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ABOUT THE BIDIRECTIONAL SEPARATOR CIRCUIT USED IN THE INDUCTION MACHINE ANALYSIS

BY

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Abstract. The Park transformation is a well-known three-phase to two-phase transformation used in ac machine analysis, balanced or unbalanced supplied with sinusoidal or non-sinusoidal voltage. When the analysis is done with a soft as Pspice, specialized in electrical circuits simulation, a special circuit implementation is required to achieve Park transformation.

The paper presents the bidirectional separator circuit that can be used in Park transformation implementation. So, the analysis of the three-phase induction machine connected to a non-sinusoidal, unbalanced three-phase voltage or current source can be done. The induction machine analysis was performed using the three-phase model and also the *d-q* model implemented in SimPowerSystems (Matlab Simulink) and PSpice.

Key words: induction machine; bidirectional separator circuit; Park transformation.

1. Introduction

The Park transformation (or d-q transformation) is a mathematical transformation of three-phase time-domain signals from a (stationary) three-phase system (*abc*) to a (rotating) two-phase system (*dqo*). This transformation is very useful when used in combination with symmetrical components method in electrical engineering (Paap, 2000; Cociu *et al*., 2011; Cociu & Cociu, 2014),

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and power system engineering (Ferraz *et al.*, 2012) in order to simplify the analysis of three-phase circuits and electrical machines. The effect of time varying inductances is eliminated by using a single rotating reference frame when three-phase induction and synchronous machines are analyzed. A typical application of Park transformation in induction machine analysis is shown in Fig. 1.

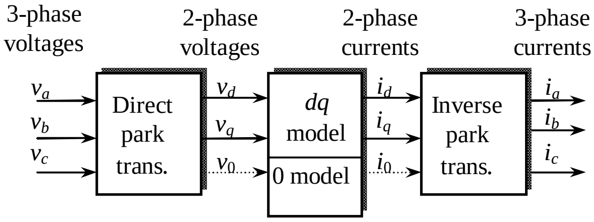

Fig. 1 – Classical use of Park transformation in induction machine analysis.

The advantages of using the two-phase model instead of three-phase model in studying electrical machines are well known (White & Woodson, 1959). The equivalent two phase machine is supplied by a two-phase voltage system obtained from the true three-phase supplying system through the Park transformation. When established the Park relations between the three-phase and two-phase quantities, no additional restriction on time variation was imposed. Therefore, the Park relations remain valid even in non-sinusoidal or unbalanced conditions.

Using the bidirectional separator allows calculating the three - phase currents in one step. The separator runs at the same time the direct voltage conversion and the inverse currents conversion.

2. Bidirectional Separator Structure

The bidirectional separator (transformer) is an electric circuit shown in Fig. 2. It comprises two separated ports 1-1′ and 2-2′. To the port 1-1′ is connected a current source (mirror of the current i_2) with a high value resistor $R_1 \to \infty$. To the port 2-2′ is connected a voltage source (mirror of the voltage v_1) with a reduced value resistor $R_2 \to 0$. Even though the two circuits are galvanically isolated, they influence each other via the two controlled sources: a source or impedance connected to one of the ports is mirrored in the other. The separator can work having connected to both ports either voltage or current sources. At each port it may behave as either a generator or a load.

If an input voltage v_1 is applied across port 1-1′ then the output voltage across port 2-2′, connected to any *Z* impedance, is $v_2 = v_1$, through the controlled voltage source e_2. If the output current through *Z* impedance is i_2, then the same current value is reflected in the input circuit by means of the controlled current source *J*. *Z* impedance connected to terminals 2-2′ is reflected with the same value between terminals1-1′. The voltage (or current) source connected across terminals 1-1′ is reflected between terminals 2-2′.

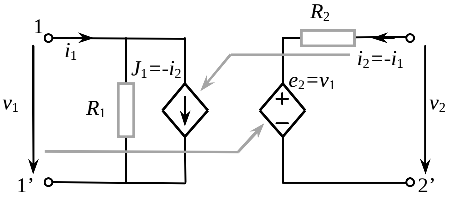

Fig. 2 – The bidirectional separator structure.

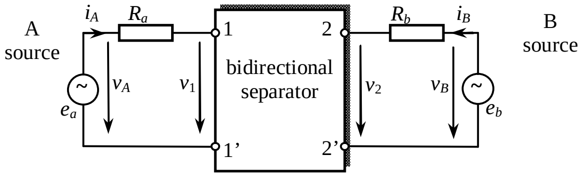

Fig. 3 – Test circuit for the bidirectional separator.

The bidirectional separator is a very flexible structure. So it can be supplied by a voltage or current source to terminals 1-1′ or 2-2′ and the load can be also connected to terminals 2-2′ or 1-1′.

The operating mode of the separation circuit is the same in both dc and ac conditions, with no restrictions on how the input voltage varies.

The bidirectional separator circuit can work having either a voltage source or current source connected to each port. Bidirectional nature comes from the fact that the separator can be supplied at any two terminals 1-1′ or 2-2′, as shown in Fig. 3.

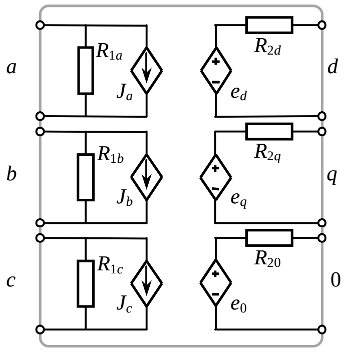

Fig. 4 – The bidirectional separator circuit used in Park transformation.

Although the separator configuration is not symmetrical the circuit in Fig. 3 is used to verify its bidirectional operation. Source A and source B can be dc or ac voltage or current sources (Cociu & Cociu, 2015).

Using the configuration of the bidirectional separator, a bidirectional circuit which allows performing at the same time the direct and inverse Park transformation can be done, as in Fig. 4.

The controlled voltage sources e_d, e_q, e_0 and the controlled current sources J_a, J_b, J_c have the following expressions, corresponding to the direct and inverse Park transforming equations:

$$\begin{aligned} u_d &= \sqrt{\frac{2}{3}}\left[u_a\cos\theta + u_b\cos\left(\theta - \frac{2\pi}{3}\right) + u_c\cos\left(\theta + \frac{2\pi}{3}\right)\right], \\ u_q &= -\sqrt{\frac{2}{3}}\left[u_a\sin\theta + u_b\sin\left(\theta - \frac{2\pi}{3}\right) + u_c\sin\left(\theta + \frac{2\pi}{3}\right)\right], \\ u_0 &= \sqrt{\frac{1}{3}}\left(u_a + u_b + u_c\right). \end{aligned} \tag{1}$$

$$\begin{aligned} J_a &= \sqrt{\frac{2}{3}}\left(i_d\cos\theta + i_q\sin\theta + i_0\frac{1}{\sqrt{2}}\right), \\ J_b &= -\sqrt{\frac{2}{3}}\left[i_d\cos\left(\theta - \frac{2\pi}{3}\right) + i_q\sin\left(\theta - \frac{2\pi}{3}\right) + i_0\frac{1}{\sqrt{2}}\right], \\ J_c &= \sqrt{\frac{1}{3}}\left[i_d\cos\left(\theta + \frac{2\pi}{3}\right) + i_q\sin\left(\theta + \frac{2\pi}{3}\right) + i_0\frac{1}{\sqrt{2}}\right]. \end{aligned} \tag{2}$$

The bidirectional separator and Park bidirectional transformer are electric circuits that can be implemented in PSpice (Justus, 1993; Cociu & Cociu, 2014), SimPowerSystems (Simulink) or other specialized soft, by using adequate code.

3. Using the Park Bidirectional Transformer in Unbalanced Supply

The Park bidirectional transformer is not a software to calculate Park transformation but an electrical circuit. The three-phase input has six terminals grouped in three pairs that can connect to three-phase power in a realistic manner. Moreover, with this two-phase output load, the machine draws three-phase currents corresponding to the operating mode, thus giving a true loading of the three-phase power supply. Determining the three-phase currents is done in a single step, simultaneously with the voltages transformation.

Using Park bidirectional transformer for unbalanced voltages two particular cases can occur, that can be easily resolved as in Fig. 5.

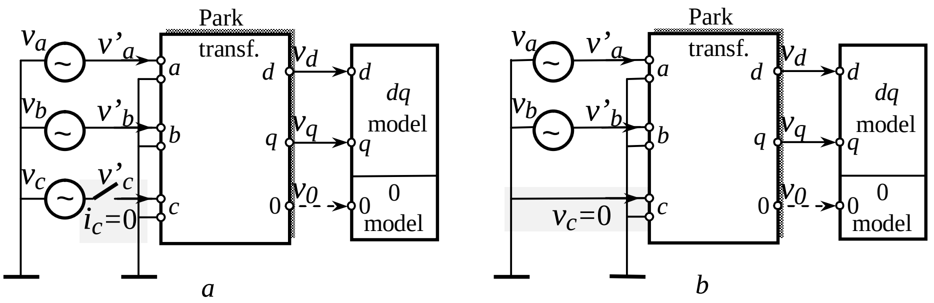

Fig. 5 – The bidirectional Park transformer circuit in special situations: *a* – open circuit at input *c*; *b* – short circuit at input *c*.

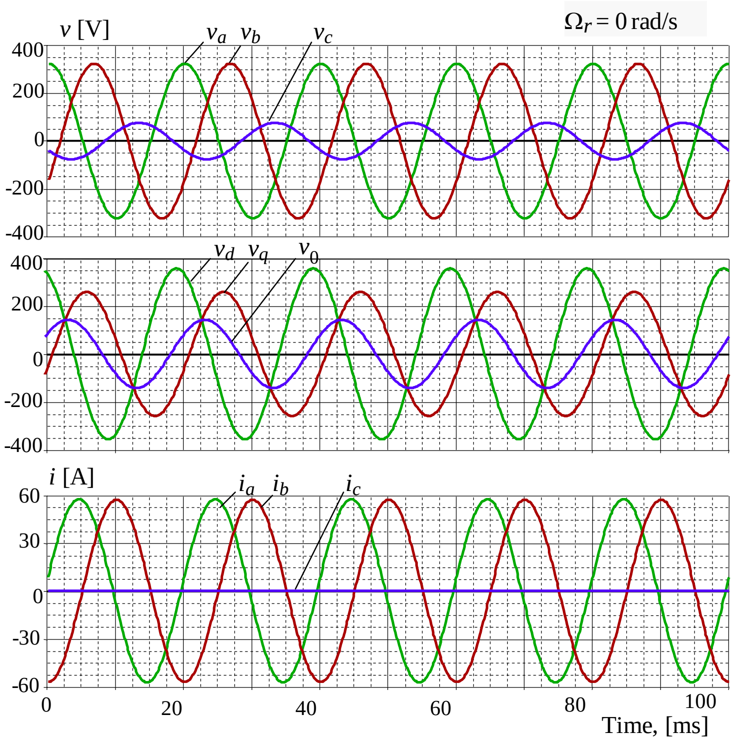

Fig. 6 – Input and output voltages and currents in unbalanced supply – open circuit at input *c*.

In the first case (Fig. 5 *a*) one of the three input voltages is missing, due to the open circuit. Implementation in this situation is accomplished by connecting a very high value resistor $R_c \to \infty$ to the input *c*. Thus as input known quantities we have the voltages v_a, v_b, and also the current $i_c = 0$. This is not a typical case and the equations system (1) cannot be used. The unknown input three-phase quantities to be determined are i_a, i_b and v_c instead of the three input currents.

To illustrate the simulated results in above listed cases, a three-phase induction machine is considered, characterized by the following ratings:

$$P_n = 5\ \text{kW};\quad U_{1n} = 400\ \text{V};\quad f_1 = 50\ Hz;\quad \text{Y} - conn.$$

$$R_s = 1.1\ \Omega;\quad R_r = 1.1\ \Omega$$

$$L_{\sigma s} = 10\ \text{mH};\quad L_{\sigma r} = 10\ \text{mH}\quad L_m = 130\ \text{mH}$$

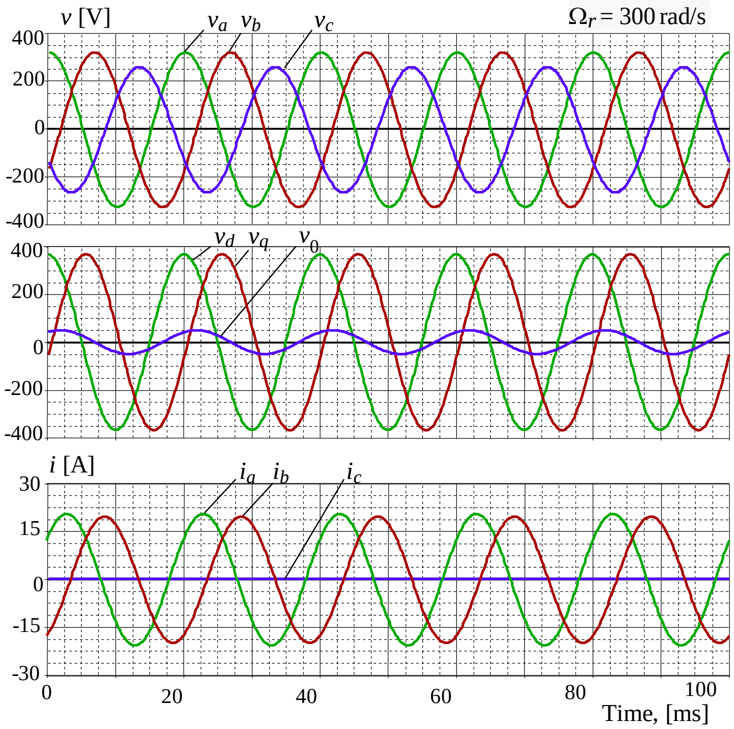

Fig. 7 – Input and output voltages and currents in unbalanced supply – open circuit at input *c*.

At the Park transformer output it was considered an induction motor in steady operating with Ω_r rotor angular speed. At input a phase of the supply power is missing, so the circuit corresponding to the input *c* is open. Fig. 6 shows the results obtained for three-phase voltages and currents and also for the two-phase voltages when the rotor is at standstill ($\Omega_r = 0$ rad/s). Fig. 7 shows the same quantities when Ω_r equals 300 rad/s. As can be seen, the results are different in the two cases. The input quantities imposed v_a, v_b and $i_c = 0$ are the same in both cases but the quantities calculated i_a, i_b, v_c and v_d, v_q, v_0 have different values. This shows that input reflects the output load status. Note that the voltage v_c occurs by induction, its value has no effect on the phenomena which occurs in the machine.

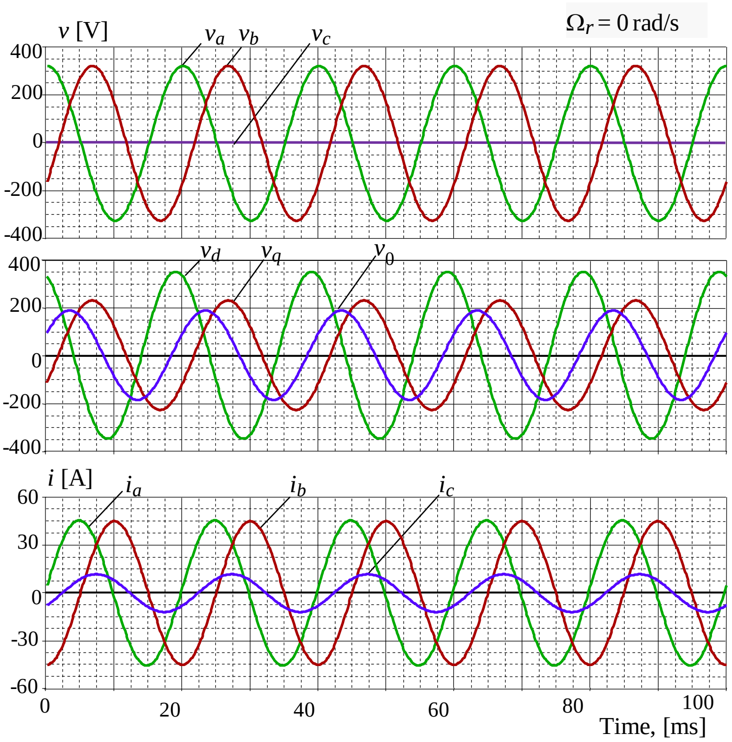

Fig. 8 – Input and output voltages and currents in unbalanced supply – short circuit at input *c*.

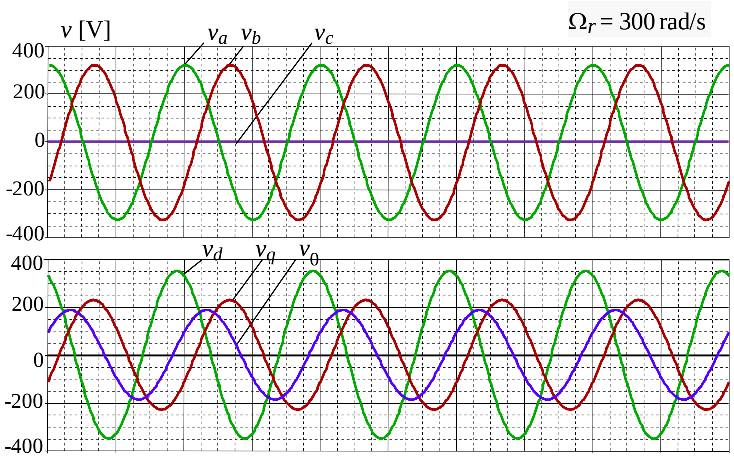

Fig. 9 – Input and output voltages in unbalanced supply – short circuit at input *c*.

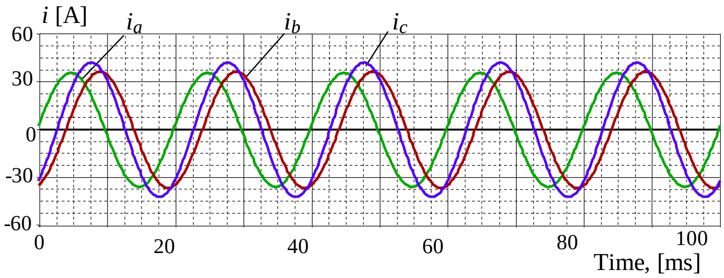

Fig. 9bis – Input currents in unbalanced supply - short circuit at input *c*.

3. Using the Park Bidirectional Transformer in Non-Sinusoidal Supply

In the following we present an example of using the Park bidirectional transformer in non-sinusoidal supply. A three-phase voltages system with a specific rectangular shape supplies an induction motor, as in Fig. 10. The supply voltages are non-sinusoidal, with a frequency of 50 Hz, having the same waveform and shifted in time by 6.666 ms.

The supply voltage fundamental corresponds to the nominal value of the motor supply voltage.

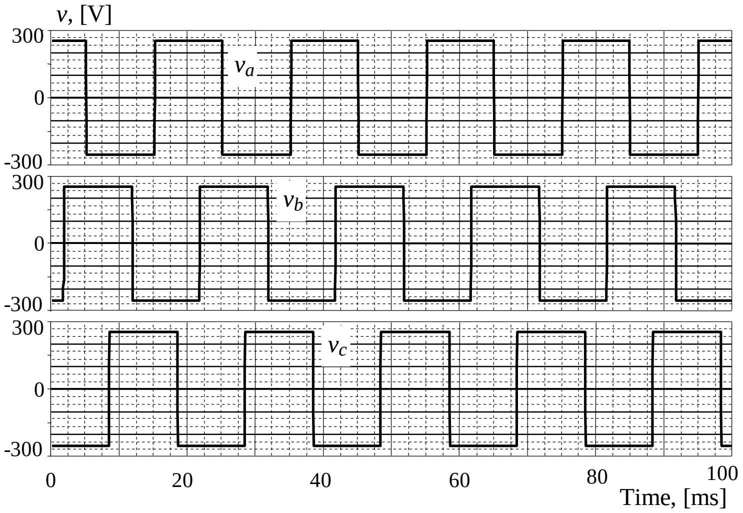

Fig. 10 – Three-phase rectangular shape supply voltages.

By applying the Park Transform to the three-phase voltage system, the two-phase voltage system, shown in Fig. 11 is obtained. The two-phased voltages, u_d and u_q, are different in shape and also differ from the original three-phase signals. The specific shape of the direct u_d component, when compared to the u_a voltage is due to the existence of the third harmonic and its multiples. The u_q orthogonal voltage is delayed from the u_d direct voltage by a quarter of a period, a natural occurrence when speaking of a two-phase voltage system. However, the shapes of the two two-phased voltages are different. This underlines spectrally different components or components with different characteristics.

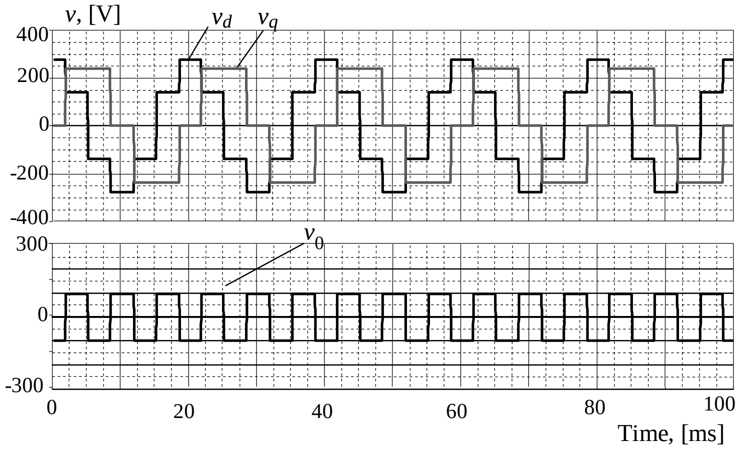

Fig. 11 – Orthogonal and homopolar components in case of rectangular input voltages.

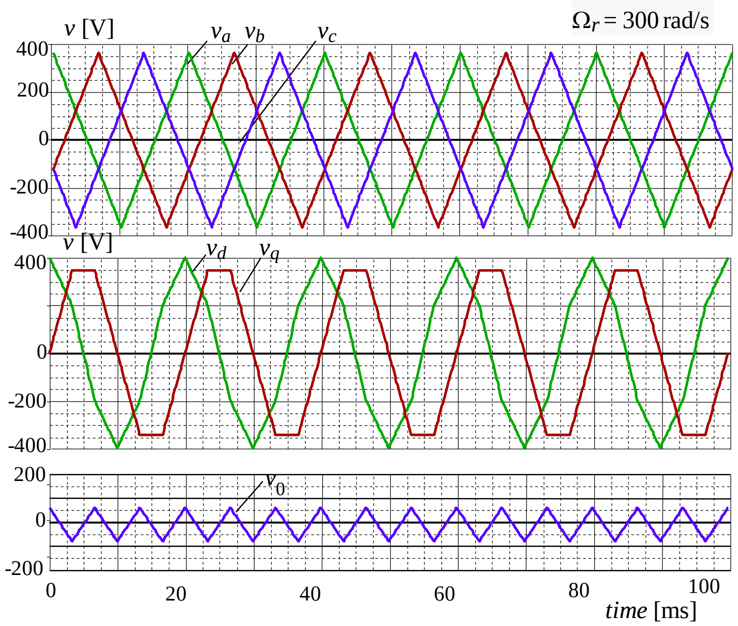

Fig. 12 – Triangular input voltages and orthogonal and homopolar components.

Fig. 12 shows another example of a non-sinusoidal three-phase power supply. This time the supply voltages are triangular with a frequency of 50Hz and shifted in time by 6.666 ms. To easy compare the two examples in this case the supply voltage fundamental is also corresponding to the nominal value of the supply voltage. It can be noted the same qualitative results, namely the different shape of the two-phase voltage compared to that of the three-phase one and the (apparent) difference between the two two-phase voltages.

4. Example of Using the Park Bidirectional Transformer in Induction Motor Behavior Study

In the following we present an example of using the Park bidirectional transformer in the study of induction motor behavior. A three-phase voltages system supplies an induction motor, as in Fig. 10. Note that the input voltages v_c is missing. Therefore the supply is simultaneously asymmetric and non-sinusoidal.

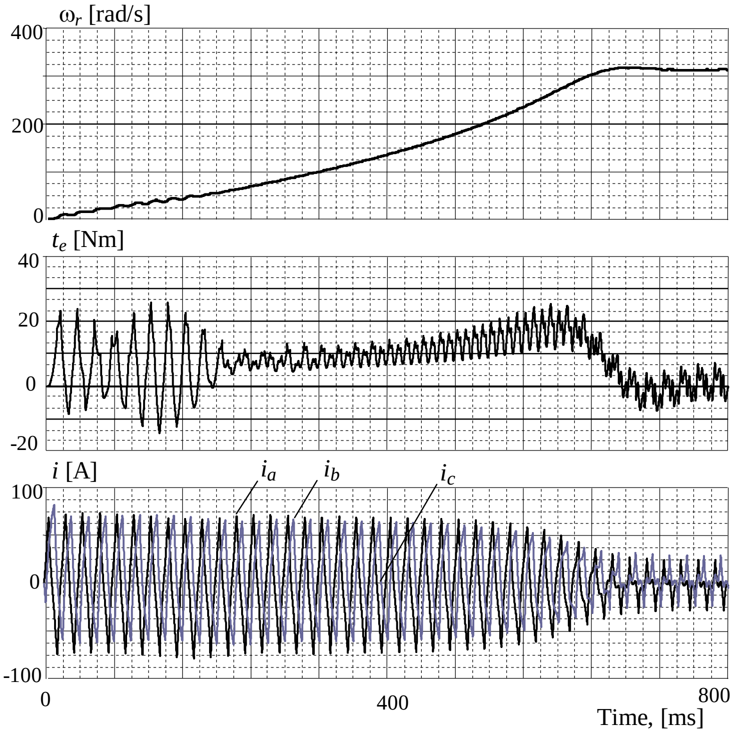

Fig. 13 –Main quantities variation in case of asymmetric and non-sinusoidal supply.

Fig. 13 shows the simulation of the motor starting. It has been considered variation of angular speed, the electromagnetic torque and also of the stator currents.

Due to the asymmetric and non-sinusoidal supply, electromagnetic torque values have permanent variations even in steady-state operation.

Therefore the angular speed has small oscillations around the mean value. The currents drawn change values with the increase of angular speed, their shape being much different from the sinusoidal.

All the results presented in this paper have been compared to those obtained by using the three-phase model for the induction machine. The results are identical for the drawn currents as well as for the electromagnetic torque and speed.

7. Conclusions

Using bidirectional separator in Park Transform implementation proves to be extremely useful in induction machine study. Both the direct transformation of voltages and inverse transformation of currents are performed in a single step. The load connected to the two-phase system is reflected correctly at the three-phase input of the bidirectional separator.

The examples of using the bidirectional separator in balanced sinusoidal operation and in unbalanced non-sinusoidal as well, led to good simulations, with no problems of convergence in all cases.

Comparing the outcomes thus obtained with those obtained by using the more complex three-phase model led to identical results.

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CONSIDERAŢII PRIVIND UTILIZAREA CIRCUITULUI SEPARATOR BIDIRECŢIONAL ÎN STUDIUL MAŞINII ASINCRONE

(Rezumat)

Transformarea Park din trei în două faze este binecunoscută şi utilizată cu succes în analiza maşinilor de c.a., în regim echilibrat sau dezechilibrat, alimentate cu tensiune sinusoidală sau nesinusoidală. În cazul în care analiza se face cu un soft precum PSpice, specializat în simularea circuitelor electrice, este nevoie de o implementare specială pentru a realiza transformarea Park.

Lucrarea prezintă circuitul separator bidirecţional care poate fi utilizat în efectuarea transformării Park. În acest caz, se poate realiza o analiză eficientă a comportării maşinii asincrone trifazate, alimentată cu tensiuni nesinusoidale, în sistem echilibrat sau nu. S-au analizat comparativ rezultatele obţinute prin utilizarea modelului trifazat (considerat etalon) şi cele obţinute cu modelul *dq*. Transformarea Park s-a realizat prin implementarea separatorului bidirecţional în SimPowerSystems (Matlab Simulink) şi PSpice.