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The principles of the electric drive control of antennas and solar batteries rotation system for spacecrafts based on a dual-fed switched reluctance drive

S A Bronov[1,2,3]**, N A Nikulin**[1]**, P V Avlasko**[1]**, D V Volkov**[1]**, E A Stepanova**[1]**,
D D Krivova**[1]**, A A Bisov**[1]**, R M Nikitin**[1] **and D E Alfimov**[1]

[1] Institute of Space and Information Technologies, Siberian Federal University, Krasnoyarsk, Svobodny 79, Russia, RU-660041
[2] Department of Information Technologies and Systems, Krasnoyarsk State Agrarian University, Krasnoyarsk, Mira 90, Russia, RU-660049

[3] E-mail: nulsapr@mail.ru

Abstract. A perspective electric drive based on a dual-fed switched reluctance drive with two multiphase windings on the stator and a toothed rotor has been considered. The electric drive can be used in spacecrafts for antenna and solar panels rotation systems. The possibilities of the electric drive control to achieve a high smoothness of rotation at low speed have been studied. The possible control options with different combinations of frequencies and amplitudes of supply voltages of two windings were shown.

1. The problem of systems' development

In spacecrafts the precision electric drives are used for antenna and solar batteries rotation systems [1–3]. These electric drives should have good transient responses and smooth motion in a steady state at a low rotation speed. The synchronous motors and a mechanical gearbox are usually used for this purpose. The angular velocity at the gearbox output is:

$$\omega_r = \frac{\omega_\mu}{i_{red}},$$

where ω_μ — is the angular velocity of the magnetic field; i_{red} — is a gear box ratio.

If a magnetic field is set up by one multi-phase winding, then

$$\omega_r = \frac{\omega_\mu}{i_{red}} = \frac{\omega_1}{p_\mu i_{red}},$$

where ω_1 — is the angular frequency of the multi-phase voltage; p_μ — is the number of pole pairs of a multi-phase winding.

Such electric drives have two problems.

Problem 1. The electric drive should have a low speed but the electric motor, as a rule, has a high speed.

Problem 2. To ensure the smooth rotation of the rotor, the motor should be powered by high-frequency voltage. But in this case the speed will be high as well.

To solve both problems it is necessary to use a mechanical gearbox with $i_{red} > 1000$. But the mechanical gearbox with a high gear ratio reduces the electric drive reliability.

2. Problem solution

It is proposed to use an alternative type of the electric motor which has two multi-phase windings instead of one winding on the stator (as in a conventional motor) (figure 1). Each of these windings is powered by its own multi-phase voltage and creates two electromagnetic fields that rotate towards each other and form a common field. The angular velocity of the rotor in this case is:

$$\omega_r = \frac{\omega_\mu}{i_{red}} = \frac{\omega_1 - \omega_2}{Z_R i_{red}}, \tag{1}$$

where ω_1 — is the angular frequency of the first multi-phase voltage; ω_2 — is the angular frequency of the second multi-phase voltage; Z_R — is the number of rotor's teeth (can be >100).

On condition $\omega_1 = \omega_2$ the angular velocity of the rotor $\omega_r = 0$ and the rotor does not move. At large but close values ω_1 and ω_2 the rotor speed ω_r can have very small value. The high frequency of switched power supply ensures a smooth rotation of the rotor even at very low speeds.

A synchronous motor in transient modes tends to fall out of synchronism. For this purpose, it is required to control the load angle which for this engine is:

$$\theta_M \cong -\arcsin\left(\frac{\sigma L_1 L_2 \omega_1 \omega_2 M_{s0}}{L_{1,2} U_{1m} U_{2m}}\right), \tag{2}$$

where L_1, L_2 — are the inductances of the first and the second multi-phase windings; $L_{1,2}$ — mutual windings' inductance; U_{1m} U_{2m} — are the amplitudes of the first and the second voltages; M_{s0} — is the load moment; $\sigma = 1 - L_{1,2}^2/(L_1 L_2)$.

Supply voltage for a three-phase motor:

$$\left.\begin{array}{l} u_{1a}(t) = U_{1m}(t) \cdot \sin[\omega_1(t) \cdot t + \varepsilon_1(t)]; \\ u_{1b}(t) = U_{1m}(t) \cdot \sin[\omega_1(t) \cdot t + 120° + \varepsilon_1(t)]; \\ u_{1c}(t) = U_{1m}(t) \cdot \sin[\omega_1(t) \cdot t + 240° + \varepsilon_1(t)]; \end{array}\right\} \left.\begin{array}{l} u_{2a}(t) = U_{2m}(t) \cdot \sin[\omega_2(t) \cdot t + \varepsilon_2(t)]; \\ u_{2b}(t) = U_{2m}(t) \cdot \sin[\omega_2(t) \cdot t + 120° + \varepsilon_2(t)]; \\ u_{2c}(t) = U_{2m}(t) \cdot \sin[\omega_2(t) \cdot t + 240° + \varepsilon_2(t)]. \end{array}\right\} \tag{3}$$

For modelling other expressions are used:

$$\left.\begin{array}{l} \dfrac{d\theta_1}{dt} = f_{\omega1}(t); \\ \dfrac{d\theta_2}{dt} = f_{\omega2}(t); \end{array}\right\} \left.\begin{array}{l} u_{1a}(t) = U_{1m}(t) \cdot \sin[\theta_1 + \varepsilon_1(t)]; \\ u_{1b}(t) = U_{1m}(t) \cdot \sin[\theta_1 + 120° + \varepsilon_1(t)]; \\ u_{1c}(t) = U_{1m}(t) \cdot \sin[\theta_1 + 240° + \varepsilon_1(t)]; \end{array}\right\} \left.\begin{array}{l} u_{2a}(t) = U_{2m}(t) \cdot \sin[\theta_2 + \varepsilon_2(t)]; \\ u_{2b}(t) = U_{2m}(t) \cdot \sin[\theta_2 + 120° + \varepsilon_2(t)]; \\ u_{2c}(t) = U_{2m}(t) \cdot \sin[\theta_2 + 240° + \varepsilon_2(t)]; \end{array}\right\} \tag{4}$$

The expressions (1) and (2) indicate the possible motor control options.

For its control the frequencies ω_1 and ω_2, the amplitudes U_{1m} and U_{2m}, the phases ε_1 and ε_2 of supply voltages (figure 2) can be changed in different combinations.
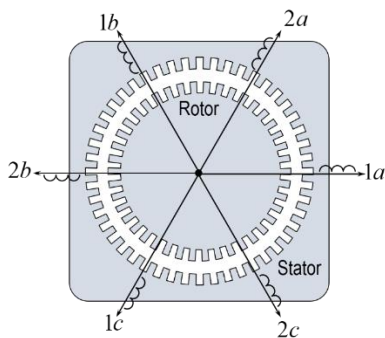
Figure 1. Stator and rotary plates.
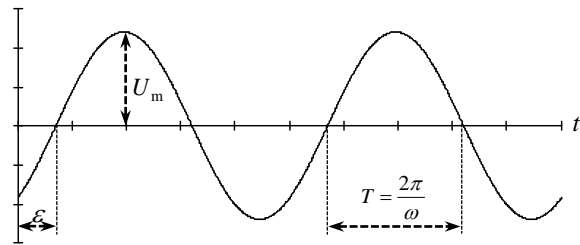Two 3-phase Windings.

Figure 2. Adjustable parameters
of sinusoidal voltage supply.

The result of adjusting the drive angle of rotation while changing the frequencies is illustrated by the graph (figure 3, a). The angles of the vectors rotation of the first θ_1 and the second θ_2 voltage are shown as well as the angle of the rotor rotation: $\theta_r = \theta_1 - \theta_2$ (figure 3, b).
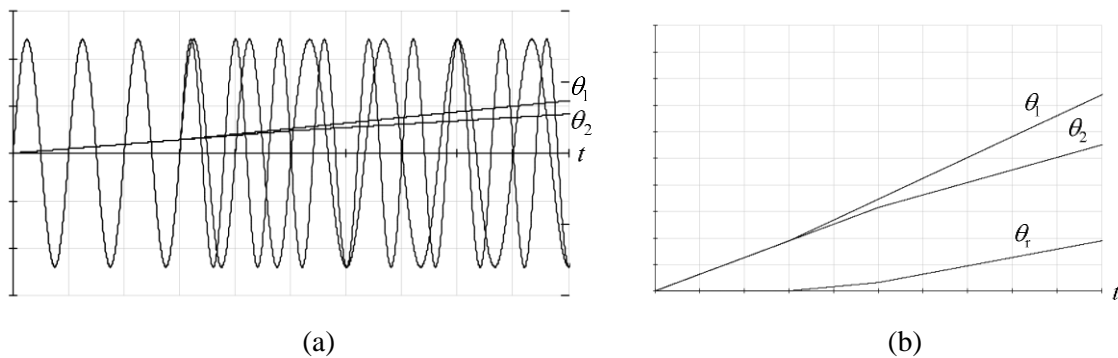

(a)

(b)

Figure 3. Adjusting the rotation angle by changing the voltage frequencies.

The drive control system (Figure 4) solves three tasks:
1) adjusting the angle of rotation θ_r in accordance with the desired law of motion;
2) speed control ω_r .
3) adjusting the load angle in the range $-\pi/2 < \theta_M < \pi/2$.
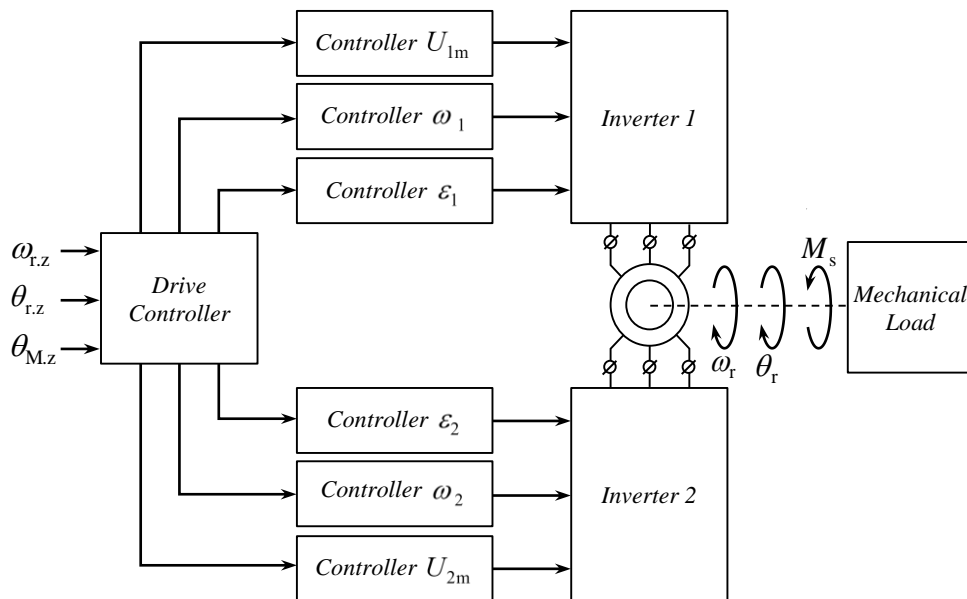
Figure 4. Electric drive control system.

For this purpose, the main Drive Controller and the Controllers regulators of the changed variable are used.

The inverters produce pulse supply voltages with pulse-width modulation. The pulse-width modulation enables to change all the considered control parameters: the frequency, amplitude and phase of each voltage.

Thus, there is a redundancy of controlling variables which allows not only to implement the desired law of the speed and angle of rotation change but to obtain various additional effects as well.

The control goal is the choice of frequencies ω_1 and ω_2 in order to provide a given speed ω_r in accordance with (1).

For this we can distinguish three main methods for controlling by changing the frequency:

1) ω_1 increase and ω_2 decrease;

2) ω_1 increase and ω_2 increase;

3) ω_1 decrease and ω_2 decrease.

All these methods ensure getting the desired speed $\omega_r = \omega_1 - \omega_2$ but affect the load angle differently. To stabilize the load angle according to (2), it is necessary to change the frequencies so that their work remained unchanged: $\omega_1\omega_2 = q_\omega = \mathrm{const}$.

Then, taking into consideration $\omega_r = \omega_1 - \omega_2$:

$$\omega_1 = 0{,}5\omega_r + \sqrt{\left(0{,}5\omega_r\right)^2 + q_\omega} \ , \ \ \omega_2 = \omega_1 - \omega_r \ .$$

The graph of frequency changes depending on the speed change during the motor acceleration is shown in the figure (figure 5).
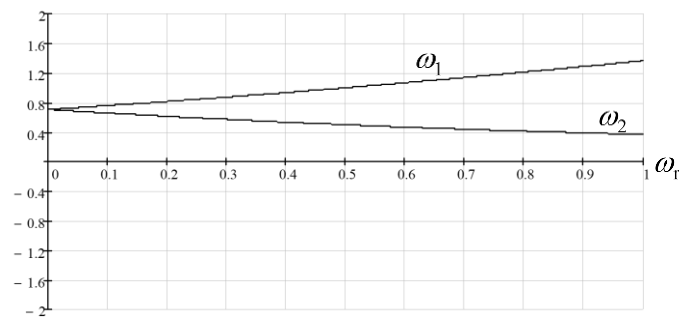
Figure 5. Dependence of frequencies on a given speed.

When the frequencies increase the angle of the load decreases and the motor can fall out of synchronism. In accordance with (2) when increasing the frequencies, it is required to increase the voltage amplitudes, thus, the load angle won't change.

In this motor there is a possibility to combine the changed frequencies and amplitudes with each other, therefore, in this case there is a control redundancy.

You can change the frequency and amplitude of the same voltage and you can change the frequency of one voltage and the amplitude of another.

In this regard you should consider that the possibilities of the voltage amplitude increase are limited by the power source, that is why it is always advisable to strive for the smallest amplitude increase.

3. Conclusion
Due to the dual power motor supply the considered electric drive has the characteristics that meet the high requirements for electric drives for spacecrafts: high uniformity of rotation at low speeds. The control methods for static modes are given. The further research will be related to the transient modes.

References
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