Study Of Starting Duty Of Wind Power Plant With Asynchronous Generators

Rauf Mustafayev, Laman Hasanova
•
Azerbaijan Scientific-Research and Disigned-Prospecting Institute of Energetics,
Baku, Azerbaijan AZ1012, Aven. H.Zardabi-94
mustafyevri@mail.ru, gasanovalg@mail.ru

Abstract

Presently, the park of wind power plants (WPP) consists mostly of frequency controlled asynchronous generators. As the generators the squirrel-cage asynchronous machines and generators made on the basis of double fed asynchronous machines (DFAM) are used. When WPPs locate far from the powerful sources of energy generation of power system and they are connected with the power system by "weak" power grids, i.e. by grids, which are not equipped with reactive power sources, then the unwanted voltage dips may occur when connecting the WPPs to the power system in the places of their connection to the power system.
The comparative analysis on the developed three-coordinated mathematical models of asynchronous machines of start by underfrequency relay and connection of WPPs with the above asynchronous generators to the power system has been carried out.
It has been found, that in terms of impact of starting duties on electric power networks the most preferable are the systems of WPPs with squirrel-cage asynchronous generators. The values of starting currents when start by underfrequency relay of WPPs with squirrel-cage asynchronous generators are almost 48% lower than in the system of WPPs with DFAM eactive power compensation of asynchronous generators wind power and small hydroelectric power stations increases the reliability of connecting them to the so-called "weak" power grids of power systems. The methods of reactive power compensation for asynchronous generators of various designs.

Keywords: wind power plants, asynchronous machines, double fed asynchronous machines

I. Introduction

Today small hydropower industry and wind energetics take the leading positions according to the quantity of installed capacities and electric power output, generated by renewable power sources.

Park of modern industrial wind power plants (WPP) consists of highly economical and reliable complexes, based on the latest blade wind motors, high-tech gearboxes and controlled electromechanical converters [1]. For all this the unit capacity of WPPs increases from year to year and now reaches the value of 6–7,5 MW.

II. Controlled induction generators used in wind turbines

The vast majority of electromechanical converters of WPPs consist of the controlled asynchronous machines both with squirrel-cage rotor with a frequency converter, feeding the stator winding of machine, and phase-wound rotor equipped with a frequency converter, feeding a rotor winding of machine (so-called double fed machine (DFAM)).

The advantages and disadvantages of each of above-stated options are well-known. Without going into details of these known ontions let's only note, that in the option of squirrel-cage rotor the simple, reliable generator combines with a frequency converter, made for a full power of generator, and in the option of phase-wound rotor the relatively complicated, more expensive and less reliable generator combines with a frequency converter, feeding the rotor's winding of generator and made for only 20–30% of generator's power.

In both options, these asynchronous generators in steady- state operation modes correspond in full measure to the technological requirements of optimal operation of WPPs, i.e. control of a rotational frequency of wind aggregate (wind motor, gearbox and generator) allows improving its productivity by 15–20% [1].

The purpose of this paper is the study issues of starting duties of WPPs, equipped both with squirrel-cage asynchronous generators and the generators, made on the basis of double fed asynchronous machines. These issues are particularly urgent in those cases, when WPPs and wind parks, containing several dozens of WPPs, are connected to the so-called "weak" power networks, i.e., the networks distanced sufficiently from power centers and insufficiently compensated by reactive powers. In these cases, the connection modes of WPPs with asynchronous generators to them can lead to significant voltage dip of network in startup period [2].

Studies are carried out on the developed three-coordinate models of controlled three-phase asynchronous machines, whose equations are given in [3, 4].

At the first stage let's study the startup issues of WPP, containing a squirrel-cage asynchronous generator, stator winding of which is supplied from a frequency converter, performed on fully controlled power transistors (IGBT-transistors) and controlled on the principles of sinusoidal PDM. The system's diagram of connection to power network is shown in Fig. 1.

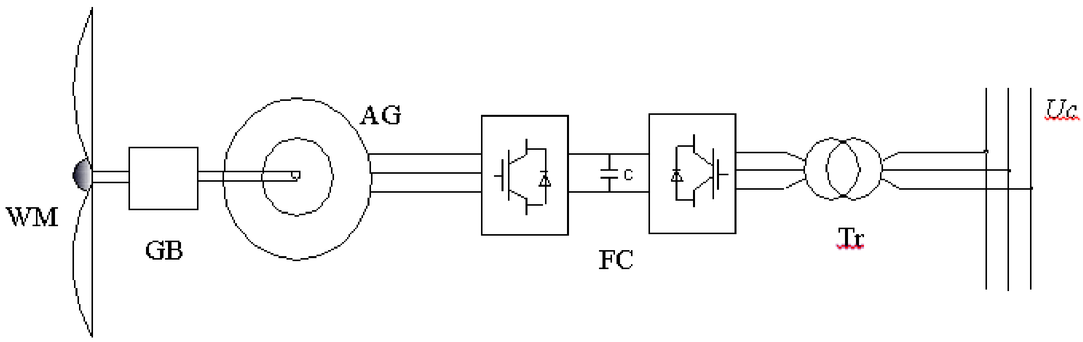

Figure 1: *Grid connection diagram of wind turbines with squirrel-cage induction generator*

Here WM – wind motor, GB – gearbox, AG – squirrel-cage asynchronous generator, FC – frequency converter, operating on power IGBT transistors, Tr – coupling transformer of connection with the system.

As it has been noted in [3], the equations for frequency controlled squirrel-cage asynchronous generator are reasonable to represent in the axes α_s, β_s, γ_s fixed in space, in this case the equations will be presented in the form of:

$$\left.\begin{aligned}
&p\Psi_{s\alpha}=U_{s\alpha}-r_{s\alpha}\cdot i_{s\alpha}\\
&p\Psi_{s\beta}=U_{s\beta}-r_{s\beta}\cdot i_{s\beta}\\
&p\psi_{s\gamma}=U_{s\gamma}-r_{s\gamma}\cdot i_{s\gamma}\\
&p\psi_{r\alpha}=U_{r\alpha}-\frac{1}{\sqrt{3}}\cdot\omega_r\left(\psi_{r\beta}-\psi_{r\gamma}\right)-r_{r\alpha}\cdot i_{r\alpha}\\
&p\psi_{r\beta}=U_{r\beta}-\frac{1}{\sqrt{3}}\cdot\omega_r\left(\psi_{r\gamma}-\psi_{r\alpha}\right)-r_{r\beta}\cdot i_{r\beta}\\
&p\psi_{r\gamma}=U_{r\gamma}-\frac{1}{\sqrt{3}}\cdot\omega_r\left(\psi_{r\alpha}-\psi_{r\beta}\right)-r_{r\gamma}\cdot i_{r\gamma}\\
&m_{эм}=\frac{\sqrt{3}}{2}p_m\cdot x_m\left[\left(i_{s\alpha}\cdot i_{r\gamma}+i_{s\beta}\cdot i_{r\alpha}+i_{s\gamma}\cdot i_{r\beta}\right)-\left(i_{s\alpha}\cdot i_{r\beta}+i_{s\beta}\cdot i_{r\gamma}+i_{s\gamma}\cdot i_{r\alpha}\right)\right]\\
&p\omega_r=\frac{p_m}{J^*}\left(m_{em}-m_{WM}\right)\\
&i_{s\alpha}=k_{s\alpha1}\cdot\psi_{s\alpha}+k_{s\alpha2}\cdot\psi_{s\beta}+k_{s\alpha3}\cdot\Psi_{s\gamma}+k_{s\alpha4}\cdot\psi_{r\alpha}+k_{s\alpha5}\cdot\psi_{r\beta}+k_{s\alpha6}\cdot\psi_{r\gamma}\\
&i_{s\beta}=k_{s\beta1}\cdot\psi_{s\alpha}+k_{s\beta2}\cdot\psi_{s\beta}+k_{s\beta3}\cdot\Psi_{s\gamma}+k_{s\beta4}\cdot\psi_{r\alpha}+k_{s\beta5}\cdot\psi_{r\beta}+k_{s\beta6}\cdot\psi_{r\gamma}\\
&i_{s\gamma}=k_{s\gamma1}\cdot\psi_{s\alpha}+k_{s\gamma2}\cdot\psi_{s\beta}+k_{s\gamma3}\cdot\Psi_{s\gamma}+k_{s\gamma4}\cdot\psi_{r\alpha}+k_{s\gamma5}\cdot\psi_{r\beta}+k_{s\gamma6}\cdot\psi_{r\gamma}\\
&i_{r\alpha}=k_{r\alpha1}\cdot\psi_{s\alpha}+k_{r\alpha2}\cdot\psi_{s\beta}+k_{r\alpha3}\cdot\Psi_{s\gamma}+k_{r\alpha4}\cdot\psi_{r\alpha}+k_{r\alpha5}\cdot\psi_{r\beta}+k_{r\alpha6}\cdot\psi_{r\gamma}\\
&i_{r\beta}=k_{r\beta1}\cdot\psi_{s\alpha}+k_{r\beta2}\cdot\psi_{s\beta}+k_{r\beta3}\cdot\Psi_{s\gamma}+k_{r\beta4}\cdot\psi_{r\alpha}+k_{r\beta5}\cdot\psi_{r\beta}+k_{r\beta6}\cdot\psi_{r\gamma}\\
&i_{r\gamma}=k_{r\gamma1}\cdot\psi_{s\alpha}+k_{r\gamma2}\cdot\psi_{s\beta}+k_{r\gamma3}\cdot\Psi_{s\gamma}+k_{r\gamma4}\cdot\psi_{r\alpha}+k_{r\gamma5}\cdot\psi_{r\beta}+k_{r\gamma6}\cdot\psi_{r\gamma}
\end{aligned}\right\}\quad(1)$$

where:

$$\begin{bmatrix}
k_{s\alpha1} & k_{s\alpha2} & k_{s\alpha3} & k_{s\alpha4} & k_{s\alpha5} & k_{s\alpha6}\\
k_{s\beta1} & k_{s\beta2} & k_{s\beta3} & k_{s\beta4} & k_{s\beta5} & k_{s\beta6}\\
k_{s\gamma1} & k_{s\gamma2} & k_{s\gamma3} & k_{s\gamma4} & k_{s\gamma5} & k_{s\gamma6}\\
k_{r\alpha1} & k_{r\alpha2} & k_{r\alpha3} & k_{r\alpha4} & k_{r\alpha5} & k_{r\alpha6}\\
k_{r\beta1} & k_{r\beta2} & k_{r\beta3} & k_{r\beta4} & k_{r\beta5} & k_{r\beta6}\\
k_{r\gamma1} & k_{r\gamma2} & k_{r\gamma3} & k_{r\gamma4} & k_{r\gamma5} & k_{r\gamma6}
\end{bmatrix}=\begin{bmatrix}
x_{s\alpha} & -0{,}5\cdot x_m & -0{,}5\cdot x_m & x_m & -0{,}5\cdot x_m & -0{,}5\cdot x_m\\
-0{,}5\cdot x_m & x_{s\beta} & -0{,}5\cdot x_m & -0{,}5\cdot x_m & x_m & -0{,}5\cdot x_m\\
-0{,}5\cdot x_m & -0{,}5\cdot x_m & x_{s\gamma} & -0{,}5\cdot x_m & -0{,}5\cdot x_m & x_m\\
x_m & -0{,}5\cdot x_m & -0{,}5\cdot x_m & x_{r\alpha} & -0{,}5\cdot x_m & -0{,}5\cdot x_m\\
-0{,}5\cdot x_m & x_m & -0{,}5\cdot x_m & -0{,}5\cdot x_m & x_{r\beta} & -0{,}5\cdot x_m\\
-0{,}5\cdot x_m & -0{,}5\cdot x_m & x_m & -0{,}5\cdot x_m & -0{,}5\cdot x_m & x_{r\gamma}
\end{bmatrix}^{-1}$$

$U_{s\alpha}$, $U_{s\beta}$, $U_{s\gamma}$, $U_{r\alpha}$, $U_{r\beta}$, $U_{r\gamma}$ – phase voltages of stator and rotor; $i_{s\alpha}$, $i_{s\beta}$, $i_{s\gamma}$, $i_{r\alpha}$, $i_{r\beta}$, $i_{r\gamma}$ - phase currents of stator and rotor; $\psi_{s\alpha}$, $\psi_{s\beta}$, $\psi_{s\gamma}$, $\psi_{r\alpha}$, $\psi_{r\beta}$, $\psi_{r\gamma}$ – flux linkages of stator and rotor circuits $r_{s\alpha}$, $r_{s\beta}$, $r_{s\gamma}$, $r_{r\alpha}$, $r_{r\beta}$, $r_{r\gamma}$ – resistances of stator and rotor circuits; $x_{s\alpha}$, $x_{s\beta}$, $x_{s\gamma}$, $x_{r\alpha}$, $x_{r\beta}$, $x_{r\gamma}$ – full inductances of stator and rotor windings; x_m – mutual induction reactance; ω_r – rotational frequency of WPP's rotor, p_m – number of pairs of generator's poles; p – differentiation symbol with respect to synchronous time $\tau = 314\cdot t$ sec.

It should be noted that two kinds of frequency control are used - scalar and vector ones [5, 6]. The simplest control of them according to degree of realization is a scalar one. When study the issues of start by underfrequency relay, it is reasonable from the point of view of comparing the results of study of starting duties impact on electric power network to turn to the scalar control.

The asynchronous generator of WPP with the capacity of $P_{\text{WPP}} = 1500$ kW and $U_{\text{WPP}} = 690$ V voltage is taken as the studied object (generator's parameters are given in the Appendix).

At the first stage let's consider the direct start of generator (in practice it isn't used) for different values of driving torque on generator's shaft, which correspond to the specific wind speeds when connecting the generator to electric power network. The studies are conducted by the system of equations (1), which are recorded in the axes α_s, β_s, γ_s, fixed in space. In this process as the machine is with squirrel cage rotor $U_{r\alpha}$, $U_{r\beta}$, $U_{r\gamma} = 0$, and stator voltages are equal to

$$\left.\begin{aligned}
U_{s\alpha}&=U_s\cdot\sin\tau\\
U_{s\beta}&=U_s\cdot\sin\left(\tau-2{,}094\right)\\
U_{s\gamma}&=U_s\cdot\sin\left(\tau+2{,}094\right)
\end{aligned}\right\}\quad(2)$$

III. Study starting modes of wind turbines equipped with squirrel-cage induction generators

The fluktogrammas of change of generator's operating conditions are presented in Fig. 2: rotational frequency of generator's rotor ω_r (Fig. 1,*a*), electromagnetic torque of generator m_{em} (Fig. 2, *b*), and phase stator currents of generator isα, $i_{s\beta}$, $i_{s\gamma}$ (Fig. 2 *c*, *d*, *e*). It is seen from the fluktogrammas, that at a value of driving torque equal to $m_{em} = -0{,}3$ ("minus" sign indicates a generator mode) the time of connecting of generator to network constitutes about $\tau \approx 400$ rad. ($t = 1{,}27$ s.), the values of starting currents isα, $i_{s\beta}$, $i_{s\gamma}$ reach 5,2 of multiple value, while their duration is not less than 1 second. ($\tau_{start} = 316$ rad.). The value of driving torque equal to $m_{\mathrm{WM}} = -0{,}3$ corresponds roughly to the wind speed equal to $\mathrm{V} = 6$ m/s. When connecting the generator to network in the presence of a driving torque $m_{\mathrm{WM}} = -1$ (wind speed is about $\mathrm{V} = 9{,}5$ m/s), the character of process remains the same as in Fig. 1, but the duration of connection to network and correspondingly the duration of starting currents reduces by 33% and constitutes ($\tau_{start} = 210$ rad.).

It is natural, that the significant amounts of starting currents affect negatively on a network voltage, if it is distanced from the other power supply units and is lightly compensated one (it means the lack of reactive power sources). Therefore, this method of connection of asynchronous generator to network isn't used in practice.

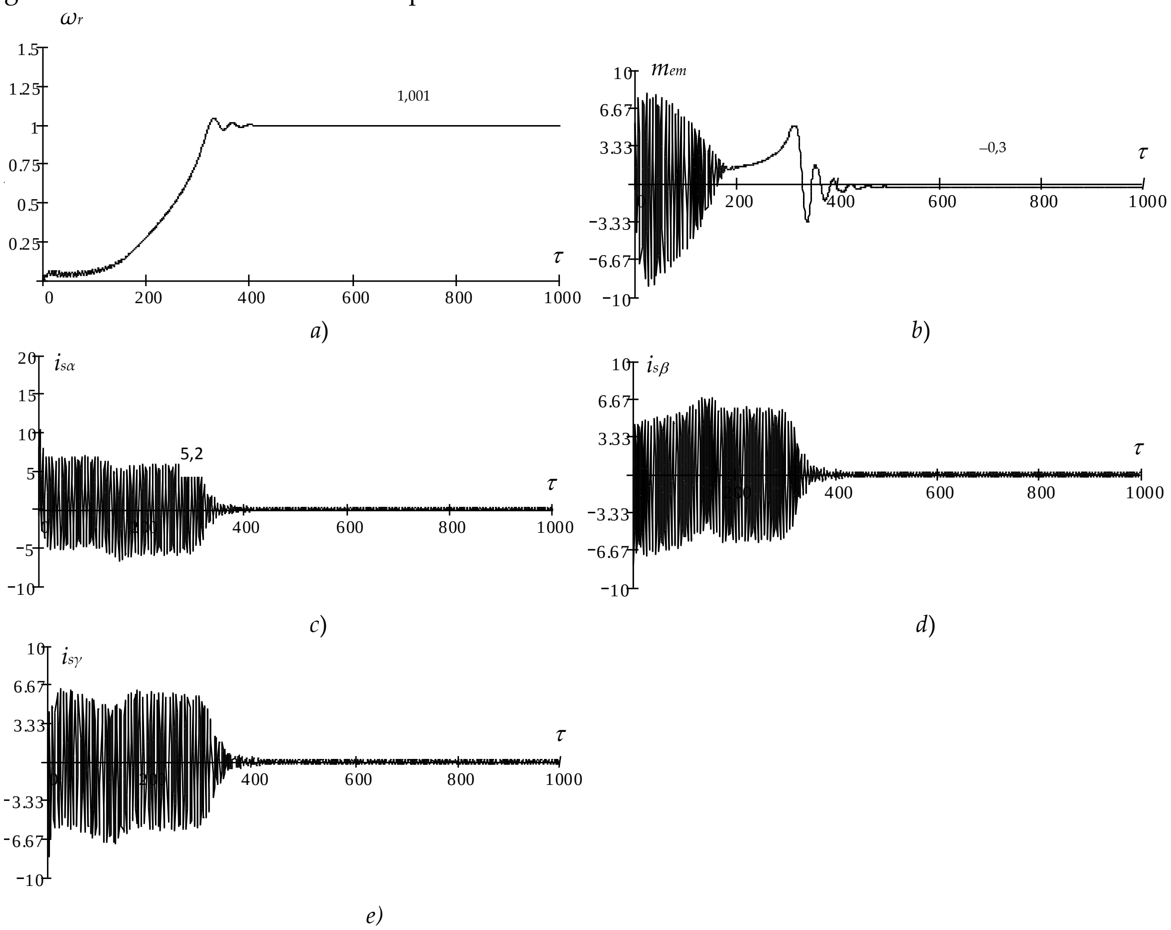

Figure 2. *Fluctogramms of change in operating parameters of induction generator of wind turbines when direct on-line starting*

If there is a frequency converter connected to the stator winding of asynchronous generator, which has a short-circuited rotor, the start by underfrequency relay is carried out. In this process both the amplitude and frequency of supplying the generator voltage should be changed in the equations (2). With linear change of amplitude and frequency, the equations (2) by the same expression will take the form:

$$\left.\begin{aligned} U_{s\alpha} &= k_{us}\cdot\sin k_{fs}\cdot\tau \\ U_{s\beta} &= k_{us}\cdot\sin\left(k_{fs}\cdot\tau-2{,}094\right) \\ U_{s\gamma} &= k_{us}\cdot\sin\left(k_{fs}\cdot\tau+2{,}094\right) \end{aligned}\right\} \qquad (3)$$

where $k_{us}=k_{ou}+k_u\cdot\tau$ and $k_{fs}=k_{of}+k_f\cdot\tau$.

With simultaneous linear change of k_{us} and k_{fs}, $k_{0u}=k_{0f}$ and $k_u=k_f$ their initial value and rates of rise are equal. It is necessary to pay attention to one circumstance: with a linear change of frequency k_{fs} its rate of rise in accordance with [7] should be coordinated with the inertia constant of system and a value of driving torque on the WPP's shaft.

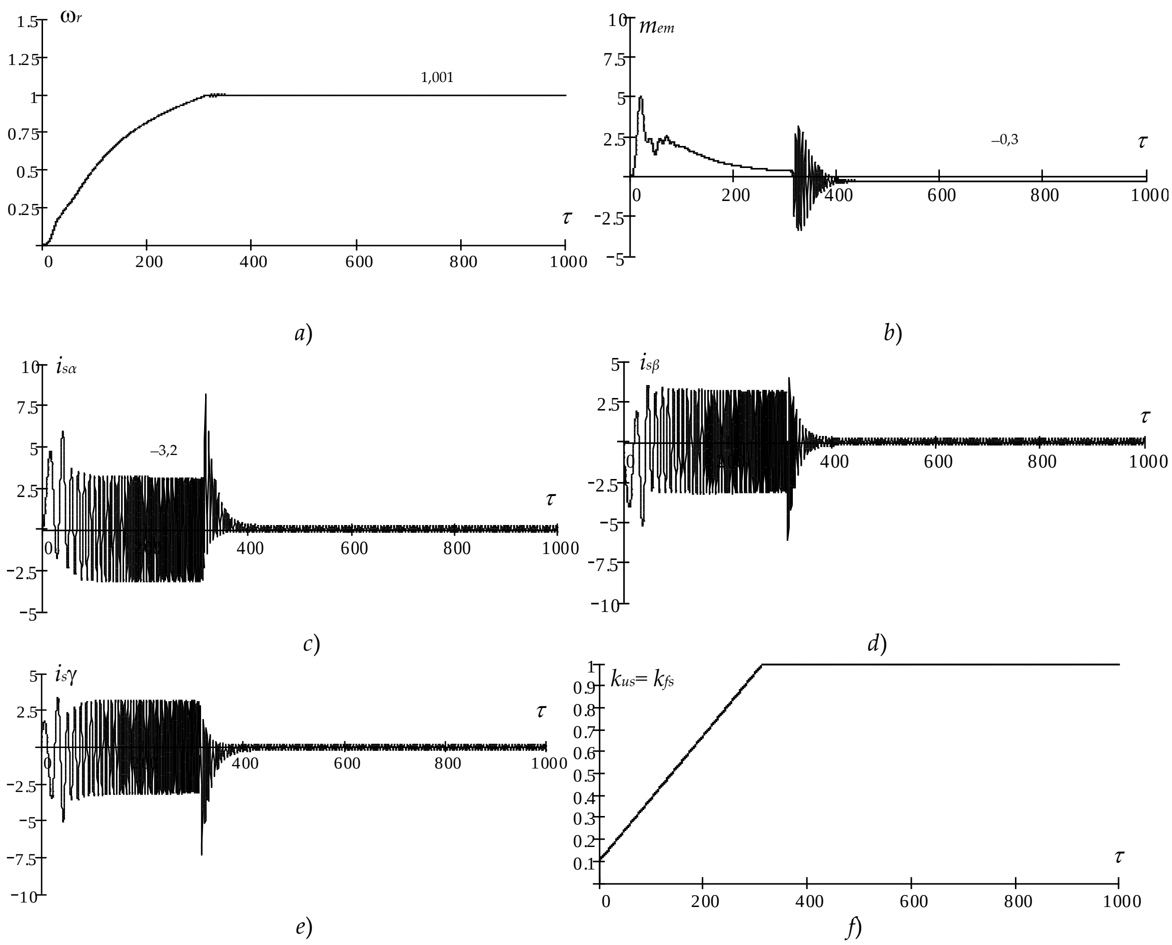

Figure 3. *Fluctogramms of change of operating parameters of the wind turbines with squirrel-cage induction generator in frequency starting*

The fluktogrammas of operating conditions change of the same generator when a start by underfrequency relay according to the expression $k_{us}=k_{fs}=0{,}1+0{,}0028\cdot\tau$ are presented in Fig. 3, herewith a driving torque just as with direct startup was equal to $m_{WM}=-0{,}3$ (wind speed – 5,8-6 m/s). Rotational frequency of WPP ω_r (Fig. 3,*a*) varies practically smoothly from 0 to 1,001, which indicates that a speed of frequency change k_{fs}, and together with it the amplitude of voltage k_{us} (Fig. 3, *f*) has been selected the optimum one [7]. The average value of electromagnetic torque m_{em} (Fig. 3, *b)* at the initial section is less than $m_{em\ av.} = 2{,}5$ (with direct startup $m_{em} = 6{,}7$ (Fig. 2, *b*)). And the most important fact is, that when the start by underfrequency relay the average current values $i_{s\alpha}$, $i_{s\beta}$, $i_{s\gamma}$ in the starting condition practically within the whole startup period do not exceed the values of $i_{s\alpha n} = i_{s\beta n} = i_{s\gamma n} = 3{,}2$ (Fig. 3 *c, d, e*), and their duration constitutes 315–320 rad. Thus, when the start by underfrequency relay with a practically constant duration of action of starting currents their average values reduce almost by 40%. And this allows asserting with a high probability that a voltage drop in the electric power network in the points of WPPs connection will also reduce by~ 40%.

IV. Study starting modes of wind turbines equipped with double-fed induction generator

At the second stage let's consider the issues of startup of WPP's asynchronous generator, carried out on the basis of double fed machine. Diagram of connection to electric power network is shown in Fig. 4 [8].

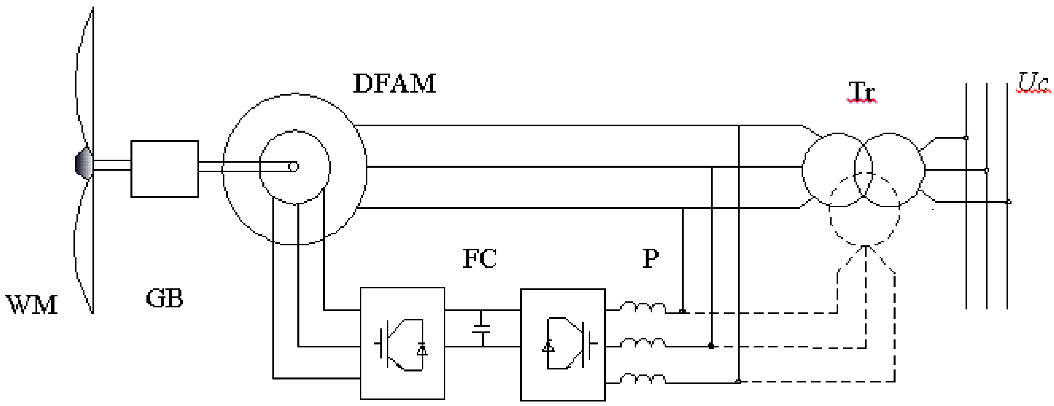

Figure 4: *Grid connection diagram of wind turbines with double fed induction machine*

Here: WD – wind motor, GB – gearbox, DFAM – asynchronous generator made on the basis of double fed asynchronous machine, the FC – frequency converter made on fully controlled power transistors (IGBT – transistors); R – inductive reactor; Tr – coupling transformer of connection with the power system (it can be two-winding one (solid lines) or triple-winding one (dashed lines)). When study the issues of start by underfrequency relay of WPPs with these generators, it is expedient to turn to the form of records of machine's differential equations in three-coordinate system of coordinates α_r, β_r, γ_r, rotating with the rotor speed ω_r [3].

In this case, the first 6 equations of the system (1) are replaced by the following 7 ones, the others remain unchanged:

$$\left.\begin{aligned}
&p\Psi_{s\alpha}=U_{s\alpha}\cdot\sin\theta+\frac{1}{\sqrt{3}}\cdot\omega_r\left(\psi_{s\beta}-\psi_{s\gamma}\right)-r_s\cdot i_{s\alpha}\\
&p\Psi_{s\beta}=U_{s\beta}\cdot\sin\left(\theta-\frac{2\pi}{3}\right)+\frac{1}{\sqrt{3}}\cdot\omega_r\left(\psi_{s\gamma}-\psi_{s\alpha}\right)-r_s\cdot i_{s\beta}\\
&p\Psi_{s\gamma}=U_{s\gamma}\cdot\sin\left(\theta+\frac{2\pi}{3}\right)+\frac{1}{\sqrt{3}}\cdot\omega_r\left(\psi_{s\alpha}-\psi_{s\beta}\right)-r_s\cdot i_{s\gamma}\\
&p\Psi_{r\alpha}=k_{ur}\cdot\sin\left(k_{fr}\cdot\tau\right)-r_r\cdot i_{r\alpha}\\
&p\Psi_{r\beta}=k_{ur}\cdot\sin\left(k_{fr}\cdot\tau-\frac{2\pi}{3}\right)-r_r\cdot i_{r\beta}\\
&p\Psi_{r\gamma}=k_{ur}\cdot\sin\left(k_{fr}\cdot\tau+\frac{2\pi}{3}\right)-r_r\cdot i_{r\gamma}\\
&p\theta=1-\omega_r
\end{aligned}\right\}\tag{4}$$

The rest equations (1) of system: electromagnetic torque, movement, connection of the currents with flux linkages, matrix of determination of this connection factors remains unchanged. One variable is added here – θ, the interior angle of machine, i.e. the angle between axis α_{so} of three-coordinate system of stator's coordinates, moving with the synchronous speed ω_s and axis α_r of three-coordinate system of rotor's coordinates, moving with a speed of machine's rotor ω_r

Technology of start by underfrequency relay of double fed machine of WPP, which can consist of two stages, is the following [2]: at the first stage in the presence of driving torque on the shaft of WPP $-m_{\text{WM}}$ the winding of stator is shorted-circuited, and the frequency converter, feeding the winding of rotor of DFAM changes linearly the amplitude and frequency of voltage supplying the voltage winding. But because of the limited capacity of converter and its output parameters, this change does not exceed a value of 15–25% of the total machine's capacity. At the second stage after acceleration of WPP's rotor under the influence of driving torque of WPP $-m_{em}$ and start by underfrequency relay, when the rotor's speed reaches 20–25% of the synchronous one, the rotor's winding of generator is short-circuited, and the full line voltage is supplied to the stator's winding, which is connected directly to electric power network. Upon reaching the synchronous speed the generator rotor's windings come into operation, and WPP operates in a steady-state mode with connecting the automatic control of WPP's rotational frequency with the help of frequency converter as a function of wind speed value in a certain range of its variation.

All of described above has been implemented on the three-coordinate mathematical model of DFAM of WPP [3], the results of which are shown in Fig. 5.

As it has been noted, at the first stage the voltage of stator $U_s = U_{s\alpha}=U_{s\beta}=U_{s\gamma}= 0$ (winding is short-circuited) and the rotor winding is fed from the frequency converter according to the linear expression $k_{us}=k_{fs}=-\left(0{,}01+0{,}00028\cdot\tau\right)$. The fluktogramma of change of rotational frequency of rotor ω_r is given in Fig. 5, *a*. In the process of start by underfrequency relay from the rotor side in the presence of driving torque of wind motor $m_{\text{WM}}=-0{,}3$ (which corresponds to wind speed $\text{V}=6$ m/s) in the range of from 0 to 500 radian the rotational frequency of WPP's rotor rises to $\omega_r=0{,}28$, in this process all operating conditions of generator - the electromagnetic torque m_{em} and currents of stator $i_{s\alpha}$, $i_{s\beta}$, $i_{s\gamma}$ do not exceed 1–1,5 of values in relative units. After 500-th radian the winding of stator is connected to the network voltage U_s, and winding of DFAM's rotor is short-circuited U_r=0. A direct startup of asynchronous generator occurs, but the acceleration begins not from zero, and with the initial rotor's speed equal to $\omega_r=0{,}28$. The time of startup of this stage constitutes about $\tau_{rn.}=120$ rad. (from 500 rad. up to 620 rad.), while the average value of starting electromagnetic torque is equal to $m_{em\,av.}=3{,}3$, stator currents $i_{s\alpha}$ (Fig. 5, *c*), $i_{s\beta}$ (Fig. 5, *d*) $i_{s\gamma}$ (Fig. 5, e) reach the value of $i_{s\alpha}\approx i_{s\beta}\approx i_{s\gamma}\approx 5{,}8$.

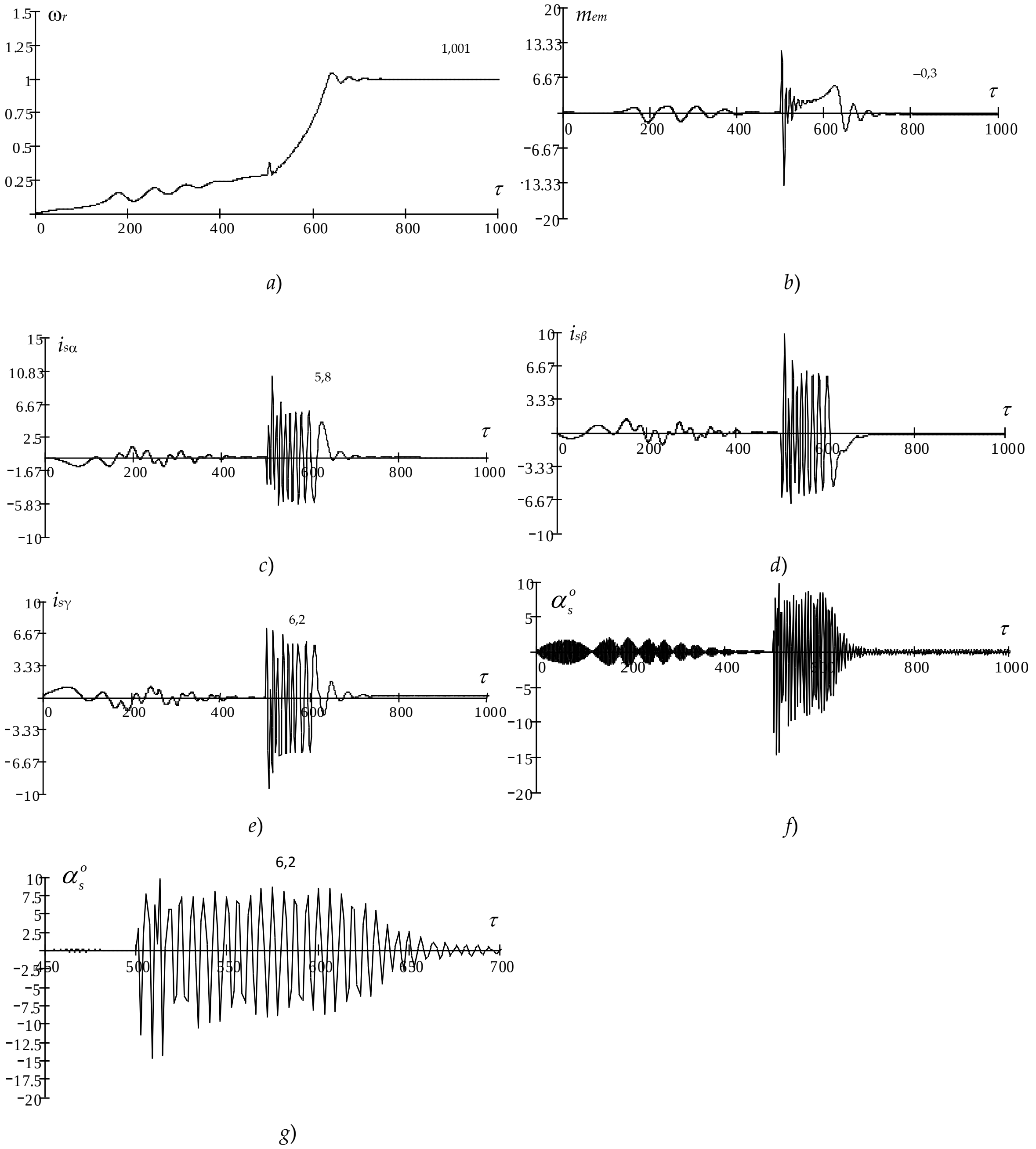

Figure 5. *Fluctogramms of change of operating parameters of double-fed induction generator of wind turbine when frequency-direct on-line starting*

In order to carry out a comparative analysis of start by underfrequency relay processes of asynchronous generators of WPPs, made with the squirrel-cage rotor and winding of rotor (DFAM) it needs to transfer the currents received on mathematical model of DFAM into the system of fixed coordinates. By trivial conversions let's determine, for example, a current in the fixed in space system of coordinate α_s^o, it is determined by the correlation [9]:

$$i_{s\alpha}^{o} = i_{s\alpha} \cdot \cos(\theta + \omega_s \cdot \tau) + i_{s\beta} \cdot \cos\left(\frac{2\pi}{3} - \theta - \omega_s \cdot \tau\right) - i_{s\gamma} \cdot \cos\left(\frac{\pi}{3} - \theta - \omega_s \cdot \tau\right) \quad (5)$$

Where $i_{s\alpha}^{o}$ – reduced current of DFAM's stator along the axis α_s, fixed in space, $i_{s\alpha}$, $i_{s\beta}$, $i_{s\gamma}$ – currents of DFAM's stator recorded in the axes rotating with the rotor speed ω_r. θ –angle between the axis rotating with the rotor speed ω_r and the axis rotating with synchronous speed ω_s, and finally $\omega_s \cdot \tau$ – angle between the fixed in space axis and axis rotating with synchronous speed $\omega_s = 1$.

Current in one phase α_s^o determined by the expression (5) is presented in Fig.5, *f*, (unfolded fluktogramma of this current is shown in Fig. 5, *g*).

As it is seen from the fluktogramma the average starting value of this current reaches the value of $i_{s\alpha cp} = 6{,}2$ and its duration is equal to 130 radian.

Thus, comparing the results of studies of start by underfrequency relay modes of frequency controlled squirrel-cage asynchronous generator of WPP,and frequency controlled from the rotor side DFAM of WPP, it should be noted, that in terms of impact on electric power network, the starting currents of the first generator constitute of the order of 3,2 relative units with the time of their action $\tau_n = 315$ radian, and the starting currents of DFAM constitute of the order of 6,2 relative units with the time of their action $\tau_n = 130$ radian. In the first case the total starting time constitutes 400 radian, and in the second case – 620 radian.

Conclusion

1. The methods of comparative analysis of start by underfrequency relay of WPP, containing the frequency controlled squirrel-cage asynchronous generator, and WPP, containing the asynchronous generator, made on the basis of double fed machine, the rotor windings of which is supplied from a frequency converter, has been developed.

2. The most preferable option out of the investigated ones, in terms of impact on the electric power networks in the place of WPP's connection, is the one with the frequency controlled generators with squirrel-cage rotors, starting current of which when the start by underfrequency relay is almost 2 times lower than the starting current when startup of WPP with DFAM, although its duration is 2.4 times longer than the starting current of DFAM. However, the total time of output to steady-state modes for WPP with squirrel-cage asynchronous generator is 1,5 times less than for the generator with DFAM.

3. And finally, the energy expended for startup process in the first case is 55% lower than the one expended for startup of DFAM.

References

[1] World Wind Resource Assessment Report by the WWEA Technical Committee. December 2014, WWEA Technical Paper Series (TP-01-14), Bonn, Germany.

[2] www.elespec-ltd.com. Elspec Power Quality Solutions. Wind Energy: Reactive Power Compensation Systems.

[3] Mustafayev R., Hasanova L. Mathematical models of controlled three-phase asynchronous machines. Electricity, №5, 2016.

[4] Kopylov I.P. Mathematical modeling of electrical machine. M. High school. 1987.

[5] Dejan Schreiber High power converters for renewable power sources. Translation of A.Kolpakov. Power electronics, №5, 2010.

[6] Guzeev B.V. Khakimyanov M.I. Modern industrial high-voltage frequency converters for control of asynchronous and synchronous motors. "Oil and Gas Business" Electronic scientific journal, № 3, 2011.

[7] Guzeev B.V. Khakimyanov M.I. Modern industrial high-voltage frequency converters for control of asynchronous and synchronous motors. "Oil and Gas Business" Electronic scientific journal, № 3, 2011.

Appendix

Item 1

a) Parameters of WPP's generator; resistances in relative units:

P_n = 1500 kW	r_s=0,0086	x_m=3,459
U= 690 V	r_r=0,01	x_s=3,5399≈3,54
p_m=2	$x_{\sigma s}$=0,0809	x_r=3,5461
J_{total} = 52,4 kgm ^{2} (WPP's rotor)	$x_{\sigma r}$=0,871	
$n_н$=1500 $^{rev}/_{min.}$	$M_{ном} = \frac{9550 \cdot P_н}{n_н} = 9550$ Nm	

b) Calculated and basic values of parameters

U_{phase}=398 B	$P_{баз} = \frac{3}{2} \cdot U_{баз} \cdot I_{баз} = 1664{,}256$ кW
$U_{basic} = \sqrt{2} \cdot U_{фаз} = 562{,}8$ B	$M_{баз} = \frac{P_{баз}}{\omega_{баз}} = 5300{,}17$ Nm
I_{phase} = 1394 A	
I_{basic}= $\sqrt{2} \cdot I_{фаз} = 1971{,}4$ A	$J_{баз} = \frac{M_{баз}}{\omega_{баз}^2} = 0{,}0537$ kgm^2

c) Values of parameters in relative units

$$m_H^* = \frac{M_{ном}}{M_{баз}} = 1{,}8 \qquad J^* = \frac{J_{общ}}{J_{баз}} = 975{,}6 \qquad \frac{p_m}{J^*} = \frac{2}{975{,}6} = 0{,}00205$$

Item 2. Algorithm of study on the three-phase model of start by underfrequency relay of squirrel-cage asynchronous machine with a linear change of amplitude and frequency of the stator's voltage. Amplitude of the phase voltage of stator winding for all three phases changes according to the ratio: $k_{us} = k_{fs} = k_0 + k \cdot \tau = 0{,}1 + 0{,}00286 \cdot \tau$.

$$D(\tau, Y) = \begin{bmatrix} (0{,}1 + 0{,}00286 \cdot \tau) \cdot \sin[(0{,}1 + 0{,}00286 \cdot \tau) \cdot \tau] - 0{,}0086 \cdot I_{s\alpha} \\ (0{,}1 + 0{,}00286 \cdot \tau) \cdot \sin[0{,}1 + 0{,}00286 \cdot \tau) \cdot \tau - 2{,}094] - 0{,}0086 \cdot I_{s\beta} \\ (0{,}1 + 0{,}00286 \cdot \tau) \cdot \sin[0{,}1 + 0{,}00286 \cdot \tau) \cdot \tau + 2{,}094] - 0{,}0086 \cdot I_{s\lambda} \\ -0{,}01 \cdot I_{r\alpha} - 0{,}578 \cdot Y_4 \cdot Y_6 + 0{,}578 \cdot Y_5 \cdot Y_6 \\ -0{,}01 \cdot I_{r\beta} - 0{,}578 \cdot Y_5 \cdot Y_6 + 0{,}578 \cdot Y_3 \cdot Y_6 \\ -0{,}01 \cdot I_{r\gamma} - 0{,}578 \cdot Y_3 \cdot Y_6 + 0{,}578 \cdot Y_4 \cdot Y_6 \\ 0{,}00205 \cdot [5{,}99 \cdot [(I_{s\alpha} \cdot I_{r\gamma} + I_{s\beta} \cdot I_{r\alpha} + I_{s\gamma} \cdot I_{r\beta}) - (I_{s\alpha} \cdot I_{r\beta} + I_{s\beta} \cdot I_{r\gamma} + I_{s\gamma} \cdot I_{r\alpha})] - 0{,}00205 \cdot (-0{,}3)] \end{bmatrix}$$

$$Y_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where $Y_0 = \psi_{s\alpha}$; $Y_1 = \psi_{s\beta}$; $Y_2 = \psi_{s\gamma}$; $Y_3 = \psi_{r\alpha}$; $Y_4 = \psi_{r\beta}$; $Y_5 = \psi_{r\gamma}$; $Y_6 = \omega_r$.

$I_{s\alpha} = 8{,}123 \cdot Y_0 + 2{,}119 \cdot Y_1 + 2{,}119 \cdot Y_2 - 3{,}936 \cdot Y_3 + 1{,}968 \cdot Y_4 + 1{,}968 \cdot Y_5$

$I_{s\beta} = 2{,}119 \cdot Y_0 + 8{,}123 \cdot Y_1 + 2{,}119 \cdot Y_2 + 1{,}968 \cdot Y_3 - 3{,}936 \cdot Y_4 + 1{,}968 \cdot Y_5$

$I_{s\gamma} = 2{,}119 \cdot Y_0 + 2{,}119 \cdot Y_1 + 8{,}123 \cdot Y_2 + 1{,}968 \cdot Y_3 + 1{,}968 \cdot Y_4 - 3{,}936 \cdot Y_5$

$I_{r\alpha} = -3{,}936 \cdot Y_0 + 1{,}968 \cdot Y_1 + 1{,}968 \cdot Y_2 + 7{,}825 \cdot Y_3 + 1{,}828 \cdot Y_4 + 1{,}828 \cdot Y_5$

$I_{r\beta} = 1{,}968 \cdot Y_0 - 3{,}936 \cdot Y_1 + 1{,}968 \cdot Y_2 + 1{,}828 \cdot Y_3 + 7{,}825 \cdot Y_4 + 1{,}828 \cdot Y_5$

$I_{r\gamma} = 1{,}968 \cdot Y_0 + 1{,}968 \cdot Y_1 - 3{,}936 \cdot Y_2 + 1{,}828 \cdot Y_3 + 1{,}828 \cdot Y_4 + 7{,}825 \cdot Y_5$

The factors linking the currents with flux linkages are determined from the inverse matrix consisting the machine's parameters, i.e. from the matrix of equation (12):

$$\begin{bmatrix} 3{,}54 & -1{,}73 & -1{,}73 & 3{,}46 & -1{,}73 & -1{,}73 \\ -1{,}73 & 3{,}54 & -1{,}73 & -1{,}73 & 3{,}46 & -1{,}73 \\ -1{,}73 & -1{,}73 & 3{,}54 & -1{,}73 & -1{,}73 & 3{,}46 \\ 3{,}46 & -1{,}73 & -1{,}73 & 3{,}546 & -1{,}73 & -1{,}73 \\ -1{,}73 & 3{,}46 & -1{,}73 & -1{,}73 & 3{,}546 & -1{,}73 \\ -1{,}73 & -1{,}73 & 3{,}46 & -1{,}73 & -1{,}73 & 3{,}546 \end{bmatrix}^{-1}$$

Item 3. Algorithm of study on the three-phase mathematical model of double fed machine, the equations of which are recorded in three-phase coordinate system α_r, β_r, γ_r, rotating with a rotor speed of machine is:

$$D(\tau, Y) = \begin{bmatrix} \sin(Y_6) + 0{,}577 \cdot Y_7 \cdot (Y_1 - Y_2) - 0{,}0086 \cdot I_{s\alpha} \\ \sin(Y_6 - 2{,}09439) + 0{,}577 \cdot Y_7 \cdot (Y_2 - Y_0) - 0{,}0086 \cdot I_{s\beta} \\ \sin(Y_6 + 2{,}09439) + 0{,}577 \cdot Y_7 \cdot (Y_0 - Y_1) - 0{,}0086 \cdot I_{s\lambda} \\ (-0{,}01 - 0{,}000286 \cdot \tau) \cdot \sin[(-0{,}01 - 0{,}00286 \cdot \tau) \cdot \tau] - 0{,}01 \cdot I_{r\alpha} \\ (-0{,}01 - 0{,}00286 \cdot \tau) \cdot \sin[-0{,}01 - 0{,}00286 \cdot \tau) \cdot \tau - 2{,}094] - 0{,}01 \cdot I_{r\beta} \\ (-0{,}01 - 0{,}00286 \cdot \tau) \cdot \sin[-0{,}01 - 0{,}00286 \cdot \tau) \cdot \tau + 2{,}094] - 0{,}01 \cdot I_{r\gamma} \\ 1 - Y_7 \\ 0{,}00205 \cdot [5{,}99 \cdot [(I_{s\alpha} \cdot I_{r\gamma} + I_{s\beta} \cdot I_{r\alpha} + I_{s\gamma} \cdot I_{r\beta}) - (I_{s\alpha} \cdot I_{r\beta} + I_{s\beta} \cdot I_{r\gamma} + I_{s\gamma} \cdot I_{r\alpha})] - 0{,}00205 \cdot (-0{,}3)] \end{bmatrix}$$