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The Analysis of Biphasic Short Circuit Regimes to Doubly-fed Induction Generators Connected to a Power System

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Abstract - **The paper presents analysis of the biphasic short circuit regimes at the terminals of doubly fed induction generator connected to the national power system of the Republic of Moldova. Research related to connecting wind farms to the national electricity system have shown vulnerability related to the supply or consumption of reactive power especially in short circuit regimes with locking rotor inverter. Reactive power consumption asynchronous generator increases essentially under unbalanced and is related to increased rotor reactance about negative sequence currents. The biphasic short-circuit is the high degree of asymmetry 100% ($U_1/U_2=1$). Besides increasing the reactive component of current are increasing resulting critical current value. Under asymmetrical regimes because direct and reversed sequence components interaction appear dual-frequency pulses (100Hz) of active and reactive powers, dangerous mechanical couples due to resonance of mechanical parts.**

Keywords - *wind farm, asynchronous generator, power system, short-circuit, power fluctuations*

I. INTRODUCTION

The impact of offshore wind power on power systems, primarily determined by the active and reactive power supplied to the system. The active power delivered is influenced by the wind speed and the reaction of control system, and that the reactive power of the wind generator operating mode, the control system response and the voltage unbalance of the electrical network. It is known that a pronounced asymmetry of the phase voltages can occur in an asymmetrical fault.

Inverter in the rotor asynchronous generator locks to avoid damage to the short circuit overcurrent regimes. In this regime DFIG operates as a simple asynchronous generator, consuming reactive power from the system. So wind generators regime influence power system and can lead to voltage instability.

The study presents a biphasic short-circuit to a wound rotor induction generator.

It involves a biphasic short circuit to the inverter locked and rotated by the wind turbine rotor, the principle diagram for the analyzed case is shown in Fig. 1.

Equivalent schemes direct and negative phase sequences are shown in Fig. 2.

Since the inverter is locked rotor power is missing (Fig. 2) - the rotor is shorted. The equivalent scheme of negative sequence voltage supply is missing from the system - so that the scheme is shorted.

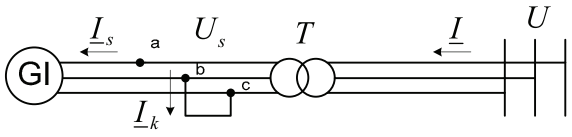

Fig.1. Electric scheme.

The short circuit point potential equivalent nodes in both schemes are the same and these points of both schemes can be joined together. As a result, we obtain single line complex diagram (Fig. 2).

The study prepared by the method proposed was developed in [1].

The resultant impedance circuits connected in parallel with respect to the short-circuit point will be determined by the relationship:

$$\frac{1}{Z_{ab}}=\frac{1}{Z_1}+\frac{1}{Z_2}+\frac{1}{Z_t} \tag{1}$$

Where: Z_1, Z_2 direct and negative sequence impedance of the equivalent circuit of asynchronous generator;

Z_t – transformer impedance;

Z_{ab} – equivalent impedance of connected in parallel schemes in relation to points a, b.

After determining the resulted impedance the equivalent scheme is obtained (Fig. 3).

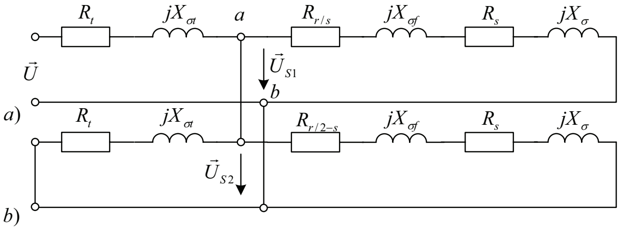

Fig. 2. Equivalent single line complex diagram:
a) direct sequence;
b) negative sequence.

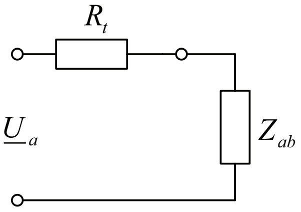

Fig. 3. Equivalent scheme.

Denoting with U_a the phase "a" voltage for direct sequence current can be written:

$$\underline{I}_1 = \frac{\underline{U}_a}{Z_{ab} + Z_t} \tag{2}$$

and direct sequence $\vec{U}_{S1}$ and negative $\vec{U}_{S2}$ components voltage applied to short circuit point is obtained:

$$\underline{U}_{S1} = \underline{U}_{S2} = \underline{U}_a \frac{Z_{ab}}{Z_{ab} + Z_t} \tag{3}$$

So direct and negative sequence current components are:

$$\underline{I}_1 = \frac{\underline{U}_{S1}}{Z_1} = \underline{U}_a \cdot \frac{Z_{ab}}{Z_{ab} + Z_t} \cdot \frac{1}{Z_1} \tag{4}$$

$$\underline{I}_2 = \frac{\underline{U}_{S2}}{Z_2} = \underline{U}_a \cdot \frac{Z_{ab}}{Z_{ab} + Z_t} \cdot \frac{1}{Z_2} \tag{5}$$

Asynchronous generator stator windings are crossed by currents:

$$\begin{aligned} \underline{I}_{sa} &= \underline{I}_1 + \underline{I}_2 \\ \underline{I}_{sb} &= a^2 \underline{I}_1 + a \underline{I}_2 \\ \underline{I}_{sc} &= a \underline{I}_1 + a^2 \underline{I}_2 \end{aligned} \tag{6}$$

Currents consumed from the network:

- in phase „a“ I_{sa};
- in phases „b“ and „c“:

$$I_b = -I_c = -\frac{j\sqrt{3}U}{2Z_t} \tag{7}$$

Considering that the reactance transformer ($U_{sc} = 5 - 10\%$) is much smaller than the generator impedances Z_1 and Z_2, transformer impedance can be ignored, then the relations (4) and (5) become:

$$\underline{I}_1 = \underline{U}_a \frac{1}{Z_1};\ \underline{I}_2 = \underline{U}_a \frac{1}{Z_2} \tag{8}$$

In this case $\underline{U}_{S1} = \underline{U}_{S2} = \frac{1}{2} \cdot \underline{U}_a$ then:

$$\underline{I}_1 = \frac{1}{2} \frac{\underline{U}_a}{Z_1};\ \underline{I}_2 = \frac{1}{2} \frac{\underline{U}_a}{Z_2} \tag{9}$$

If we draw circular diagram then $\frac{U}{Z_1}$ will correspond slipping **s** and $\frac{U}{Z_2}$ to sliding **2-s**. Dividing these values to 2 and adding we obtain symmetrical components of phase currents. Among the more symmetrical components are negative sequence current and the phase currents usually flow through the phase "a" equal to:

$$\underline{I}_{sa} = \underline{I}_{S1} + \underline{I}_{S2} = \frac{1}{2} U_a \left(\frac{1}{Z_1} + \frac{1}{Z_2} \right) \tag{10}$$

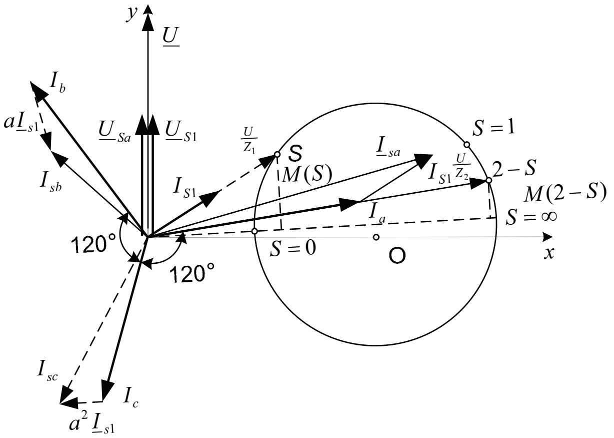

Fig. 4. Circular diagram of asynchronous generator to a biphasic short-circuit.

Circular diagram is shown in Fig. 4.

The electromagnetic torque developed by the asynchronous generator to biphasic short-circuit can be calculated using direct and negative sequence components. Symmetrical voltage components are $U_{S1} = U_{S2} = \frac{U_{\max}}{2}$.

So the voltage applied to the phase "b" and "c" in the short circuit point will form:

$$U_{bc} = \frac{U_{\max}}{2}(e^{j\omega_0 t} + e^{-j\omega_0 t}) \tag{11}$$

Accepting:

$$\begin{cases} \frac{1}{Z_1} = G_1 - jB_1 \\ \frac{1}{Z_2} = G_2 - jB_2 \end{cases} \tag{12}$$

currents will be written in the form:

$$\begin{aligned} \underline{I}_{S1} &= \frac{U_{\max}}{2}(G_1 - jB_1) \\ \underline{I}_{S2} &= \frac{U_{\max}}{2}(G_2 - jB_2) \end{aligned} \tag{13}$$

and the resultant stator current will be:

$$\begin{aligned} \underline{i}_s &= \underline{I}_{S1} e^{j\omega_0 t} + \underline{I}_{S2} e^{-j\omega_0 t} = \\ &= \frac{U_{\max}}{2}\left[(G_1 - jB_1) e^{j\omega_0 t} + (G_2 - jB_2) e^{-j\omega_0 t} \right] \end{aligned} \tag{14}$$

The electromagnetic torque can be provided by the stator magnetic flux and stator currents.

The magnetic flow will be determined from the relationship $\vec{U}_S = \frac{d\vec{\psi}_S}{dt}$ with the relationship:

$$\begin{aligned} \vec{\psi}_S &= \int \vec{U}_S dt = \int \frac{U_{\max}}{2}(e^{j\omega_0 t} + e^{-j\omega_0 t}) dt = \\ &= \frac{U_{\max}}{2j\omega_0}(e^{j\omega_0 t} - e^{-j\omega_0 t}) \end{aligned} \tag{15}$$

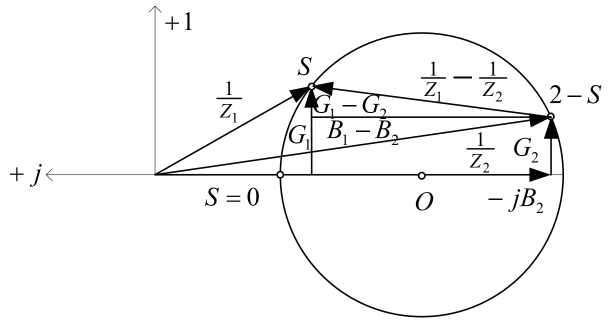

Fig. 5. Circular diagram for determining admittance electromagnetic torque pulsations.

And then the electromagnetic flow will be presented in next form:

$$M=\frac{3}{2}\operatorname{Im}(\overset{*}{\vec{\psi}}_S\,\vec{I}_S)=\frac{3}{2}\frac{U_{\max}}{2\omega_1}(G_1-G_2)+ \\ +\frac{3}{2}\left(\frac{U_{\max}}{2}\right)^2\frac{1}{\omega_1}[(G_2-G_1)\cos(2\omega_1 t)+(B_2-B_1)\sin(2\omega_1 t)] \quad (16)$$

Reactive power absorbed from the grid is determined by the relationship:

$$Q=\operatorname{Im}(\vec{U}\,\overset{*}{\vec{I}})=\operatorname{Im}(\vec{U}_{S1}\,\overset{*}{\vec{I}}_{S1}+\vec{U}_{S2}\,\overset{*}{\vec{I}}_{S2})= \\ =\operatorname{Im}(\vec{U}_{S1}\,\overset{*}{\vec{I}}_{S1})+\operatorname{Im}(\vec{U}_{S2}\,\overset{*}{\vec{I}}_{S2}) \quad (17)$$

If we ignore the transformer reactance (≈ 5%) compared to generator reactance $x_1\approx 300\%$, $Z_2\approx 20\%$ observe that the component of negative sequence $\vec{I}_{S2}$ is 5-7 times directly, and thus the consumption of reactive power on the network exceeds the supply of reactive power.

In this case $\frac{1}{Z_1}$ and $\frac{1}{Z_2}$ can be ignored comparing to $\frac{1}{Z_t}$ and $\underline{U}_{S1}=\underline{U}_{S2}$, and current components (9) will be:

$$\underline{I}_{S1}=\frac{1}{2}\cdot U\cdot\frac{1}{Z_1};\ \underline{I}_{S2}=\frac{1}{2}\cdot U\cdot\frac{1}{Z_2} \quad (18)$$

If we denote the generator reactance under breaking X_k then the impedance of direct and negative sequence is obtained:

$$\begin{cases} Z_1=\dfrac{R_r}{S}+j\,s\,X_k \\ Z_2=\dfrac{R_r}{2-s}+j\,(2-s)\,X_k \end{cases} \quad (19)$$

II. CASE STUDY

The calculation of two-phase short-circuits to a DFIG generator type VESTAS-V52-2MW.

TABLE I.
NOMINAL PARAMETERS

Nominal voltage	U_n	690 V
Nominal current	I_n	1900 A
Nominal frequency	f_n	50 Hz
Nominal power	P_n	2 MW

TABLE II.
BASE VALUES

Base voltage	V_b	400 V
Base current	I_b	1900 A
Base frequency	ω_b	314 rad/s
Base impedance	Z_b	0,21 Ω
Base power	S_b	760 kVA

TABLE III.
ASYNCHRONOUS MACHINE PARAMETERS

Stator resistance	R_s	0,0022 Ω	0,01 u.r.
Rotor resistance	R_r	0,0018 Ω	0,009 u.r.
Stator leakage inductance	$L_{s\sigma}$	0,12 mH	0,18 u.r.
Rotor leakage inductance	$L_{r\sigma}$	0,05 mH	0,07 u.r.
Magnetization resistance	R_m	42 Ω	198 u.r.
Mutual inductance	L_m	2,9 mH	4,4 u.r.
Stator leakage reactance	$X_{s\sigma}$	0,038 Ω	0,179 u.r.
Rotor leakage reactance	$X_{r\sigma}$	0,0157 Ω	0,075 u.r.

Equivalent schemes (transformer is ignored):

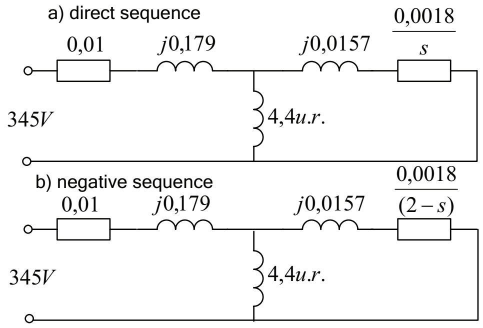

Fig. 6. Equivalent schemes (transformer is ignored).

Ignoring the magnetizing currents obtains the equivalent schemes:

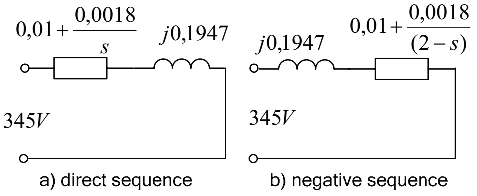

Fig. 7. Equivalent schemes (magnetizing currents are ignored).

Using relations (13) we can calculate the direct and negative sequence currents.

We calculate currents and powers for different slides.

TABLE IV.
CURRENTS AND POWERS FOR DIRECT SEQUENCE

s	G1	B1	Re(Is1)	Im(Is1)	P1	Q1
0	0	0	0	0	0	0
0,001	0,546	-0,059	0,471	-0,051	0,406	-0,044
0,002	1,051	-0,225	0,906	-0,194	0,782	-0,167
0,003	1,488	-0,475	1,283	-0,410	1,107	-0,353
0,004	1,844	-0,780	1,590	-0,673	1,371	-0,581
0,005	2,117	-1,114	1,826	-0,961	1,575	-0,829
0,006	2,313	-1,453	1,995	-1,253	1,721	-1,081
0,007	2,445	-1,782	2,109	-1,537	1,819	-1,325
0,008	2,523	-2,091	2,176	-1,803	1,877	-1,555
0,009	2,561	-2,374	2,209	-2,048	1,905	-1,766
0,01	2,567	-2,631	2,214	-2,269	1,910	-1,957
0,1	0,724	-5,032	0,624	-4,340	0,538	-3,743
1	0,310	-5,117	0,267	-4,414	0,231	-3,807
1,9	0,288	-5,120	0,248	-4,416	0,214	-3,809
1,99	0,287	-5,120	0,247	-4,416	0,213	-3,809
1,999	0,287	-5,120	0,247	-4,416	0,213	-3,809
2	0,287	-5,120	0,247	-4,416	0,213	-3,809

TABLE V.
CURRENTS AND POWERS FOR NEGATIVE SEQUENCE

s	G2	B2	Re(Is2)	Im(Is2)	P2	Q2
0	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,001	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,002	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,003	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,004	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,005	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,006	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,007	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,008	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,009	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,01	0,287	-5,120	0,247	-4,416	0,213	-3,809
0,1	0,288	-5,120	0,248	-4,416	0,214	-3,809
1	0,310	-5,117	0,267	-4,414	0,231	-3,807
1,9	0,724	-5,032	0,624	-4,340	0,538	-3,743
1,99	2,567	-2,631	2,214	-2,269	1,910	-1,957
1,999	0,546	-0,059	0,471	-0,051	0,406	-0,044
2	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

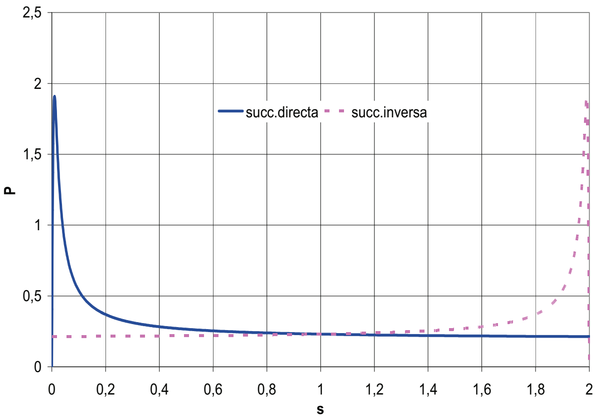

Fig. 8. Dependence P = f (s) for direct and negative sequences.

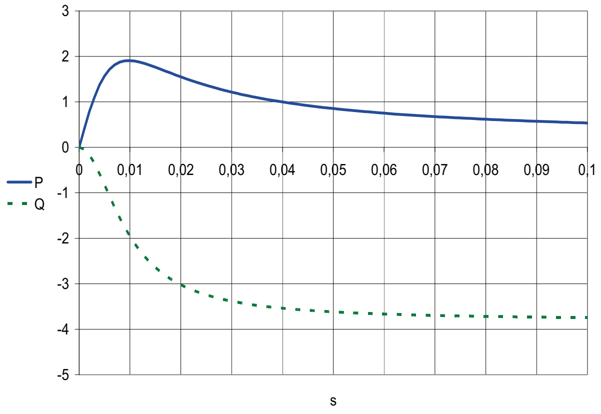

Fig. 10. Dependence P, Q = f (s) for direct sequence (s < 0,1).

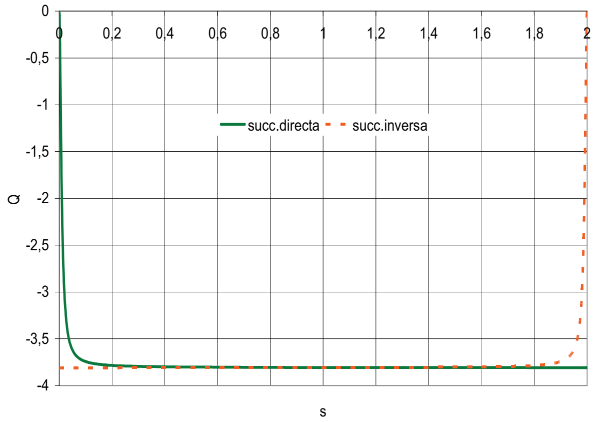

Fig. 9. Dependence Q = f (s) for direct and negative sequences.

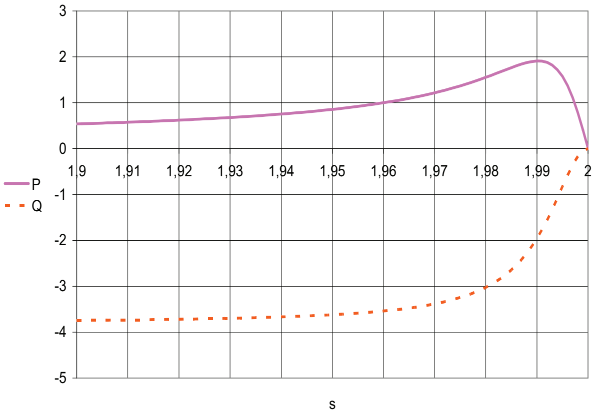

Fig. 11. Dependence P, Q = f (s) for negative sequence (s > 1,9).

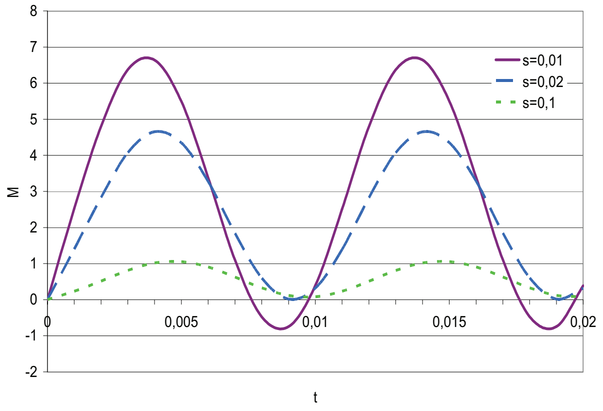

Fig. 12. Dependence M = f (t) for different values of slip s.

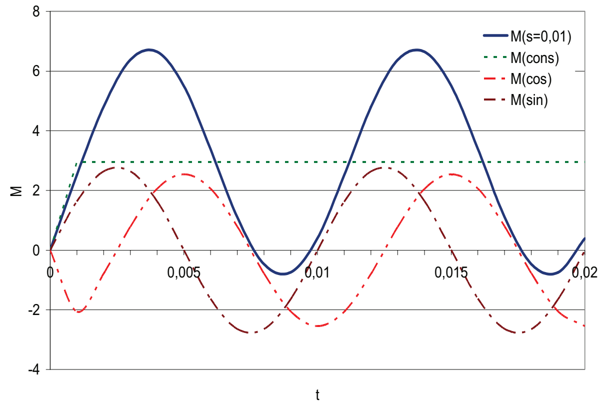

Fig.13. Components torque M = f (t) for s = 0.01.

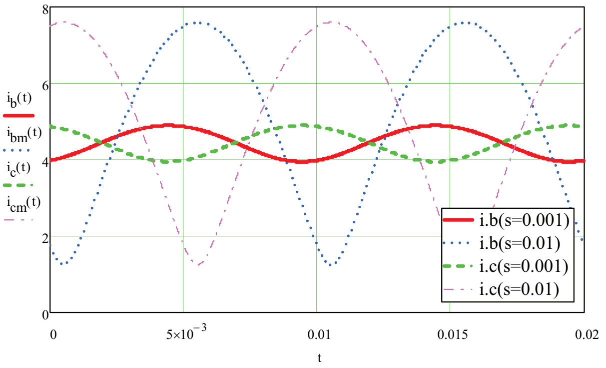

Fig. 14. Currents in phases b and c.

Analysis of the calculations results:

1. Fig. 14 shows that the slides of approximately 1% of the affected phase current values increased approximately 8 times.
2. The active power consumption amounts to 2 units (Fig. 8-11).
3. The reactive power consumption amounts to 4 units (Fig. 8-11).
4. Electromagnetic torque pulsation amplitude exceeds 6 relative units (Fig. 12-13).

III. CONCLUSIONS

The paper presents the algorithm for calculating operating parameters for a two-phase circuit.

Calculation results show that direct sequence components peak between small slides and the negative sequence - near equal to 2-s sliding.

Short circuit currents increase to growth slipping (Fig.13).

Direct and negative sequences of active power (Fig. 10 and Fig. 11) follow mechanical characteristics of the asynchronous machine.

In the biphasic short-circuit electromagnetic torque pulsation frequency is double amplitudes which grow together with slipping (Fig. 12 and Fig. 13) and can exceed the average.

They produce mechanical vibration to operated installation and are dangerous in terms of resonance occurring.

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