by the relation:

$$M_k = \frac{m_1}{\omega_0} \cdot \frac{v_1^2}{x_1 + x_2^{'}} \tag{18}$$

where:

m_1 – number of phases of the stator circuit

ω_0 - $2\pi f_1$ is the pulse of the current

x_1, $x_2^{'}$ - the dispersion reactances of the stator and rotor, respectively

The inductive reactances are given by the relations of the form:

$x=2\pi f_1 L$

where:

L-is the inductivity of the respective winding (stator or rotor)

In general, in the machine catalogue or on the indicative tag, the critical couple is given by the relation:

$$M_k = \lambda \cdot M_n \tag{19}$$

where:

λ – is the coefficient of the motor over load

M_n – is the nominal couple of the motor

For the asynchronous motors destined to the driving of the water pumps, λ varies within the limits $1.8 < \lambda < 2.5$ and is established when the motor is designed.

As it results from Figure 1.5, to the critical couple M_k corresponds the critical slide s_k given by the relation:

$$s_k = \frac{r_2^{'}}{x_1 + x_2} \tag{20}$$

where:

$r_2^{'}$ - is the phase resistance of the rotor circuit compared to the stator

When the operation parameters are different from the nominal ones we obtain the artificial operation characteristics.

When the supply voltage is $U_1^{'} < U_1$, the motor will operate on the artificial characteristic 2, where the critical couple varies with the square voltage, the value of the critical slide remaining unchanged. [3-5,8]

The critical couple $M_k^{'}$ will be much smaller in relation with Mk, according to the relation:

$$\frac{M_k^{'}}{M_k} = \left(\frac{U_1^{'}}{U_1}\right)^2 \tag{21}$$

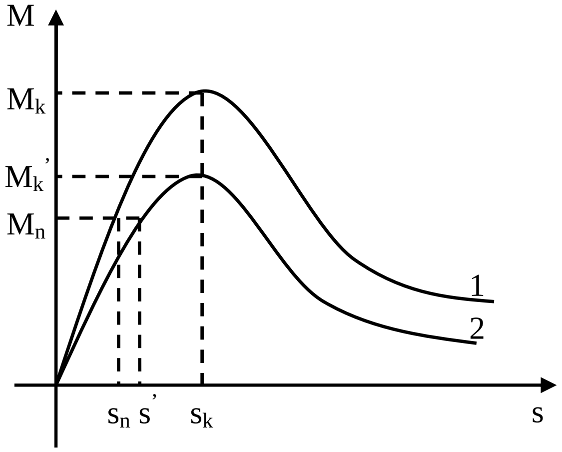

Figure 5. The artificial characteristic of the asynchronous motor operation 1 –natural characteristic at $U_1=U_n$;, 2- artificial characteristic at $U_1^{'} < U_n$.

What is important is that the artificial characteristic should not exceed the maximum admissible value from the thermal point of view.

If the motor operates on the artificial characteristic, the slide $s' > s_n$, the losses in the machine will be:

$$p = p_n \left(\frac{U_1^{'}}{U_1}\right)^2 \cdot \frac{1+\left(\frac{s_k}{s_n}\right)^2}{1+\left(\frac{s_k}{s}\right)^2} \tag{22}$$

It results that the variable power losses on an artificial mechanic characteristic, obtained by the change of the supply voltage, depend on the variable losses on the natural mechanic characteristic at the nominal load (p_n), the square ratio of voltages $\left(\frac{U_1^{'}}{U_1}\right)^2$ and the slide s at which the motor operates on the artificial mechanic characteristic, through the relation

$$x = \frac{1+\left(\dfrac{s_k}{s_n}\right)^2}{1+\left(\dfrac{s_k}{s}\right)^2} \tag{23}$$

If s>s$_n$, it results that $\frac{s_k}{s} > \frac{s_k}{s_n}$ and thus the ratio is higher than one (x>1) which determines the losses to be amplified. it results that at lower voltages the iron mechanical loses are lower, when s<s$_n$.

In the case of the asynchronous motor operation on an artificial mechanic characterise obtained by the change of the supply voltage frequency f$_1$, one modifies both the critical couple M$_k$ and the critical slide s$_k$.

For s$_k$ and M$_k$ the following expressions result:

$$S_k = \frac{r_2^{'}}{x_1 + x_2^{'}} = \frac{r_2^{'}}{2\pi f_1 (L_1 + L_2^{'})} = \frac{K_1}{f_1} \tag{24}$$

$$M_k = \frac{m_1}{\omega_0} \cdot \frac{U_1^2}{x_1 + x_2^{'}} = \frac{m_1}{2\pi f_1} \cdot \frac{U_1^2}{2\pi f_1 (L_1 + L_2^{'})} = \frac{K_2}{f_1^2} \tag{25}$$

where:

L$_1$ and L$_2'$– are the dispersion inductivities of the stator-rotor windings

K$_1$ and K$_2$ – are the constant depending on the motor electric parameters

$$K_1 = \frac{r_2^{'}}{2\pi (L_1 + L_2^{'})} \tag{26}$$

$$K_2 = \frac{m_1 U_1^2}{4\pi^2 (L_1 + L_2^{'})} \tag{27}$$

One remarks that for f$_1'$< f$_1$, thus when the frequency drops, both the critical couple and the critical slide grow, i.e. s$_k$′ > s and M$_k$′ > M$_k$.

In this situation, if the natural mechanic characteristic is curve 1, the artificial mechanic characteristic for f$_1'$< f$_1$ is curve 2. [9-10].

For f$_1'$< f$_1$ the asynchronous motor will function on the artificial characteristic 2.

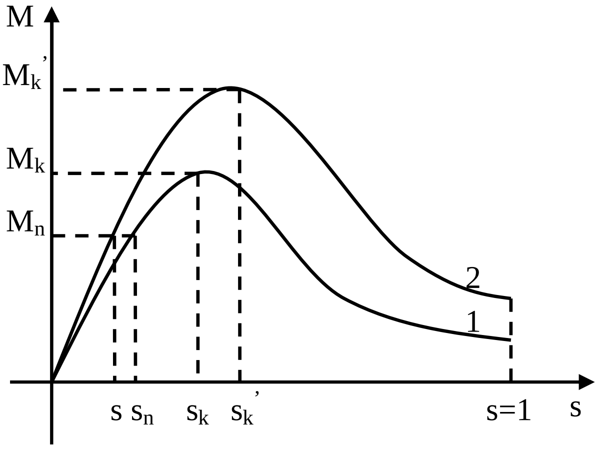

Figure 6. Artificial operation characteristics at $f_1^{'} < f_1$

If one considers that the variable losses on the natural mechanic characteristic at nominal load:

$$p_n = 3I_{2n}^{'2}(r_1 + r_2^{'}) \tag{28}$$

and the variable losses on the artificial characteristic 2, at a load $M \neq M_n$:

$$p_f = 3I_2^{'2}(r_1 + r_2^{'}) \tag{29}$$

the following relation results:

$$p_f = p_n \cdot \frac{I_2^{'2}}{I_{2n}^{'2}} \tag{30}$$

In order to express these losses depending on the frequency, one considers the relation [7-9]:

$$\frac{M}{M_n} = \frac{\frac{m_1}{2\pi f_1^{'}} I_2^{'\,2} \frac{r_2^{'}}{s}}{\frac{m_1}{2\pi f_1} I_{2n}^{'\,2} \frac{r_2^{'}}{s_n}} = \frac{f_1 \cdot I_2^{'\,2} \cdot s_n}{f_1^{'} \cdot I_{2n}^{'\,2} \cdot s} \tag{31}$$

Furthermore, one calculates the ratio

$$\frac{M_k^{'}}{M_k} = \frac{k_2 \cdot f_1^2}{f_1^{'2} \cdot k_2} = \frac{f_1^2}{f_1^{'2}} \tag{32}$$

$$\frac{s_k^{'}}{s_k} = \frac{f_1}{f_1^{'}} \tag{33}$$

At the same time, we may write the relation:

$$\frac{M_k^{'}}{M_k}=\frac{M}{M_n}\cdot\frac{s_n\left(s^2+s_k^{'\,2}\right)}{s\left(s_n^2+s_k^{'\,2}\right)} \tag{34}$$

Considering the ratios of couples and critical slides one may write:

$$\frac{f_1^2}{f_1^{'2}}=\frac{f_1\cdot I_2^{'\,2}\cdot s_n}{f_1\cdot I_{2n}^{'\,2}\cdot s}\cdot\frac{s_n\left[s^2+s_k^2\left(\frac{f_1}{f_1^{'}}\right)^2\right]}{s\left(s_n^2+s_k^2\right)} \tag{35}$$

$$\frac{f_1^2}{f_1^{'2}}=\frac{I_2^{'\,2}\left[1+\left(\frac{s_k}{s}\right)^2\cdot\left(\frac{f_1}{f_1^{'}}\right)^2\right]}{I_{2n}^{'\,2}\left[1+\left(\frac{s_k}{s_n}\right)^2\right]} \tag{36}$$

It results:

$$\frac{I_2^{'\,2}}{I_{2n}^{'\,2}}=\frac{f_1}{f_1^{'}}\cdot\frac{1+\left(\frac{s_k}{s}\right)^2}{1+\left(\frac{s_k}{s}\right)^2\cdot\left(\frac{f_1}{f_1^{'}}\right)^2} \tag{37}$$

It results, for the motor losses when they operate on an artificial characteristic at $f_1^{'}< f_1$.

$$p_f=p_n\cdot\frac{f_1}{f_1^{'}}\cdot\frac{1+\left(\frac{s_k}{s_n}\right)^2}{1+\left(\frac{s_k}{s}\right)^2\cdot\left(\frac{f_1}{f_1^{'}}\right)^2} \tag{38}$$

The interpretation of the ratio $\frac{I_2^{'\,2}}{I_{2n}^{'\,2}}$ involves certain difficulties, as it depends both on the frequencies ratio, and on the slide s, and each of them may take different values, independent from each other. That is why the establishment of the value of the square currents ratio must be made by calculations based on concrete data [5,8].

For a first appreciation of the manner in which the currents ratio is changed one may resort to a plot like that presented in Figure 7 , showing the variation of the currents ratio depending on different values of frequencies ratio.

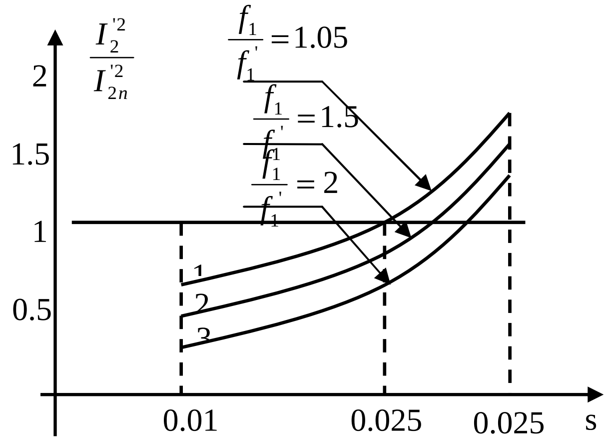

Figure 7. Variation of the ratio $\frac{I_2'^2}{I_{2n}'^2} = f(s)$

From the examination of the curves in the figure we remark that for frequency values $f_1' < f_1$, but close in value (curve 1) the ratio of the square currents $\frac{I_2'^2}{I_{2n}'^2}$ is below the unit, for slides smaller that the nominal slide $s_n = 0.025$ it becomes higher than the unit for a slide $s > s_n$. Along with the drop of frequency f1′ in relation with the nominal frequency f_1 (curves 2 and 3), the square currents ratio remains below the unit also for slides with (5-10)% higher than the nominal slide, and then it becomes higher than the unit.

It results that the variable power losses p_f at the motor operation on the artificial characteristic, in are even smaller in relation with the variable losses p_n on the natural mechanic characteristic at nominal load, when the frequencies ratio $\frac{f_1}{f_1'}$ is higher than the unit .[1-3,10].

For slides lower than (10-20)% of the nominal slide s_n and for frequencies f_1' (50-75)% smaller than f_1, the square currents ratio becomes higher than the unit , thus $p_f > p_n$.

As regards the other losses in the case of the motor operation on an artificial mechanic characteristic, when the frequency is changed one has to take into account the following:

- the additional losses due to the heating of the motor determined by the magnetisation current is considered to be 0.5% of the P_n of the motor;
- the losses in iron , those by hysteresis, varies along with the frequency, i.e.:

$$p_H = (p_H)_n \cdot \left(\frac{f_1}{f_1^{'}} \right) \tag{39}$$

where:

$(p_H)_n$ - are the losses by hysteresis at nominal frequency

- losses by swirl currents vary along the square frequencies , i.e. :

$$p_t = (p_t)_n \cdot \left(\frac{f_1}{f_1^{'}} \right)^2 \tag{40}$$

where:

$(p_t)_n$ - are the losses corresponding to the nominal frequency

As it is practically difficult to separate the losses by hsystersis from those by swirl currents, one may consider that the total losses in iron , i.e., those through swirl currents and hysteresis taken together, are given by the relation:

$$p_{fe} = (p_{fe})_n \cdot \left(\frac{f_1}{f_1^{'}} \right)^{\beta} \tag{41}$$

where:

β = (1.2-1.6) depending on the sheet quality.

It results that, when the motor operates on an artificial mechanic characteristic at a frequency $f_1 < f_1^{'}$, the losses in iron are lower than the nominal ones.

The mechanical losses change depending on the point on the artificial mechanic characteristic on which the motor operates.

It results that from the point of view of losses, in the operation in conditions of low frequency compared to the nominal one, the motor operates more economically.

4. Conclusions

The powering at variable frequency of the synchronous motors for the driving of the cooling water pumps represents an efficient modality of water debit adjustment in the cooling installations of hydro generators.

Depending on the number of hydro units that are in operation and the power disloadd in the network one establishes the cooling water debit necessary for an operation of the hydro generator in normal conditions of temperature of the stator winding, rotor winding and stator magnetic core.

The adaptation of the cooling water debit at the operation regime of the hydro generator is made through the corresponding change of the frequency of the motor supply voltage of the asynchronous motors.

Thus one creates the possibility of exploiting the asynchronous motors of cooling water pumps driving in optimum conditions both in the start-up regime and the operation regime in load.

The method presented for the adjustment of the cooling water debit of the hydro generator by the supply with variable frequency power of the asynchronous motor presents a series of advantages:

- reduction of the electric power consumption by the adaptation of the rotation speed of asynchronous driving motors to the necessary water debit
- the automatic change of the cooling water debit depending on the heat regime of hydro unit operation for the avoidance of condense inside the hydro generator
- reduction of the electromagnetic stresses from the asynchronous mottos during the asynchronous start-up regime
- increase of the safety degree in the operation of electric motors
- Increase of the life duration of the electro pumps assuring the cooling water for the hydro units.

Acknowledgement

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/132395.

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