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ABOUT ADJUSTING THE MAGNETIC FLUX OF ELECTRIC MACHINES IN THE CASE OF THEIR OVER RATED ROTATIONAL SPEEDS

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Abstract. In this paper are analyzed situations requiring the adjustment of the excitation magnetic flux in the case of electric machines working in technological processes that require the operation at over rated speeds. There are presented some measures that are required in such situations. An example is an oil extraction plant where, in technological process, periodically are repeating time intervals in which the electric machine is working at over-synchronous speeds.

There are analyzed the phenomena that occur in the operation at over-synchronous speeds of the DC machine and the induction machine and the way in which should be acted in each case. The paper also presented some practical aspects regarding special electric drives modeled in MATLAB using its library of SPS (SimPowerSystems), Electric Drives Models (DTC and field-oriented control). It was proposed a custom variant, which may be extended and performed by future researches.

Key words: induction machine; DC machine; magnetic flux adjustment; over-synchronous speed.

1. Introduction

As long as an electrical machine is operating at a speed not exceeding the nominal one, the excitation flux of the machine may remain at the nominal

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level, that is, at the level that was considered when designing it, *i.e.* 0.8 Wb. But the electrical machine can be included in a technological process that can also require it to operate at higher than nominal speeds.

For example, in the case of oil extraction with a Canadian pump, the main process of complete extraction requires two "segments":

a) an upward stroke of the pump, in which the kilometers of extraction rods, together with the piston of the pump, performs an ascending movement to the surface of the well;

b) a downward stroke of the pump, in which the aforementioned assembly carries a downward movement towards the bottom of the pump, at the bottom of the extraction well.

This technologically-driven "backward-and-forward motion" makes the electric drive machine of the extraction system work during a complete extraction stroke in both motor (in the ascending stroke) and generator mode (in the downward stroke), when the machine speed is usually higher than synchronous speed and when the magnetic flux has to be "corrected", depending on the speed of the machine, properly.

This issue is important from several points of view, considering that a complete extraction stroke, depending on the characteristics of the extraction system, can take 6,...,14,...,20 s, meaning the driving machine passes through the two modes of operation frequently, without greatly achieving the "balance" of time between ascending and descending stroke; afterwards, the transient acceleration/deceleration processes, also conditioned by the specific time constants, should be taken into consideration, and these time constants have significant values at such a technological installation, which is also of particular importance in starting of such installations.

On the other hand, if the driving machine works in the generator mode, it means that it provides energy, that is, it actually works in brake mode, which can be in the two variants:

– with energy recovery;

– without energy recovery or the dynamic regime.

Most often, especially in this kind of simulations, the second variant is used.

2. The Case of the Direct Current (DC) Machine

First of all, the DC machine is emphasized, because it is not so complex and many of the collateral aspects, which have their importance, can be easier explained.

For this type of machine, the moment of electromagnetic torque can be determined with the classic expression:

$$M = kI_a\Phi, \tag{1}$$

that is, the machine's electromagnetic torque can be changed in two ways:

a) by modifying the rotor current of the machine I_a, possibly by adjusting the supply voltage of the machine (the case of the machine with separated sources for supplying the rotor circuit, respectively the excitation circuit);

b) by modifying its excitation flux Φ, eventually by modifying the excitation current.

However, this extremely "simple" scheme, which refers to the "decoupling" aspect of the DC machine, is valid only for the completely compensated DC machine.

What does this thing mean? From the DC machine theory, it is known that due to the effect of the reaction field of induced, produced by the load current of the machine, *i.e.* its rotor current, the flux inside in the machine air gap changes within certain limits, depending on the operating current, which in turn, is imposed by the technology in which the drive is implemented. Thus, the "decoupling" allowed according to (1) is not valid, but this problem is solved by fitting a corresponding compensation winding within the polar parts of the excitation poles of the machine; in this way, the DC machine is compensated (practically, all DC machines above 25,...,30 kW are made fully compensated) and the "decoupling" effect provided by relation (1) remains valid.

On the other hand, taking into consideration the mechanical characteristic of the DC machine, also expressed by the classical relationship:

$$\Omega = \frac{U}{k\Phi} - \frac{R_a}{k^2\Phi^2} M \ , \tag{2}$$

in which the notations are known and are not explained here, by diminishing the excitation current, over rated speeds can be obtained. In this way, the machine can operate at higher speeds than the nominal ones. From (2) it can be seen that by decreasing the excitation flux, both the ideal idle angular velocity ($\Omega_0 = U/k\Phi$), and the slope of the mechanical characteristic ($R_a/k^2\Phi^2$) that is, these mechanical characteristics of the flux will not be parallel to the natural mechanical characteristics of the DC machine, as is shown in Fig. 1. In Fig. 1, there are a number of elements to which have to paying attention to. Firstly, it should be noted that in the coordinate system ($\Omega_0 M$) the product $\Omega \times M$ represents a power and it appears as a equilateral hyperbola (because it is of the form $y = a/x$), and it could be called the limiting hyperbola (at the nominal power level).

This because all the operation points of this hyperbole located at "right" can not be considered admissible because they will be disposed in an area where the nominal power of the machine will be exceeded. On the "left" of this hyperbole, there could be many operating points with over rated speeds, but "something" must be reduced.

It can be reduced the excitation flux of the machine Φ, which in terms of the relation (1) means the reduction of the torque, if I_a remains the same (and obviously it cannot exceed its nominal value).

How does MATLAB do in the simulations that it makes? It approximates the "limitative equilateral hyperbola" with a straight line, conveniently chosen (see Fig. 1), because this line will be more "secure" than the limitative equilateral hyperbola, and has the advantage of working with a linear element.

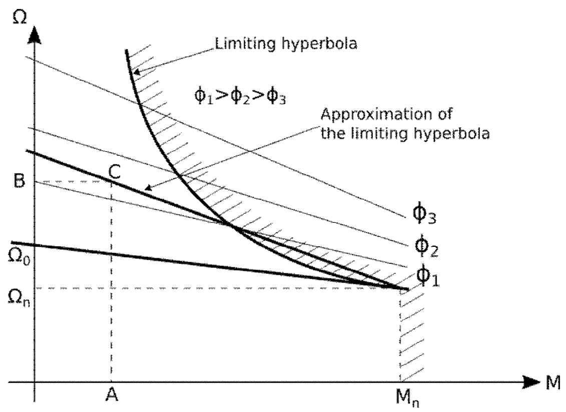

Fig. 1 – Explanatory for establishing an expression of type $\Phi = f(\Omega)$.

It can be observed that the "approximation" of the limitative hyperbole may deprive the operation of drive machine at very high speeds (see Fig. 1); but in practice it is not intended to operate at very high speeds, as would admit a limitative hyperbole, because such speeds are generally not mechanically acceptable for either an electrical machine or technological installations. However, if such high speeds are required, then special electrical machines specifically designed for that specific variant may be used.

In the case of a DC machine it should also noticed that the switching element worsens quite pronounced under operating conditions at too high rotations; this is why, for example, for a DC machine, its rotations is specified on the manufacturing label: 1,500,...,2,300 rot/min where its rated speed is 1,500 rot/min but its maximum speed is limited to 2,300 rot/min.

3. The Case of the Induction Machine

The induction machine, especially the one with the squirrel cage rotor, is most often used in the case of electrical driven of various types, of relatively small or medium powers (but sometimes also of high powers), for its reliability and robustness under various operating conditions. These issues are well-known and do not even have to be demonstrated.

In addition, the induction machine, as opposed to the DC machine described above, has a great advantage: it is self compensated, meaning it no longer needs an "additional" design element (such as the DC winding compensator), because in the determination of the electromagnetic torque it behaves "decoupled" under certain field orientation conditions, in which the system of dynamic equations is written.

Indeed, the general system of equations for a generalized electric machine can be presented as:

$$\begin{gathered}\underline{U}_s^k = R_s \underline{I}_s^k + \frac{\mathrm{d}\underline{\Psi}_s^k}{\mathrm{d}t} + \mathrm{j}\Omega_k \underline{\Psi}_s^k;\\ \underline{U}_r^k = R_r \underline{I}_r^k + \frac{\mathrm{d}\underline{\Psi}_r^k}{\mathrm{d}t} + \mathrm{j}(\Omega_k - \Omega_r)\underline{\Psi}_r^k;\\ \underline{\Psi}_s^k = X_s \underline{I}_s^k + X_m \underline{I}_r^k \quad \text{and} \quad \underline{\Psi}_r^k = X_r \underline{I}_r^k + X_m \underline{I}_s^k;\\ M_e = \Im\{\underline{\Psi}_s^{k*}.\underline{I}_s^k\} = \Im\{\underline{\Psi}_r^k.\underline{I}_r^{k*}\} = \Im\{\underline{\Psi}_m^{k*}.\underline{I}_s^k\} = \Im\{\underline{\Psi}_m^k.\underline{I}_r^{k*}\},\end{gathered} \tag{3}$$

where the notations are the usual ones, the index k refers to a coordinate system (which is rotating at speed Ω_k) and the moment of the electromagnetic torque is expressed in several variants as the product of certain magnetic fluxes and currents (items considered as spatial vectors).

The angular speed Ω_k of a given coordinate system, in the general case, may be of any value, but in the study of the induction machine is usually customized to some particular values. The most commonly used system is(d, q) that is, the one for which $\Omega_k = \Omega_s$, respectively, which rotates with synchronous speed.

It is also obvious that for the case of the asynchronous machine (especially with the specificity of the squirrel cage rotor - most commonly used variant) in the equations in (3) it will be considered $\underline{U}_r^k = 0$, without referring to the double supplying of the machine. In this way, if the coordinate system (d, q) is used and orientation is made after the rotor flux, then, when the $\Psi_{rd} = \Psi_r$, respectively $\Psi_{rq} = 0$, the main system in (3) is simplified very much and it can be noted as (Kisch, 1998):

$$\begin{gathered}\Psi_r = X_m I_{sd} - T_r \frac{d\Psi_r}{dt};\\ M_e = \frac{X_m}{X_r}\Psi_r I_{sq};\\ \Omega_r = s\Omega_s,\end{gathered} \tag{4}$$

where T_r is the time constant of the rotor circuit with the open stator winding.

From equations (4) it can be seen that in this case, the induction machine appears "decoupled" (*i.e.*, it appears with certain expressions independent of some quantitys) along the axes d and q: the component according to the "d" axis of the stator current (I_{sd}) (according with the first relationship in (4)) controls the value of the rotor flux (Ψ_r) and the component of the stator current q (I_{sq}) (according to the 2nd relation of (4)) controls the value of the electromagnetic torque. In this way, the independence of the items that produce the electromagnetic torque of an induction machine can be emphasized by the "field-orientation method".

It is also demonstrated that in a saturated electric machine or with controlled magnetizing flux, the vector of the rotor current is disposed orthogonally relative to the vector of the magnetization flux, and this occurs exactly as in the case of the DC machine.

Referring to the induction machine as a generalized electrical machine, where the stator has two windings: one disposed along the d-axis and supplied with current $I_{sd} = I_m$, which magnetizes the machine, respectively, produces the flux Ψ_m in the same direction, so this current would be the equivalent of the excitation current I_e (which produces the excitation flux Φ_e also in the same direction). But the rotor current that contributes to the torque production can only be produced in the rotor winding through the induction phenomenon due to the variation of the magnetic flux or the current I_{sq} in the stator winding disposed along the axis q and which is perpendicular to the direction of the flux (because is perpendicular to direction d). However, because the vectoric sum of currents in the stator and the rotor is equal to the current $\underline{I}_m$ (which is in phase with the flux $\underline{\Psi}_m$) then it follows that: $I_r = -I_{sq}$. The interaction between the rotor current I_r and the magnetization flux Ψ_m produces the induction machine's electromagnetic torque M_e.

In this way appears the analogy between the rotor current I_a of the DC machine and the rotor current I_r of the induction machine. The compensating current of the DC machine (which has the role of annihilating the field deformation from air gap due to the rotor load) is the equivalent of the stator component I_{sq} of the asynchronous machine, which annihilates the effect of the deformation of the flux Ψ_m, produced by the load current. So the induction machine can actually be considered "self-compensated", because it no longer needs an additional constructive element (that is, a compensating winding) as in the case of the DC machine, which compensates the armature reaction field, as has been previously said.

On the other hand, the compensated DC machine, having the separate excitation by its construction is therefore "field-oriented" and the asynchronous "field-oriented" machine, by analogy with the DC machine, performs the separation of magnetic and mechanical control.

In fact, the concept of "field-orientation" leads to the fact that orientation along the flux direction leads to the formation of the two components of the current: the active and reactive component, which separates the mechanical phenomena from the magnetic ones of the machine (Kisch, 1998).

Finally, it might be worth mentioning that an induction machine adjustment system, which is formed on the basis of the "field-orientation" principle, is usually done according to:

- transducers, which determine the response magnitudes of the control loops;
- the inverter, which supplies the asynchronous machine;
- the magnetic flux version, used in field orientation (stator, rotor or from air gap).

Measurement of the field can be done: directly (Hall probes or measuring coils mounted in the machine stator – special machine version, with relatively low reliability) or indirectly, *i.e.* by calculation, depending on the currents, voltages and/or angular speed of rotor.

Orientation by field is done (Kisch, 1998):

- most often after the rotor flux, because the necessary adjustment quantitys are determined most easily;
- after the flux in the air gap, when is measuring the rotor currents (thus not in case of the asynchronous machine with the short-circuit rotor);
- after the stator flux, but the calculations for obtaining the adjustment quantities are more laborious and therefore the dynamic performance is weaker.

The other aspect remains, which is analyzed for the case of the DC machine: what happens if the induction machine has to work by technological requirements at high angular speeds, for example, at higher than synchronous speed?

It is obvious that in this case it operates in the generator mode or more precisely in the electromagnetic brake mode, with a certain variant of energy recovery, but the magnetic flux in this variant has to be duly diminished according to the already aforementioned for the DC machine, since the two types of machines, under certain conditions, behave identically/similarly in the production of the electromagnetic torque. And the correct torque control of the motor is nevertheless a prerequisite for all speed control strategies. That is, if we want to accurately control the speed in an electric drive, then we need to control as accurately as possible the electromagnetic torque of the drive machine.

This is because, in principle, the equation of the torque can be based on power analysis but can also be expressed as a function of the spatial vectors of currents, voltages, and magnetic fluxes in several variants such as be:

$T = k\,\mathrm{Im}(\underline{I}_s * \underline{I}_r^*)$, representation only by currents ($\underline{I}_r^* = \mathrm{Im}(\underline{I}_r)$),

$T = k_1\,\mathrm{Im}(\underline{\Psi}_r * \underline{I}_r)$, representation only based on rotor parameters, (5)

$T = k_2\,\mathrm{Im}(\underline{I}_s * \underline{\Psi}_s)$, representation only based on stator parameters,

$T = k_3\,\mathrm{Im}(\underline{\Psi}_s * \underline{\Psi}_r^*)$, representation only based on magnetic fluxes,

and depending on an admissible version, the control strategy of the induction machine can be established.

Thus, scalar control strategies can be obtained, by which relatively simple algorithms are obtained, but which generate a relatively weak (sometimes very weak) response in the case of transient processes. Instead, vector control operates directly with the spatial vector model of the motor and implements the equations presented in (5).

The group of vector control algorithms includes, essentially, direct torque control (DTC) and field-oriented control strategies.

4. How Does MATLAB Work

MATLAB (version 7.4), through its library of SPS (SimPowerSystems), Electric Drives Models, has several demos including:

a) AC4 – DTC Induction Motor Drive during speed regulation;

b) AC4 – Space Vector PWM DTC Induction Motor Drive during speed regulation, that correspond to the two variants mentioned at the end of the preceding paragraph.

This paper will not present all the details of these complex schemes, with several subsystems that each have their own specificity, but we will only refer to the themes of the subject; In any case, both of these electric drive variants have the same Speed Controller subsystem, which relates to a control of the speed of the drive, in relation to a required speed graph (N *). It is conveniently set up by a Timer block, when a certain “load scheme” represented by positive and negative torques is applied to the drive motor (also by a Timer block).

This speed control (except for the corresponding acceleration/ deceleration slopes established separately) is achieved by a PI-type controller, for which the kp (proportionality), ki (integration) constants are determined. The schematic diagram of this subsystem is given in Fig. 2.

In Fig. 2 several block groups are nominated, among which, for example, in zone C there is the PI type controller with its constants kp, ki. The block that interests us in this case is named "Flux table" and its detail is given in the F area of Fig. 2 (upper right corner).

The "Saturation" block establishes an infinite upper bound with its dialog box and the lower limit to the *bs* value; the output signal of this block forms the input signal of an "Fcn" block defining a function of the form:

$bs \times nf/u(1)$",

where $u(1)$ represents the input signal, nf = 0.8 Wb and is the nominal working flux (and initial magnetic flux) set for the drive machine, which is an asynchronous machine defined by its parameters. This "Fcn" block actually performs the machine's magnetic flux adjustment, depending on its working speed. However, the parameter *bs* is not specified anywhere, and its value (even approximate) is very important for determining the modality of flux adjustment. In this situation we plotted a graph in which the drive machine works at the over rated speed; by gathering a convenient set of data (from the workspace with the graph data), the graph Flux = *f* (Vma) was plotted with Vma relative to the drive synchronization speed.

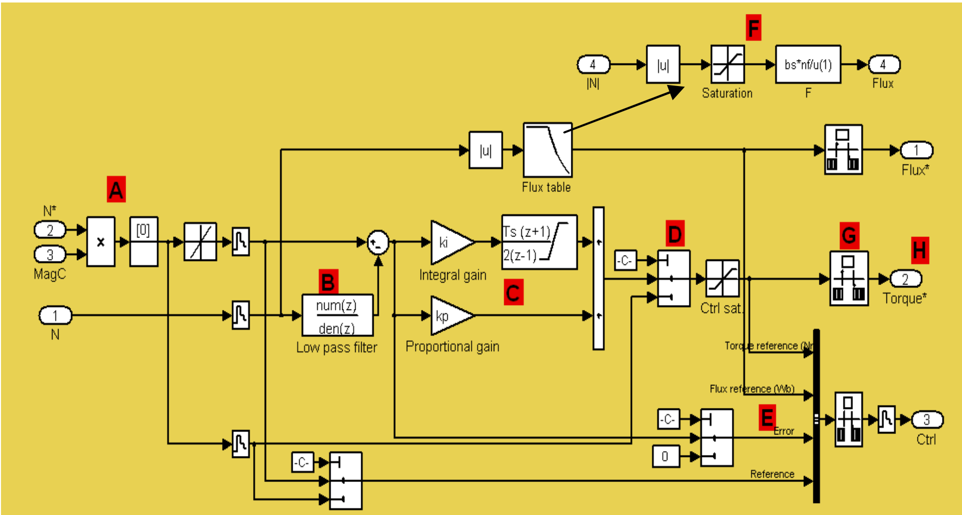

Fig. 2 - Scheme of the subsystem “Speed Controller” from the demo AC4 - DTC Induction Motor Drive during speed regulation.

This graph appears as in Fig. 3. It can be observed that the function Flux = *f* (Vma) refers in this case to a variation of Vma of 2.5%, which is not too great, but it is done under conditions in which the load torque has a pronounced negative value (*e.g.* 792 Nm), and causes the asynchronous machine to work at an over-synchronous velocity during the negative torque time. A "Basic Fitting" processing in the figure Tools results in an approximation of that curve by a linear function of the form:

$$\text{Flux} = -0.78346 \times \text{Vma} + 1.5834;\ \text{with Norm of residuals} = 0.00024878, \quad (6)$$

with the indication that Vma must be the working speed, relative to the synchronous drive speed of the asynchronous drive machine.

Fig. 3 – The curve Flux =*f* (Vma) for the given case.

In this idea, we tried to find which are the "iterations" of the parameter "bs" on a given variation range of the velocity Vma, expressed in the form:

$$bs(i)=Flux(i)*Vma(i)/0.8, \quad (7)$$

according to the expression in block Fcn presented in Fig. 2 and which manages the magnetic flux value in the machine at high speeds.

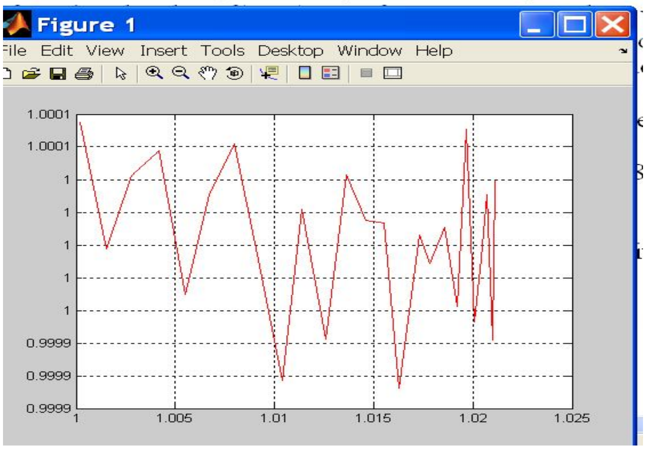

Fig. 4 – The iterations graph of the parameter "bs".

The graph of these iterations for this case is shown in Fig. 4. From Fig. 4 it can be seen that the "changes" of the parameter *bs* across the whole range of Vma variation occur around of the value "1" with some modifications at 4th decimals and therefore it can be admitted $bs \approx 1$. In other words, the function Fcn in the "Flux table" block (Fig. 2) can be determined as Flux = 0.8/u(1).

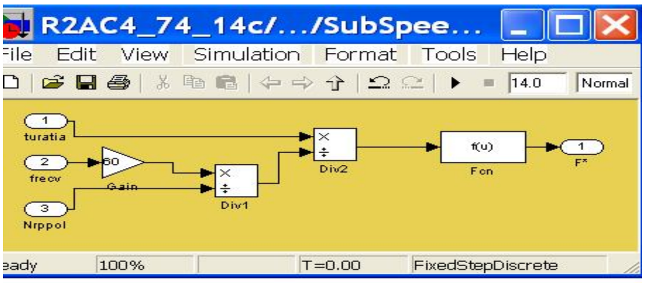

Fig. 5 –Another "Flux table" subsystem variant.

With these conclusions, another form of the "Flux table" is proposed, as in Fig. 5. The diagram is relatively simple and does not require additional comments; the Fcn block is equipped with the function from (6). In terms of the Demo type: AC4 – Space Vector PWM DTC Induction Motor Drive during speed regulation, MATLAB applies another variant to specify the flux value under high speed operation, a variant that could be very attractive in certain specific work situations.

In this case, the simplest "Lookup Table" block is used, in whose dialog box, the working speed vector and flow vector are specified in the dedicated fields (the two vectors must be the same size), as appears in Fig. 6.

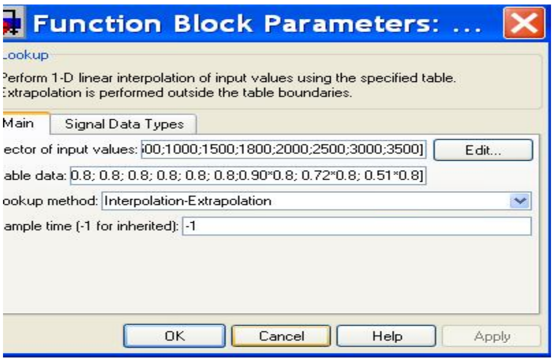

Fig. 6 – "Lookup Table" variant for defining a function of type Flux = f (Vma).

The range of speeds can be quite large, starting from the value "0", with the observation that for a set of speeds, the allowed flux is the nominal one (0.8 Wb), and then begins to decrease by multiplying its nominal value with certain subunit coefficients. The change (decrease) of the flux, as in the previous case, can be linear or realized after a convenient function of a higher order. For some speed values, intermediate to those specified in the dialog box, the block performs linear interpolation, which is very convenient in the case of a linear change in the flow. It should also be noted that the speed range shown in Fig. 6 takes into account that the working machine synchronism speed is 1,800 rot/min, corresponding to a nominal frequency of 60 Hz, the aspect that can be suitably adjusted in case of variant with a frequency of 50 Hz.

5. Conclusions

In the case of simulations of electric drives, where the technology forces high speed variations, it is necessary to adjust the magnetic flux of the machines when their speed exceeds certain specific speeds (nominal or synchronous). The paper presented theoretical aspects of the magnetic flux adjustments and some practical variants proposed in MATLAB (version 7.4) demonstrations for some specific electric drives (DTC and field-oriented control); an new variant was proposed, which could be extended and refined. By the force of things, some elements related to the problem of "decoupling" to some electric machines have been achieved, which imposes, by itself and the tangent aspect of the compensation/self-compensation of the respective electric machines.

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DESPRE AJUSTAREA FLUXULUI MAGNETIC AL MAŞINILOR ELECTRICE, ÎN CAZUL TURAȚIILOR SUPRANOMINALE ALE ACESTORA

(Rezumat)

Sunt analizate situații ce impun ajustarea fluxului magnetic de excitație în cazul maşinilor electrice ce lucrează în procese tehnologice ce impun funcționarea şi la viteze de rotație supranominale şi măsurile ce se impun în asemenea situații. Este prezentată ca exemplu o instalație de extracție a țițeiului la care în procesul tehnologic se repetă periodic intervale de timp în care maşina electrică lucreză la viteze suprasincrone. Sunt analizate fenomenele ce apar la funcționarea cu viteze suprasincrone a maşinii de curent continuu şi a maşinii de inducție şi modul în care trebuie acționat în fiecare caz în parte. Au fost prezentate şi unele aspecte practice privind unele acționări electrice mai deosebite modelate în MATLAB prin biblioteca sa din SPS (SimPowerSystems), Electric Drives Models (DTC şi field-oriented control) şi a fost propusă şi o variantă proprie, care eventual poate fi extinsă şi perfecționată.