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DESIGN OF A TRACTION CHARACTERISTIC IN THE DRIVES WITH A FREQUENCY-CONTROLLED INDUCTION MACHINE

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Abstract

The latest generation of traction drive systems is almost entirely equipped with asynchronous motors with power electronic converters. After years of rather sceptical approach to this technology, it is observed that these systems are gradually becoming more efficient. This fact is mainly concerned with application of maximum load of a converter and thermal load of a motor in order to create a traction characteristic compliant with demands. The paper presents rules and analytical basis for creating a traction characteristic of a vehicle. Two traction characteristics serve as an example here. Both of them are covered in the first zone of control with a constant stator flux. In the second zone, when the flux is reduced, one of these characteristics includes a section on a constant-power hyperbola, while an alternative characteristic includes a section along a line of constant current taken by the controlled machines. Both characteristics are coherent along a line of a torque limit due to the proximity of a break-down torque.

1. Operating conditions of an induction machine supplied by a converter circuit

Apart from the type of catenary voltage (DC or AC), operating conditions of an asynchronous machine in a traction drive system depend on:

- algorithm of operation control of a machine. [1,2,3,4,5,6,7,8,9,10,11,12],
- average value of DC voltage $U_{zk}(t)$ at input terminals of a 3-phase voltage inverter (Fig. 1) This, of course, is influenced by voltage at the pantograph of a vehicle $U_n(t)$ and equipment applied for conditioning this voltage and adjusting it to the requirements [13,14,15].

The following values were assumed as control quantities for operation of a machine:

$|U_1|$ - stator voltage amplitude,
$|\Psi_1|$ - stator flux amplitude,
f_1, f_s - stator voltage frequency,
f_2 - rotor current frequency.

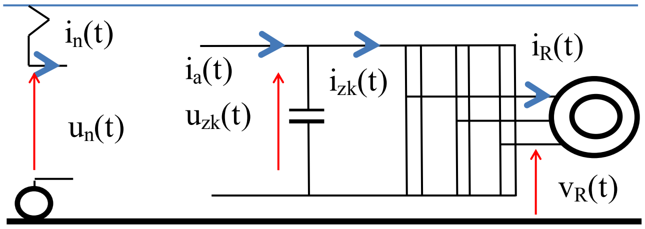

Fig.1 A scheme of a voltage converter supplying an a.c. machine in a traction vehicle

2.Basic analytical relationships

A block diagram of an asynchronous machine as a converter of electric power into mechanical power is presented in Fig.2.

The converter block represents the machine as a bidirectional converter of electric power into mechanical power. The electrical current I(f) is converted into a mechanical torque M(f) and the mechanical angle velocity Ω_M is converted in electrical voltage $U\psi_1(f)$. The first conversion describes the machine as a motor and the second as a generator. But in the block of the converter there is the intersection of these transformations. Speed coordinates of the input power are changed into force coordinates of output power. This dependence is presented as an intersection between input and output signals of the block schema.

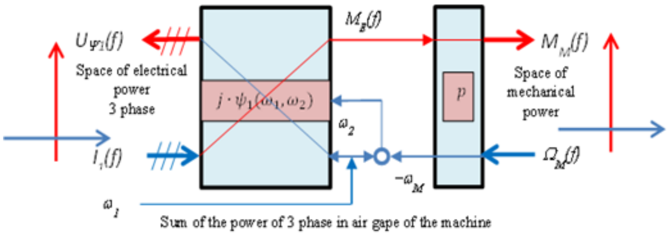

Fig. 2. Asynchronous machine as an electromechanical converter

Analytical rules of the converter operation are presented as a set of equations:

$$\begin{cases} M_M = \frac{3}{2} \cdot p \cdot Re[j \cdot \Psi_1 \cdot I_1{}^*] \\ U_{\Psi 1} = j \cdot \Psi_1 \cdot (\omega_2 + p \cdot \Omega_M) \end{cases} \tag{1}$$

Symbols used in Fig. 2 and equations (1) are:

- $U_{\Psi 1}(f)$, $I_1(f)$, amplitudes of machine's phase voltage and current. $U_{\Psi 1}(f)$ presents a stator's voltage with a voltage drop across the resistance of a stator winding omitted)
- $M_M(f)$, $\Omega_M(f)$, respectively, rotor's rotational torque and angular speed,
- $\Psi_1(\omega_1,\omega_2)$, stator's winding flux,
- $\omega_1=2\cdot\pi\cdot f_1$ - pulsation of electrical quantities in a stator,
- $\omega_2=2\cdot\pi\cdot f_2$ - pulsation of electrical quantities in a rotor,
- p - number of pairs of poles,
- ω_M - pulsation of rotor's angular speed in the electrical angular scale.

The paper presents two basic strategies of shaping traction characteristics $F(v)$ of a vehicle with asynchronous converter controlled machines.

The following zones in a traction characteristic can be distinguished:

- zone of constant stator's flux
- zone of constant voltage and constant power,
- zone of constant voltage and constant current,
- zone of constant voltage and limited torque due to proximity of a pull-out torque.

These zones are defined by dependencies describing relations between basic harmonics of voltage, current, stator flux, pulsation of a stator and rotor of a machine.

Mechanical characteristic of a machine is presented in a parametric form for a strategy of control with constant, independent from a machine load stator flux, $|\Psi_1|=const.$ in equation system (2).

$$\begin{cases} M_{\Psi 1}(|\Psi_1|,\omega_2) = \frac{3}{2}\cdot p\cdot(1-\sigma)\cdot\frac{|\Psi_1|^2}{L_1}\cdot\frac{\omega_2\cdot T_2}{1+\sigma^2\cdot\omega_2^2\cdot T_2^2} \\ \Omega_M = \frac{\omega_1-\omega_2}{p} \end{cases} \tag{2}$$

Where stator frequency dependent quantities are defined as:

$T_1 = L_1/R_1$ – stator's time constant,

L_1 -inductance, R_1 resistance,

$T_2 = L_2/R_2$ – rotor's time constant,

L_2 - inductance, R_2 resistance,

$\sigma = 1 - M^2/(L_1\cdot L_2)$ -coefficient of dispersion.

It is possible to calculate from (2) a constant (when torque is constant) or variable (when torque is varying) value of frequency in the rotor creating the required value of a rotational torque of traction motors, or the traction force. In such manner it is possible to obtain equation for the first zone of a traction characteristic. In this range of control, the torque and current is independent from stator's frequency. Relation between stator current and stator flux is shown in (3) :

$$\frac{I_{1(\omega_1,\omega_2)}}{\Psi_1(\omega_1,\omega_2)} = \frac{1}{L_1}\cdot\frac{1+j\cdot\omega_2\cdot T_2}{1+j\cdot\sigma\cdot\omega_2\cdot T_2} \tag{3}$$

For strategy of control with constant value of voltage amplitude, the mechanical characteristic of a converter is presented in the parametric form of a set of equations (4):

$$\begin{cases} M_{U1} = \frac{3}{2}\cdot p\cdot(1-\sigma)\cdot L_1\cdot\frac{|U_1|^2}{R_1^2}\cdot\frac{\omega_2\cdot T_2}{(1-\sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2)^2+(\omega_1\cdot T_1+\omega_2\cdot T_2)^2} \\ \Omega_M = \frac{\omega_1-\omega_2}{p} \end{cases} \tag{4}$$

For this strategy of control a torque is dependent not only on the amplitude of voltage $|U_1|$ and pulsation in the rotor, but on the pulsation in a stator of the fed machine as well. According to the change of stator's frequency with constant value of supplying voltage, the following undergo the changes: current, torque and power. Via the changes of rotor's pulsation it is possible to control the operating point of a machine in order to maintain either constant power or constant current or constant torque values. In traction drive systems typically there are imposed limits of constant power or constant current. The required rotor's pulsation as a function of stator's pulsation for creating the shape of a traction characteristic may be obtained from a eq. (5):

$$P_1 = \frac{3}{2}\cdot\frac{|U_1|^2}{R_1}\cdot\frac{1+(1-\sigma)\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2+\omega_2^2\cdot T_2^2}{(1-\sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2)^2+(\omega_1\cdot T_1+\omega_2\cdot T_2)^2} \tag{5}$$

For a characteristic with constant P_1 i $|U_1|$ and varying ω_1 it is possible to calculate $\omega_2=F(\omega_1)$.

After putting the received from (5) value ω_2 into eq. (4) one can obtain an equation of a traction characteristic in a zone of $P_1=const$.

For characteristics with constant values $|I_1|$ and $|U_1|$ while varying ω_1, proper value of frequency in the rotor $\omega_2=g(\omega_1)$ one can get from eq. (6) :

$$\frac{U_1(\omega_1,\omega_2)}{I_1(\omega_1,\omega_2)} = R_1\frac{1-\sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2+j\cdot(\omega_1\cdot T_1+\omega_2\cdot T_2)}{1+j\cdot\omega_2\cdot T_2} \tag{6}$$

Upon introducing received value of ω_2 into eq.(4) it is possible to obtain equation of a traction characteristic in a zone $|I_1| = \text{const}$.

The third section of traction characteristic is calculated using eq. (4) having in mind enough distance from a breakdown torque appearing for a specific rotor's frequency given by (7):

$$f_{2u} = \frac{\mp 1}{2\cdot\pi\cdot T_2}\cdot\sqrt{\frac{1+(\omega_1\cdot T_1)^2}{1+(\sigma\cdot\omega_1\cdot T_1)^2}} \tag{7}$$

3.Examples of traction characteristics

Power delivered to a machine is transferred by the lowest (basic) harmonic developed by a pulsating converter. Zero-frequency harmonics must be effectively dumped. All higher harmonics are worsening operational conditions of a machine due to distortion of non-sinusoidal shape of supplying voltage. Different strategies of a machine control are describing how the values of basic harmonics of voltage, current or magnetizing flux are changing together with changes of an operating point of a machine.

The Fig. 3 presents the basic strategies in the control of an asynchronous machine. On the plane of mechanical power.

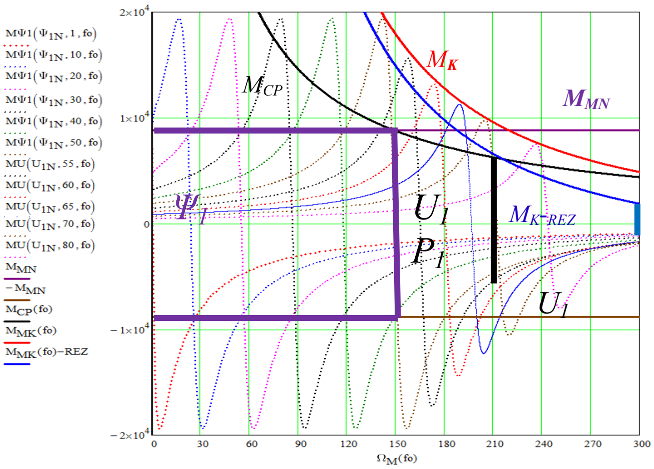

Fig. 3. Control areas (regions) of a converter-fed asynchronous machine shown on background of mechanical characteristics valid for different supply frequencies.

M_K – value of a break-down torque as a function of a stator's frequency (red colour), M_{MN} – nominal value of a torque (viollet), M_{CP} – torque along constant-power hyperbola (black), $M_{K\text{-}REZ}$ – maximum torque with maintaining some margin from break-down torque (blue).

Three areas were distinguished: constant flux, constant voltage & constant power and constant voltage & limited torque due to break-down torque. Hierarchical setting of these limits is quite clear. When rotor's speed is changing there is a switch from one limit to the other. The imposed limit is the one which reduces the most the allowed value of a rotational torque.

Operating point of an asynchronous machine is defined by three coordinates. The coordinates ω_1 and ω_2 fulfil specific role. The first one sets an idle operation speed, while the second sets a torque on a machine's shaft. Limiting level of freedom of ω_2 by linking its value with the value of ω_1 leads to creation of geometrical sites of operational points making traction characteristic. There are presented below connections between these coordinates created in a few different ways, which could be called the "methods for shaping the traction characteristic". Dependence of rotor's frequency on stator's frequency for chosen methods of shaping traction characteristic is shown in (Fig. 4).

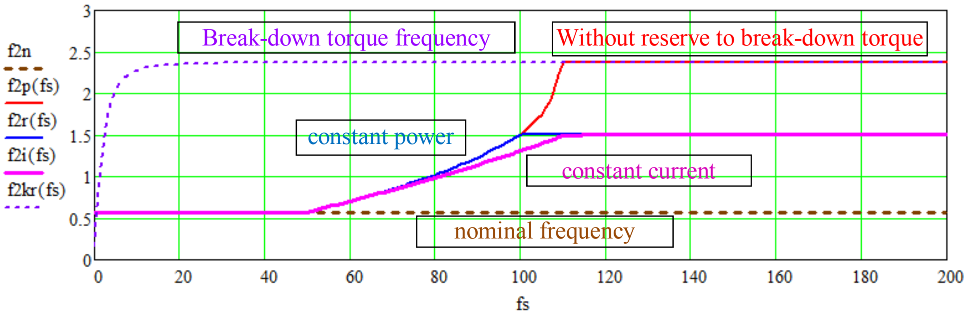

Fig. 4. Dependence of current frequency in a rotor on frequency in a stator for 5 cases of $f_2=g(f_1)$. Characteristics of "break-down frequency" and "nominal frequency" limits the area of possible changes of rotor's frequency. A characteristic „without reserve to break-down torque" uses the maximal possible value of torque developed by an asynchronous machine in constant voltage area without overloading in a range of low stator's frequency. In practice are used the characteristic of "constant power" till a save margin from a break-down torque and the characteristic of "constant current" with a safety margin to a break-down torque

The following figures (Fig. 5 and Fig.6) present graphs of changes of the selected values of the characterized operational points of an asynchronous machine as a function of currents frequency in its stator. The graphs were obtained via introduction of the presented above limits of degree of freedom of rotor's frequency. The graphs in these figures are rescaled in order to have a better view of the following quantities:

- stator's phase voltage amplitude module– symbol $|U1X(fs)|$, (red colour),
- stator's phase current amplitude module– symbol $|I1X(fs)|$, (blue),
- stator's flux amplitude module– symbol $|\Psi 1X(fs)|$, (grey),
- active power taken by an asynchronous machine symbol $P1X(fs)$, (pink),
- rotor's current frequency- symbol $f_{2n}(f_s)$, (green)
- rotational torque developed by a machine - symbol $MX(fs)$, (brown),
- break-down frequency of rotor's currents - symbol $f2kr(fs)$, (black).

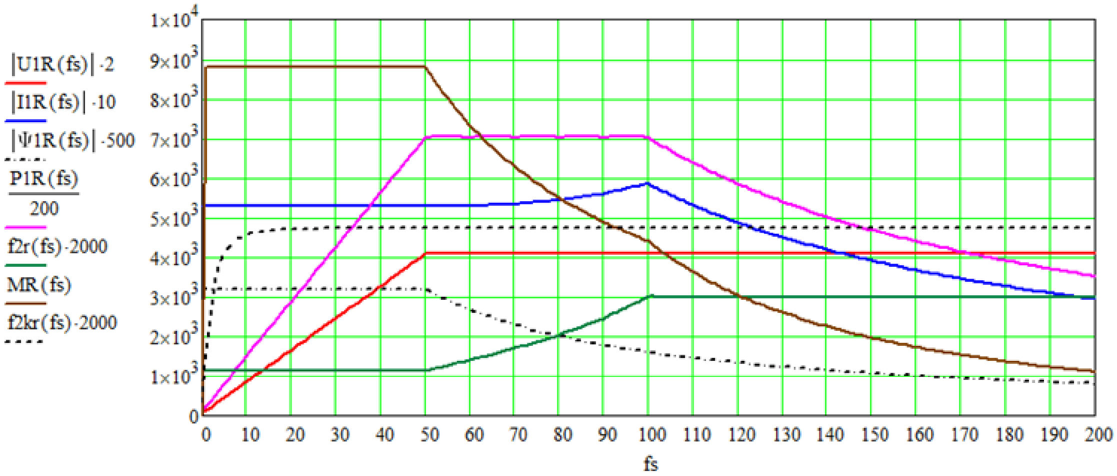

Fig. 5. Curves of voltage, current, stator's flux, power taken by a machine, frequency in a rotor, a rotational torque and break-down pulsation value in a rotor as functions of stator's voltage frequency f_s when controlled with limited area of constant power in a zone of constant stator's value „$f_{2r}(f_s)$”. Constant power is maintained only in a range assuring required margin to a break-down torque. This margin in a torque results from introduction of limits on rotor's current pulsations to 80÷90% of a break-down pulsation.

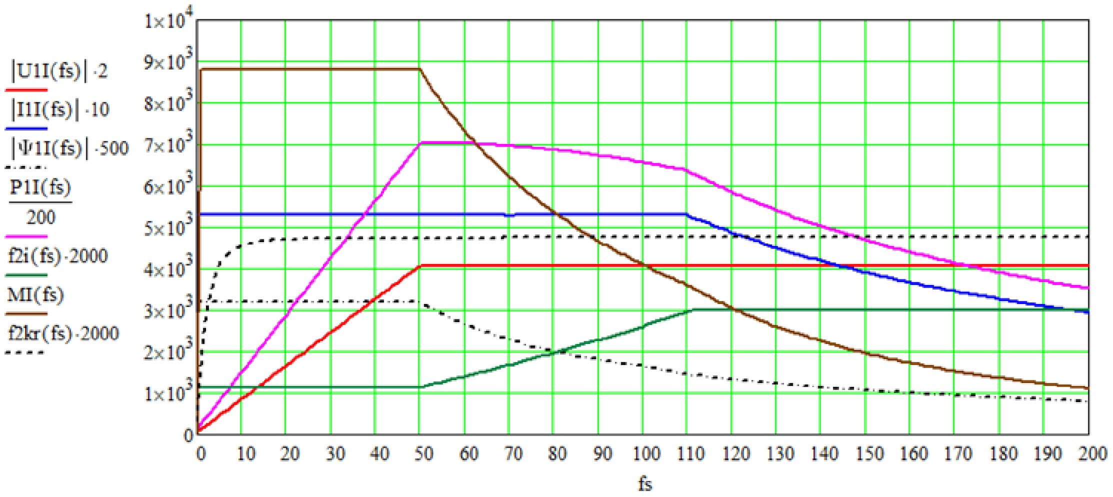

Fig 6. Curves of: voltage, current and stator's flux, power taken by a machine, rotor's frequency, rotational torque and the value of a break-down pulsation in a rotor as a function of stator's voltage frequency fs when controlled with the maximum area of a constant value stator's current module in the zone of stator's constant voltage „$f_{2i}(f_s)$”. Constant current is being maintained till the border defined by a maximum value of rotor's pulsations.

4. Conclusions

Curves (shapes) of vehicle traction characteristic with an asynchronous machine drive results from the requirements of a user commissioning a vehicle. As a comparative characteristic, may be applied the characteristic obtained with maintaining a nominal value of frequency in a rotor within the whole range of stator’s frequency. All the deviations from this characteristic are associated with additional expenses on a converter and a cooling system of all the elements of power transfer.

Increase of a torque in a zone of constant excitation causes increase of current, which means increase in commutation ability of the applied converter and requires proper enhancement of a cooling system of traction motors due to the required time of operation with maximum torque in this range of speed.

In the range of a weakened field, there are at least three possible methods of shaping a traction characteristic.

- The first one – further maintaining the same, constant value of torque
- The second one - decreasing torque in order to maintain the constant value of mechanical power (due to practically constant efficiency of a motor, it is possible to use in the control only power taken by the motor).
- And last but not least – to reduce the torque in order to maintain the constant value (as till now) of the current taken by the machine.

These three methods define completely different requirements towards commutation ability of a converter and capacity of a cooling system. Upon identifying machine parameters and defining the nominal point of operation, it is possible to calculate the shape of these characteristics using the formula presented.

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