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Modelling Starting Regime Work of the Induction Generators of Wind Turbine and Small Hydroplaning

R.I. Mustafayev[1], L. H. Hasanova[2], M. M. Musayev[3]
[1,2,3]*First Azerbaijan Scientific-Research and Disigned-Prospecting Institute of Energetics, Baku, Azerbaijan AZ1012, Aven. H.Zardabi-94*

***Abstract*— Reactive 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*—asynchronous generator, wind-power plants, small hydro power, active power, reactive power.**

I. INTRODUCTION

Asynchronous generators are widely used as an electromechanical converter in wind-power and small hydro-power plants. The main advantages of these generators are low cost, simple design, reliability in operation, resistance to the external accidents and etc. But along with this, they have some disadvantages such as reactive power consumption, voltage control inability (unable to control voltage), a significant voltage reduction in start-up of the power plant, that is particularly affected by the plants unit rating and a "weak" power grid/electrical network at the place of their installation.

Having used as above-mentioned electromechanical converters - AC machines have various designs and layouts. The simplest of them is squirrel-cage rotor induction generator, which is mainly used in small hydropower plants at the early stages of their power range. The next ones are with induction generators cage rotor with frequency inverters (VFD-Variable Frequency Drive) with fully controlled thyristors in the generators stator circuit. These converters have been applied in medium and high power wind-power plants, and practically are not used in small hydro-power engineering.

Double-fed induction machine (DFIM) is the most widely used generator in wind-power engineering. They equipped with frequency inverters connected to the rotor winding of the machine. At the same time considering undeniable advantages, these machines can be also recommended to be used in medium and relatively high power small hydro power plant.

This paperwork studies several subjects of reactive power compensation of various types and configurations of asynchronous generators rotated by renewable energy sources. It should be noted that, in considerable amount of papers works reactive power compensation of these electromechanical converters is covered [1,2,3]. But in a greater degree, they study steady state and quasi steady state operation modes. The reactive power compensation in the start-up conditions remains poorly studied [3]. Once more it should be noted that considerable amount of reactive power compensation is required namely during the start-up mode, its availability may hinder the voltage drop when the generator rotated by renewable energy sources and connected to the "weak" electric grids, thereby substantially improve their reliability.

II. ASYNCHRONOUS GENERATOR WITH CAGE ROTOR

Let us consider reactive power compensation of the asynchronous generator with cage rotor, which is widely used as an electromechanical transducer in small hydropower plants. As a result of a full-scale experiment on the generator with rated power of P_{nom}=132 kW, it was revealed that reactive power consumption of asynchronous generators slightly depends on its active/resistive load, therefore for this class of generators using non-adjustable capacitor battery is recommended. However it should be taken into consideration that, the experiment was carried out on under-loaded AC machine.

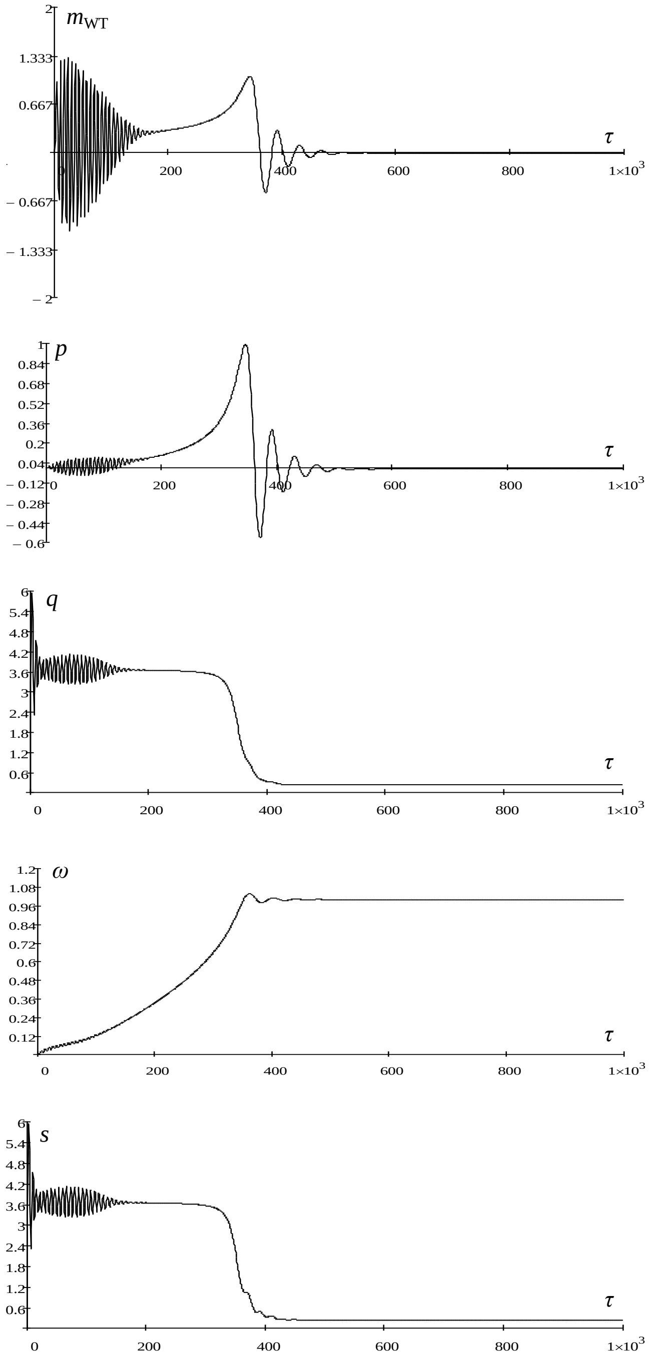
Computer simulation of asynchronous generator, made on the base of induction motor 4AH250M4 with rated power P=110 kW was performed. Operating mode of small hydropower plant generator is simulated–torque on the generator shaft is changed by changing of opening angle of mechanically driven hydro turbine wicket gate. Change of generator operation condition data is shown in Table 1.

TABLE 1
CHANGE OF GENERATOR OPERATION CONDITION DATA

№	m_{wt}, r.u.	p, r.u.	ω, r.u.	q, r.u.	s, r.u.
1	–0,01	–0,01	1	0,227	0,228
2	–0,1	–0,1	1,002	0,231	0,252
3	–0,2	–0,201	1,003	0,239	0,312
4	–0,3	–0,303	1,005	0,25	0,392
5	–0,4	–0,40	1,007	0,265	0,482
6	–0,5	–0,50	1,009	0,283	0,578
7	–0,6	–0,60	1,01	0,304	0,678
8	–0,7	–0,709	1,012	0,328	0,781
9	–0,8	–0,811	1,014	0,357	0,887
10	–0,85	–0,863	1,015	0,374	0,94

Table data analysis shows that in practice, reactive power changing from non-load running (in m_{WT} =–0,01) to rated load (in m_{WT}=–0,85) is approximately 64%.

But if it was knowingly selected oversized in terms generator power and its maximum loading conformed to the half of the rated power (row 5 on Table I), then reactive power (q_5= 0,265) exceeds the non-load running reactive power only by 16%, which conforms with full-scale experiment results, shown in [1]. In this case it is reasonable to use non-adjustable static capacitor batteries, and their value at q_5=0,265 is approximately (S_{base}=129,2 kVA) Q_5=34,2 kVAR. In the case of rated loading m_{WT}=–0,85 and q_{l0}=0,374 the power of capacitor batteries should be q_{l0}=48,3 kVAR. Generator start-up condition is also interesting enough to consider. Figure 1 (a, b, c, d) shows corresponding changes of generator operation conditions – electromagnetic torque m_{EM}, reactive power q, rotor speed ω_r, and total power S at the minimal torque of the wind(water) turbine on the generator shaft m_{WT} =–0,01 (minus denotes generator mode, and plus denotes motor mode). Fluctograms shows that the average value of the reactive power at start-up (Fig.1,b) i_s q=3,6 (rel.unit) and it remains constant within τ=350 rad. (t=1,1 sec.).Although relative reactive power at the start-up has a considerable value, but start-up duration for this type of generator is small and the absolute value of start-up reactive power in “weak” electrical grid causes small voltage drop at generator connection point for a short while.) Therefore it is not reasonable to make special efforts for reactive power compensation at generators start-up.



When generator power is 2 MW, start-up time is t_n=4÷5 sec and reactive power start-up value is q_n=4,7 rel. unit, that may have substantial influence on electrical grid at the connection point. In addition to that, reactive power reaches to considerable value at the steady state mode. For example, for the same type of generator at rated load p_g=0,832, reactive power will reach to value q_g=0,493 relative units, which is in absolute value Q_g=1130 kVAR. All above mentioned points indicates that while attempting using "pure" asynchronous generators with cage rotor for the wind-power and small hydro-power plants at the relatively high power range it creates virtually undecidable problem in reactive power compensation at start-up and regular operation, which adversely affects electrical grid functioning, especially at the "weak" points.

Parameters and equations of mathematical models of generators with rated power of $P_{nom.}$=110 kW and $P_{nom.}$=2000 kW are listed in Appendix 1.

III. ASYNCHRONOUS GENERATOR WITH SQUIRREL-CAGE ROTOR AND FREQUENCY INVERTERS IN GENERATOR STATOR CIRCUIT

Above mentioned electromechanical converters are used in relatively high power wind-power plants – with rated power of 1200–3600 kW (e.g. Siemens Wind Power GmbH). In this case frequency inverters are made on the basis of fully controlled IGBTs- transistors with PWM control.

Availability of the frequency inverters on the stator circuit of asynchronous generator rotated by renewable energy sources, allows substantially expand functional capabilities of the electromechanical converters, including reactive power compensation at the start-up mode. Let's consider this on the wind-power plant (WPP) example. As known [4], WPP is equipped with frequency inverters for the efficiency improvement (i.e. energy generation improvement) at the specific range of the wind speed variation. This range is determined by the maximum value of wind power utilization factor. As a rule of thumb, for the big WPP the power transmission into the electrical grid occurs at initial values of the wind speed – 3,5÷4 m/sec. In this case the asynchronous generator speed is minimal (i.e. frequency inverters functions at the lower borderline frequency).If wind speed range is from 6÷7 m/sec to 10÷12 m/sec, the generator rotating frequency is regulated from the minimum to the maximum value.

For the wind speed range from 3,5÷4 m/sec to 6÷7 m/sec and from10÷12 m/sec. to wind speed calculated value, at which the rated power $V_{calc.}$ (14÷15 m/sec.) is generated; the generator operates at the constant speed, with lowest in the first case and with the highest in the second case.

Let's build the mathematical model of above mentioned operation algorithm of asynchronous generator with frequency inverter on stator circuit and choose more preferred frequency inverter control with the reactive power consumption minimization and its compensation point of view.

For this purpose it is preferable to use fixed space axes – d_s, q_s, for equations of wind power unit asynchronous machine [5]:

$$\left.\begin{aligned}
&p\Psi_{ds} = U_s \cdot \cos(\tau) - r_s \cdot i_{ds}\\
&p\Psi_{qs} = -U_s \cdot \sin(\tau) - r_s \cdot i_{qs}\\
&p\psi_{dr} = \psi_{qr} \cdot \omega_r - r_r \cdot i_{dr}\\
&p\psi_{qr} = -\psi_{dr} \cdot \omega_r - r_r \cdot i_{qr}\\
&p\omega_r = \frac{1}{T_j} \cdot m_{EM} - \frac{1}{T_j} \cdot m_{WT}\\
&m_{EM} = \psi_{dr} \cdot i_{qr} - \psi_{qr} \cdot i_{dr}\\
&i_{ds} = k_s \cdot \psi_{ds} - k_m \cdot \psi_{dr}\\
&i_{qs} = k_s \cdot \psi_{qs} - k_m \cdot \psi_{qr}\\
&i_{dr} = k_r \cdot \psi_{dr} - k_m \cdot \psi_{ds}\\
&i_{qr} = k_r \cdot \psi_{qr} - k_m \cdot \psi_{qs}
\end{aligned}\right\} \qquad (1)$$

In these equations: ψ_{ds}, ψ_{qs}, ψ_{dr}, ψ_{qr} are stator and rotor magnetic linkages at the fixed axes d_s and q_s, and i_{ds}, i_{qs}, i_{dr}, i_{qr} are currents accordingly.

$$U_{ds} = U_s \cdot \cos(\tau); \qquad U_{qs} = -U_s \cdot \sin(\tau)$$

Are stator voltage components, where U_s is a module of; r_s, r_r– active resistance of asynchronous generator stator and rotor circuits; T_j – inertia constant of asynchronous generator rotor and wind (water) turbine in [rad]; t – time in radian; p –differentiation symbol for time τ; m_{EM} and m_{WT} – electromagnetic moments of wind (water) turbine. Coefficients are determined by the following expressions:

$$k_s = \frac{x_r}{x_s \cdot x_r \cdot x_m^2}; \quad k_r = \frac{x_s}{x_s \cdot x_r \cdot x_m^2};$$

$$k_m = \frac{x_m}{x_s \cdot x_r \cdot x_m^2}.$$

This notation allows considering occurrence and control of frequency inverter output parameters, installed in stator circuit of asynchronous generator with cage rotor. In this case voltage components in equations (1) will be equated as:

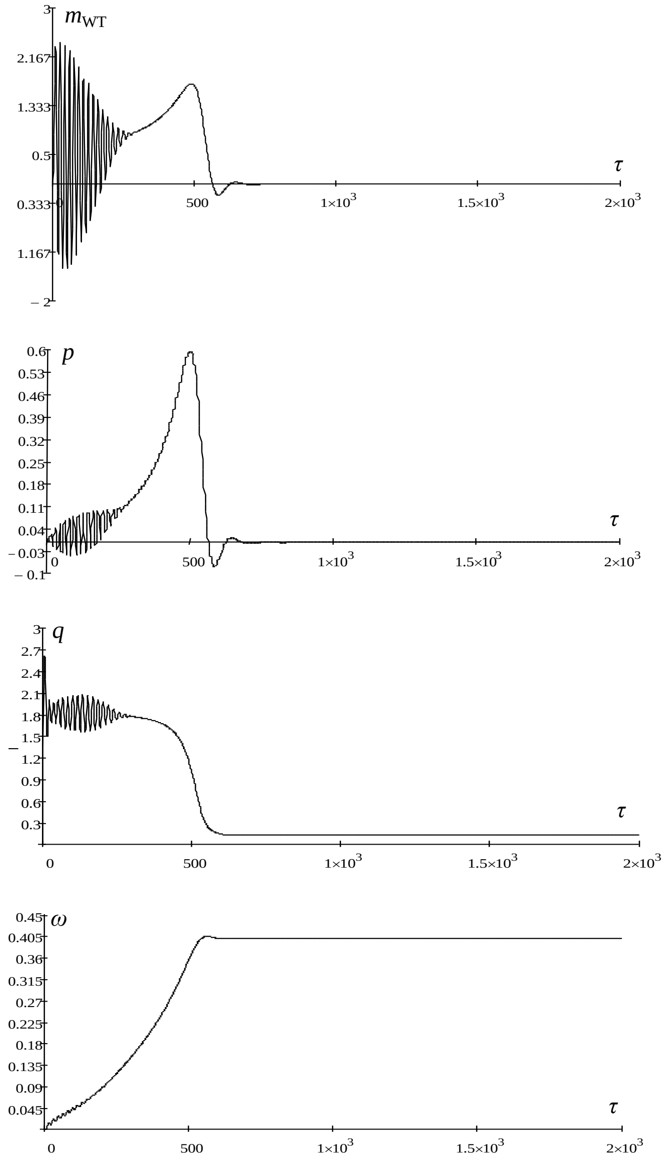
$$\left.\begin{aligned} U_{ds} &= k_{us}\cdot\cos\left(k_f\cdot\tau\right)\\ U_{qs} &= -k_{us}\cdot\sin\left(k_f\cdot\tau\right)\end{aligned}\right\}\qquad (2),$$

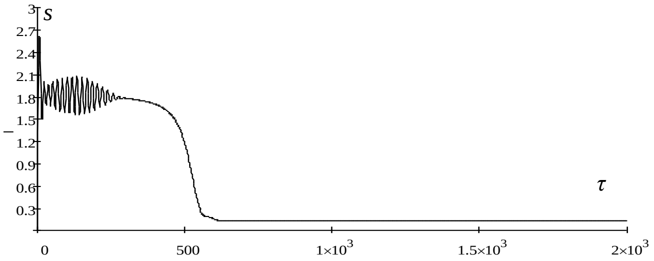
Where $k_{us}=\dfrac{U_s}{U_{s.base}}$ – amplitude component controlled value of stator voltage; $U_{s.base}$ – reference value of stator voltage; $U_{s.base}=\sqrt{2}\cdot U_{f.n.}$; $k_f=\dfrac{f}{f_{base}}$ – frequency component controlled value of stator voltage; $f_{base}=f_н$=50Hz – reference value of current frequency.

As noticed, frequency start-up is available in the wind-power plants equipped with the frequency inverters. It would appear reasonable that this start-up will be implemented prior to minimum value of wind power plant rotor speed. Let us consider the asynchronous generator with rated power of $P_{nom.}$=2000 kW, which plays electromechanical converter roleat WPP (wind power plant). For example, in Siemens 2,3 MW/93-45 WPP lower rotary speed is ~550 rev. per min, and upper is 1450 rev. per min, in other words lower rotary speed $\omega_r\approx 0{,}4$. Considering that WPP start-up directly at wind speed 3÷4 m/sec. and $k_{us}=k_{fs}=1$, then reactive power value would be q_{max}=4,7 rel. units with duration of $\tau\approx 2180$ rad. (~7 sec), which is surely unallowable.

Fluctogramm of operation conditions change at the start-up in the constant frequency $f=0{,}4\cdot f_{ftd}$ is shown in Fig. 2 (a, b, c, d, e). Fig. 2,a shows the fluctogramm generator electromagnetic torque change in driving moment of the wind-turbine engine at the generator shaft; $m_{WT}=-0{,}01$ (that corresponds to the wind speed $V_{nom.}\approx 3{,}5$ m/sec). After ending the transient process, the torque value switches from the positive, that corresponds to the motor mode, to negative value of $m_{EM}=m_{WT}=-0{,}01$, which is generator mode. The WPP rotor speed reaches the value ω_r=0,40013, which is indicating that machine is operating in generator mode (slip $S_{0,4}=-0{,}000325$) (Fig. 2,b). In Fig. 2 (c, d) fluctogramms of change of reactive power q and total power S of the generator is shown, and both have positive sign. The positive sign shows that these powers are consumed from the electrical grid; moreover they slightly differ from each other.

It also corresponds to the physics of the process, as steady-state value of active power is scanty $p=m\cdot\omega_r=-0{,}004$. Steady-state value of power factor's $\cos\varphi_{0,4}=\dfrac{p}{S}=0{,}03$.





Analyzing fluctogramm at Fig. 2 following conclusions can be made: Although during the low frequency start-up, the starting reactive power value considerably decreases and its lifetime is (q_{max}=1,9; $t_{cont.=}$520 rad.), the reactive power value remains substantially high. The availability of frequency inverter on the rotor circuit of asynchronous generator gives an opportunity of frequency starting of WPP. For sake of simplicity in implementation, let’s assume that, linear frequency start-up is carried out, which means voltage amplitude and frequency applied to generator stator windings are changing as per the following correlation:

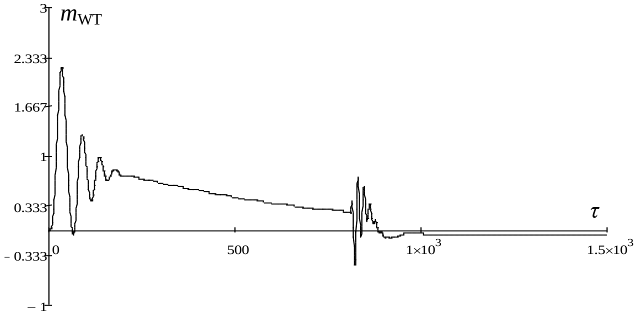
$$k_{us}=k_{fs}=k_0+k_1\cdot\tau \qquad (3)$$

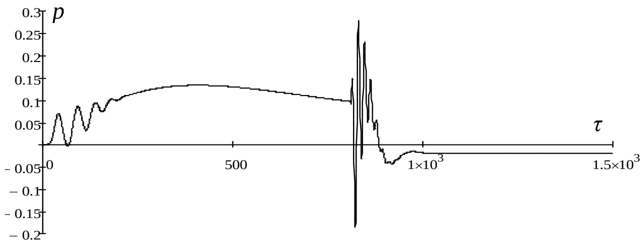
Upon that, speed of frequency rise k_f must be synchronized with the WPP shaft speed growth rate.

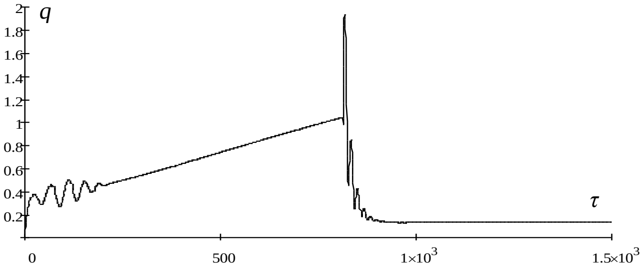
At the Fig. 3 fluctogramm of operating conditions change at the frequency start-up is shown. Amplitude and frequency are changing linearly as per correlation:

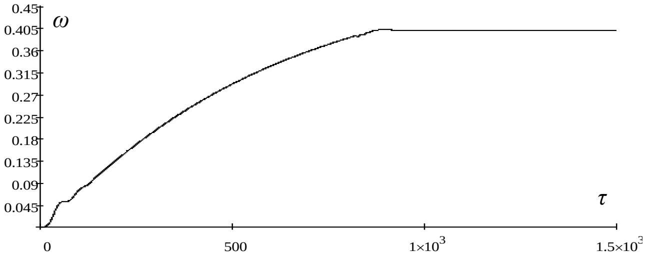
$$k_{us}=k_{fs}=0{,}1+0{,}00037\cdot\tau \qquad (4)$$

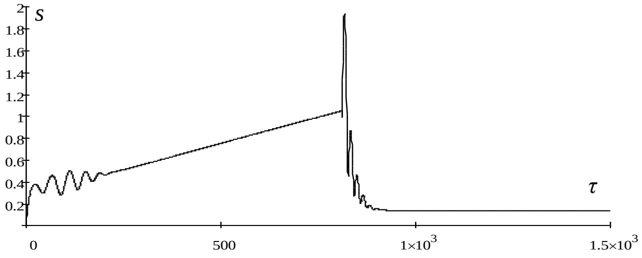
In Fig. 3,a electromagnetic torque curve at the m_{WM}=–0,05 is shown. From the curve it can be seen evidently that the average value m_{EM} at the frequency start-up at ω_r=0 does not exceed m_{EM}=1, then with relatively light oscillationstorque curve changes from the motor mode to the generator mode and sets in value m_{EM}=m_{WM}=–0,05. In Fig. 3,b fluctogramm of rotor rotation frequency change of WWP at the frequency speedup is shown k_f=k_u=0,4. Rotation frequency is set at n=0,40065. And finally, in Fig. 3,c reactive power curve at the frequency start-up is shown. The power is changing in the range of $Q_o\approx 0{,}3$ to $q_{0,4}\approx 0{,}95$, notably average value of reactive power is tangible, and its duration is $\tau_{cont.}$~ 800 rad.











After frequency start-up, let us consider reactive power at the steady state mode at low frequency in rotation frequency control zone in proportion to wind speed and at the frequency maximum value. All results are tabulated in Table 2.

Analyzing results shown in Table 2, the following conclusions can be drawn. At the start-up mode (frequency start-up) average capacity compensating reactive power starting value is $Q_{\substack{com.\\strt}} = 0{,}62$ in relative units, at the maximum loads this value equals to $Q_{\substack{com.\\\max}} = 0{,}45$ and at the medium loads this value is $Q_{\substack{com\\med}} \approx 0{,}3$, and at least at the minimum loads $Q_{\substack{com\\\min}} \approx 0{,}15$.) Thereby, for the reactive power compensation of WPP with rated power P_{rtd}=2000 kW ideally 4 sets of static capacitor batteries [static compensator], with Q_{bat}~325 kVAR power each, are required. Based on operation mode, controllable set of SCB (statistic capacitor battery) will provide capacitive power from 1300 kVAR at the start-up; 975 kVAR at the maximum load; 650kVAR at the medium loads (duration of which is absolute majority), and 325 kVAR - at the minimum loads. As only 4 stages of SCB are required, then it is possible to limit by the step control through semiconductor (thyristor) switches.

TABLE 2
CHANGE OF GENERATOR OPERATION CONDITION DATA OUT FREQUENCY START-UP

№	k_u=k_f	n	m_{EM}	p_{EM}	S	q
	Frequency start up	from 0 to 0,401	–0,05	–0,02	0,132	0,13
1	0,4	0,402	–0,15	–0,06	0,145	0,132
2	0,4	0,402	–0,16	–0,064	0,147	0,132
3	0,5	0,502	–0,174	–0,087	0,188	0,166
4	0,6	0,603	–0,251	–0,151	0,253	0,203
5	0,7	0,704	–0,342	–0,241	0,343	0,244
6	0,8	0,806	–0,448	–0,361	0,464	0,291
7	0,9	0,907	–0,568	–0,516	0,622	0,348
8	1	1,009	–0,703	–0,709	0,824	0,419
9	1	1,01	–0,75	–0,758	0,872	0,432
10	1	1,011	–0,8	–0,809	0,923	0,446
11	1	1,0116	0,83	–0,839	0,955	0,455
12	1	1,012	–0,85	0,86	0,976	0,461

As a matter of practice in compensating device power and amount selections following factors are considered: harmonics, compensability of the grid and etc.

IV. ASYNCHRONOUS GENERATOR WITH PHASE-WOUND ROTOR AND FREQUENCY CONVERTER AT THE ROTOR CIRCUIT (DOUBLE-FEED INDUCTION MACHINE)

Above mentioned generator is used as an electromechanical converter especially in wind-power plant (70-80% of all WPP field), but over the last years it tends to be used as a hydroelectric generator in small hydroelectric power plants.

Double-feed induction machine with frequency inverter at the rotor circuit allows to regulate rotor rotation frequency of the WPP in the range of ±25÷30% by the insertion of e.m.f. (electromotive force) into rotor winding with slip frequency [6].

It is easy to write and solve generator differential equations on the axes rotating at the generator rotor speed. This allows to simulate rotor voltage amplitude and frequency [6] control mode relatively simply:

$$\left.\begin{array}{l}
p\Psi_{ds} = -U_s \cdot \sin(\theta) + \psi_{qs} - \psi_{qs} \cdot s - r_s \cdot i_{ds} \\
p\Psi_{qs} = U_s \cdot \cos(\theta) - \psi_{ds} + \psi_{ds} \cdot s - r_s \cdot i_{qs} \\
p\psi_{dr} = -U_r \cdot k_{ur} \cdot \sin\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{dr} \\
p\psi_{qr} = U_r \cdot k_{ur} \cdot \cos\left(k_{fr} \cdot \tau\right) - r_r \cdot i_{qr} \\
ps = \dfrac{1}{T_j} \cdot m_{\mathrm{WP}} - \dfrac{1}{T_j} \cdot m_{EM} \\
p\theta = s \\
m_{EM} = \psi_{ds} \cdot i_{qs} - \psi_{qs} \cdot i_{ds} \\
i_{ds} = k_s \cdot \psi_{ds} - k_m \cdot \psi_{dr} \\
i_{qs} = k_s \cdot \psi_{qs} - k_m \cdot \psi_{qr} \\
i_{dr} = k_r \cdot \psi_{dr} - k_m \cdot \psi_{ds} \\
i_{qr} = k_r \cdot \psi_{qr} - k_m \cdot \psi_{qs}
\end{array}\right\} \qquad (5)$$

Here, k_{ur} and k_{fr} are factors considering rotor voltage amplitude and frequency control.

As mentioned before, in these generators rotor speed is controlled based on wind speed up and down from synchronous speed not more than 25÷30% (from 0,75÷0,7 to 1,25÷1,3 in relative units). The rated power of frequency inverter is not more than 30% of the generator rated power, and this gives comparative advantage to the WPP equipped with double-feed asynchronous generator over the WPP equipped with squirrel-cage asynchronous generator with frequency converter at the stator circuit.

In case of asynchronous generator with cage rotor the rated power of the frequency inverter must not be less than the rated power of the generator.

If these WPP perform direct starting, then in the equation (5) rotor voltage component U_r must be equated to zero.

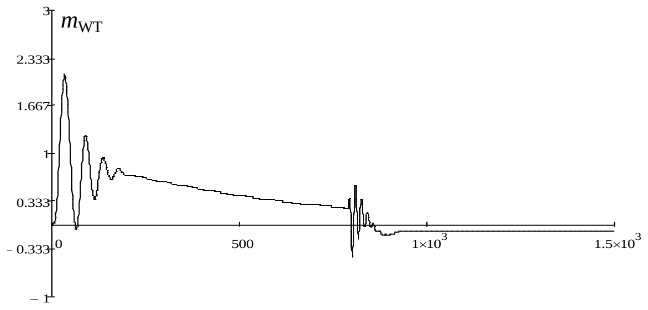
$$\left.\begin{aligned} p\psi_{dr} &= 0 - r_r \cdot i_{dr} \\ p\psi_{qr} &= 0 - r_r \cdot i_{qr} \end{aligned}\right\} \qquad (6)$$

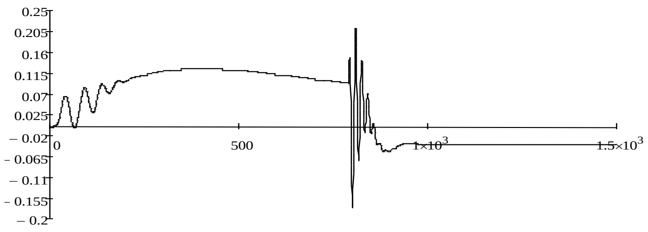
But in this case start-up value of reactive power reaches up to 5-6 multiple values, and its duration depends on plant flyweight.

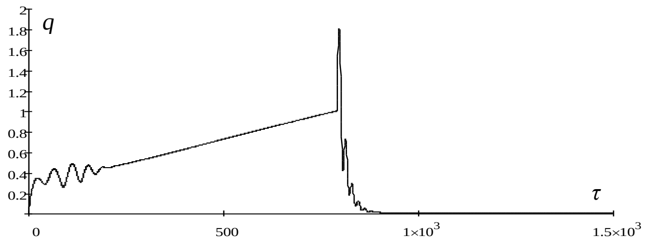
Therefore, direct connection of WPP with double-fed induction machine to “weak” electric grids is undesirable.

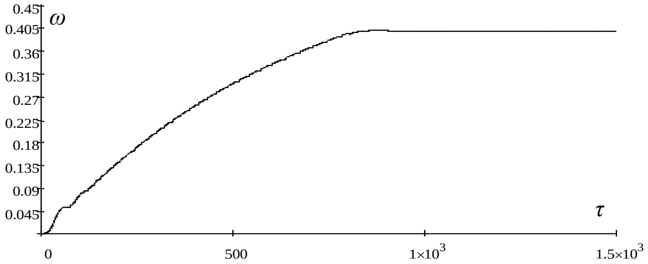
Frequency inverter on the rotor circuit enables frequency start-up, if inverter power range makes it possible.) However, it is important to note that, frequency start-up is efficient at the frequency variation from (0÷0,1) to (0,3÷0,4) units of rated value. As the lower control limit of these generators is in the range of 0,75÷0,7 relative units, and the upper control limit is in range of 1,25÷1,3 relative units, so after frequency start-up it is important to get frequency of 0,75÷0,7 rel. unit. At the Fig. 4 fluctogram of generator operating conditions change in frequency start-up at the rotor voltage amplitude and frequency changing as per following expression is shown:

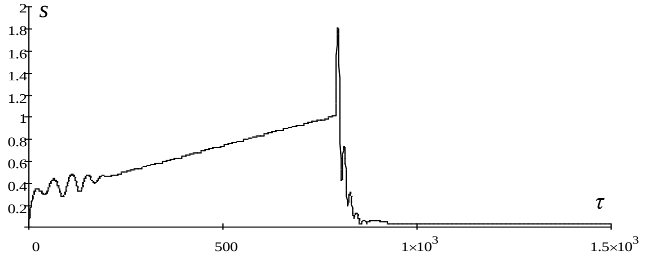
$$k_{ur} = k_{fr} = 0{,}1 + 0{,}00038 \cdot \tau \qquad (7)$$











Electromagnetic torque m_{EM}, reactive power q and WPP rotation frequency shown in Fig.4 (a, b, c) practically same with appropriate curves at the current frequency changing from the part of asynchronous generator stator.

It is well known that WPP with double-fed asynchronous generator allows rotation frequency control in proportion to wind speed at the range of 25-30%. Upon this power factor changes from 0,9 (inductive) to 0,9 (capacitive). When reactive power is consumed from electrical grid, inductive power factor cosφ=0,9 accompanied by light load, corresponding to low shaft rotation frequencies of WPP. Average value of consumed reactive power in this operating mode is q_{consm}≈0,5. Based upon frequency start-up, if assumed that the compensating capacitor battery power is Q_{cap}=0,5 (approx. Q_{cap}=1150 kVAR in absolute units in base power P=2300 kW), in this case from reactive power compensation viewpoint at the start-up and before compensation operating mode in inductive section/range, it is possible in some way to minimize negative influence of WPP to the electrical grids.)

V. CONCLUSIONS

1. As a solution of reactive power compensation in electrical grids, to which WPP with induction generators is connected, at start-up and steady-state operating conditions it is reasonable to use complete mathematical model of induction machines.
2. Using induction generators with cage rotor as an electromechanical converter in WPP (wind power plant) and small HPP (hydroelectric power plant), reactive power at the start-up mode is within the range of 3,5—4,5 relative units (larger values for high power). At the steady-state modes, the reactive power from no-load to rated load operation is changing in range of 50÷60%, that states on substantive dependence of consumed reactive power from load.
3. Having frequency converter in stator or rotor circuit of cage and phase-wound rotor induction generator it is important to carry out frequency start-up. At the amplitude and frequency changing as per linear law, it is possible considerably reduce average value of reactive power from 3,5-4,5 relative units to 0,5-0,6 relative units. In this case the calculated reactive power value of static capacitor batteries used for the compensation will be in reasonable limits.

REFERENCES

[1] Lejnyuk G.D., Nikitorovich A.V., Nghoma Jean-Peter. Compensation of asynchronous generators reactive power at small hydroelectric power plants. Scientific works of Vinnitca national technical university. Energetics and electrotechnology, 2008, No 2, p. 1-7.

[2] Zlatkovskiy A.P. Electrical equipment of country electrical facilities. M. Gosizdatselkhoz, 1953, 446 p.

[3] Elspes Power Qualitu Solutions. Wind Energy: Reactive Power Compensation Systems, www.elspec.ltd.com.

[4] Wind Energy 2006 Katalog 2006 BWE – Service GmbH.

[5] Mustafayev R.I., Hasanova L.H. Modeling and study of quasi-steady-state operation of wind turbines with asynchronous generators with frequency control, Elektrichestvo, 2009, No.6, p. 36-41.

[6] Mustafayev R.I., Hasanova L.H. Modeling of dynamic and steady state modes of operation of wind turbines with double fed induction machine. Elektrotechnics, 2008, No.9, p. 11-15.

*A*PPENDIX

a) Characteristics of small induction power generator on the base of AC motor model of 4AH 250M4:

P=110 kW
$U_{\text{н.ф}}$=220 V
$I_{\text{н.ф}}$=195,5 A
m=3
2p=4
$S_{\text{н}}$=0,015

cosφ=0,908
R_1=0,03 Ohm
$R_2^{'} = 0{,}0172$ Ohm
x_1=0,19Ohm
x_0=4,83 Ohm

J=0,968 kg·m2
$U_{base}= \sqrt{2} \cdot U_{\text{н.ф}}$ =310 V
$I_{base}= \sqrt{2} \cdot I_{\text{н.ф}}$ =277,85A
$Z_{base}= \dfrac{U_{base}}{I_{base}}$ =1,125Ohm
$P_{base} = \dfrac{3}{2} U_{base} \cdot I_{base}$ =129,2 kW

b) Characteristics of asynchronous generator on base of double fed induction motor model of AKN 2-53-12. MUKH L4:

P=2000 kW
$U_{\text{н.ф}}$=3468 V
$I_{\text{н.ф}}$=235 A
$M_{\text{н}}$=38,3kNm
n_{rtd} =500 rpm
x_0=44,59Ohm

$в_{\text{н}}$=2,5
cosφ=0,86
$\eta_{\text{н}}$=0,951
$U_{2\text{н}}$=1045
$в_{\text{н}}$=2,5
$U_{base}= \sqrt{2} \cdot U_{\text{н.ф}}$

R_1=0,17Ohm
$R_2^{'} = 0{,}18$ Ohm
$x_1 = 1{,}55$ Ohm
$x_2^{'} = 1{,}64$ Ohm
R_1=0,17Ohm
$Z_{base} = \dfrac{U_{base}}{I_{base}}$ =14,758 Ohm
$I_{base}= \sqrt{2} \cdot I_{\text{н.ф}}$