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CHARACTERISTICS OF A DOUBLY-FED ASYNCHRONOUS GENERATOR APPLIED IN WIND TURBINES[1]

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Summary

A mathematical model of a doubly-fed asynchronous generator is defined in the paper, using spatial vector theory, in relation to the reference axis associated with the stator. Expressions for characteristic quantities are derived, and operational characteristics for the torque, active and reactive power, power factor, and efficiency are plotted, from which generator operation is analysed at different rotational speeds. Based on this, possibilities and advantages of using doubly-fed asynchronous generators in wind turbines, for obtaining electrical energy from wind energy, are deduced.

Key words: *renewable sources, wind turbines, sustainable development.*

JEL: *Q1, Q19*

Introduction

For decades, electrical power was being obtained from conventional sources: coal, oil, gas, nuclear fuel. However, this production is accompanied by some undesirable effects, among which environmental pollution is the most severe, and even alarming. On the other hand, timescale for the recovery of fossil fuel is too long, and the reserves of it are being gradually exhausted.

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It is for these reasons that exploitation of alternative or renewable sources for electric energy production began at the end of the last century. Among these, wind stands out as the most important, since it has immense capacity and is cost-free, ecologically clean, and unrestricted in time.

In certain developed countries, already more than one quarter of electric power comes from wind power stations, and this share tends to grow rapidly (Petersson, 2005).

Renewable energy potential in Serbia, excluding large hydro power plants, is estimated to 25 % of the primary power consumption (Radojević et al., 2009). Next to the biomass, there is a number of different renewable energy sources, such as wind energy, small hydro power plant, geothermal energy and the solar energy. Even though the biomass energy source currently has the largest potential, it is not sustainable as wind and solar energy, which cannot be exhausted (Milanović, Cvijanović, 2009).

The energy-consumer requirements in Serbia are highest during the winter. The maximum availability of the wind energy typically occurs during the winter, while the solar energy peaks occur in the summer (Gburčik, Mastilović, Vučinić, 2013).

The amount of solar energy received over the vegetation period is also important for calculating the potential for biomass production. According to Project Report (Gburčik et al., 2013), daily amounts of solar energy during the vegetation period ranges from 4.9 kWh/m^2 on the west, to 5.7 kWh/m^2 on the southeast of Serbia.

Considering the geographical position of Serbia and the climatic conditions, the most suitable model for supplying agricultural property from renewable sources for their sustainable development is a hybrid model, which consists of wind generators and solar panels.

A region with fertile agricultural land and with locations potentially suitable for the construction of wind generators in Serbia is located north of the Danube River, i.e. wider region of the territory where wind kosava blows. This area covers about 2000 km^2 and is suitable for the construction of wind generators (Mikičić et al., 2006).

The objective of this article is to present a brief assessment of the variable-speed wind turbine with doubly-fed induction generator (DFIG) because of its advantages, such as small power converter rating and the ability to control the output power.

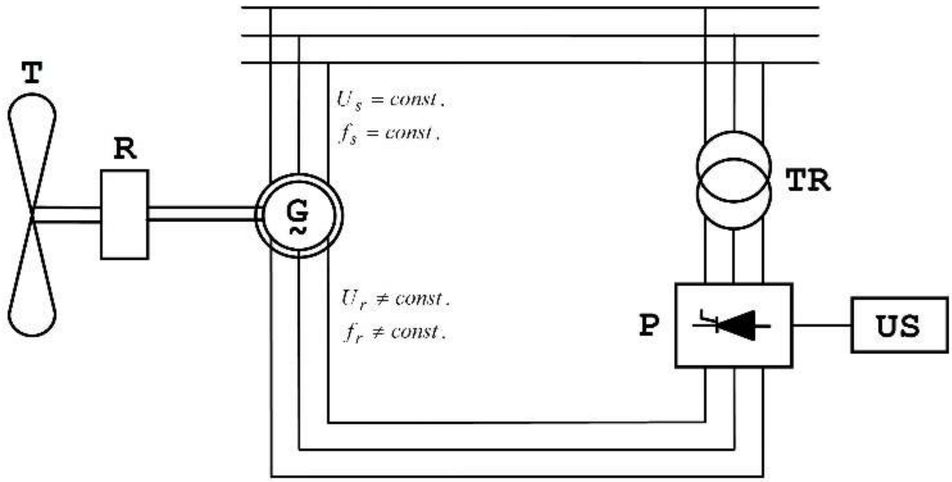
Choice of an appropriate electric generator is crucial in the process of converting wind energy into electric power, due to the stochastic nature of the wind. The essence of this conversion lies in making the wind turbine efficiency as large as possible. This means that at every wind speed maximum electric power of desired quality should be obtained (Vukić et al., 2006).

The use of standard generators comes with a lot of problems. The most acceptable solution is found in using a doubly-fed asynchronous generator, (Figure 1.), especially for high power, because it allows the rotating speed of the wind turbine to change efficiently within a wide range. The speed can change to become either lower or higher than the synchronous speed (Adjoudj et al., 2011).

The stator is connected directly to the grid, while the rotor circuit contains the voltage and frequency energy converter, which also enables the electric current to flow in both directions (Krause, 2013).

Mathematical model of a doubly-fed asynchronous generator is defined by using spatial vector theory (Justo et al., 2014; Mohammadi et al., 2014). Usually asynchronous machines are modelled using the well-known “T-form” equivalent circuit with self and mutual inductances. Expressions for all characteristic quantities are derived from general voltage and flux equations. Operational characteristics are plotted as functions of both the load and the slip angle. Conclusions about the applicability of doubly-fed asynchronous generators in wind power stations and the advantages they offer are drawn from the analysis of specific quantities (Quang, Ditttrich, 2015; Leonhard, 2001).

Figure 1. Schematic representation of a doubly-fed asynchronous generator.



Mathematical model for a doubly fed asynchronous generator

Since the operation of the doubly-fed asynchronous generator is considered in synchronous regime (controlled frequency is set independently), it is most convenient to use a mathematical model obtained from spatial vector theory (Elhassan et al., 2014; Padrón et al., 2010; Boardman et al., 2003), defined relative to the reference axis associated with the stator, the speed of which equals the synchronous speed ω_s.

Speed regulation is possible both above and under the synchronous speed, as well as in both directions (Milkić et al., 2014). Angular velocity is defined by:

$$n = \frac{60}{\Pi}\left(f_1 \mp f_2\right) \tag{1}$$

The mathematical model can be represented by the following set of complex equations (Milkić et al., 2014; Soens et al., 2003):

$$\mathbf{U}_s = -\mathbf{I}_s R_s - d\boldsymbol{\psi}_s / dt - j\omega_s \boldsymbol{\psi}_s \tag{2}$$

$$\mathbf{U}_r = -\mathbf{I}_r R_r - d\boldsymbol{\psi}_r / dt - j(\omega_s - \omega)\boldsymbol{\psi}_r \tag{3}$$

$$\boldsymbol{\psi}_s = \mathbf{I}_s L_s + \mathbf{I}_r L_m \tag{4}$$

$$\boldsymbol{\psi}_r = \mathbf{I}_s L_m + \mathbf{I}_r L_r \tag{5}$$

Using the differentiating operator p voltage and flux equations, observed in the said reference frame and expressed in relative units, are:

$$\mathbf{u}_s = -\mathbf{i}_s r_s - (p + j)\boldsymbol{\psi}_s \tag{6}$$

$$\mathbf{u}_r = -\mathbf{i}_r r_r - (p + js)\boldsymbol{\psi}_r \tag{7}$$

$$\boldsymbol{\psi}_s = \mathbf{i}_s x_s + \mathbf{i}_r x_m \tag{8}$$

$$\boldsymbol{\psi}_r = \mathbf{i}_s x_m + \mathbf{i}_r x_r \tag{9}$$

where x_s and x_r are total inductive reactances per phase of the stator and the rotor, respectively while the slip is defined as:

$$s = f_r / f_s = (\omega_s - \omega)/\omega_s \tag{10}$$

Stationary operation is considered, so plugging $p = 0$ into (6) and (7) yields:

$$\mathbf{u}_s = -\mathbf{i}_s r_s - j\boldsymbol{\psi}_s \tag{11}$$

$$\mathbf{u}_r = -\mathbf{i}_r r_r - js\boldsymbol{\psi}_r \tag{12}$$

$$\boldsymbol{\psi}_s = \mathbf{i}_s x_s + \mathbf{i}_r x_m \tag{13}$$

$$\boldsymbol{\psi}_r = \mathbf{i}_s x_m + \mathbf{i}_r x_r \tag{14}$$

The stator voltage vector $\mathbf{u}_s$ is taken to define the positive direction of the real axis, while the rotor voltage vector $\mathbf{u}_r$ leads by an angle ϑ. Hence:

$$\mathbf{u}_s = u_s \cdot e^{j0^\circ}, \quad \mathbf{u}_r = u_r \cdot e^{j\vartheta} \tag{15}$$

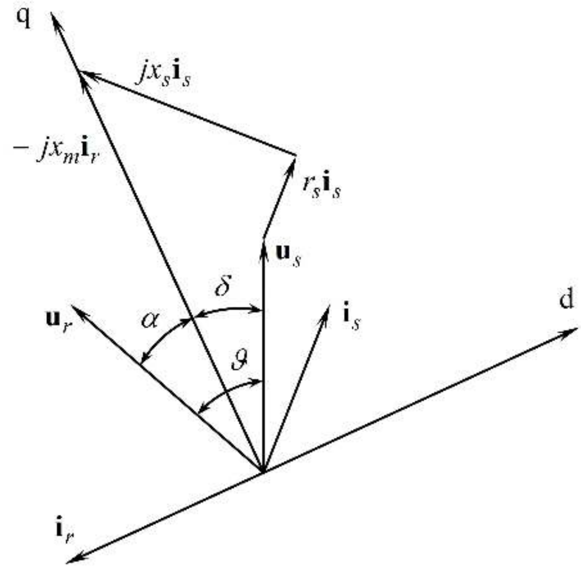
where ϑ is the phase angle between stator and rotor voltage vectors. Vector diagram for the doubly-fed asynchronous generator (Muller et al., 2002) in the synchronous operating mode shows that the phase angle between stator and rotor voltage vectors ϑ and the angle between the stator axis and the stator voltage vector δ (called the load angle, in line with synchronous machine terminology) are related as (Figure 2.):

$$\delta = \vartheta - \alpha \tag{16}$$

where the angle α is given by:

$$\alpha = arctg \frac{sr_s x_r - r_r x_s}{r_s r_r + sx_s x_r - sx_m^2} \tag{17}$$

Figure 2. Phasor diagram for a doubly fed asynchronous generator



Operational characteristics

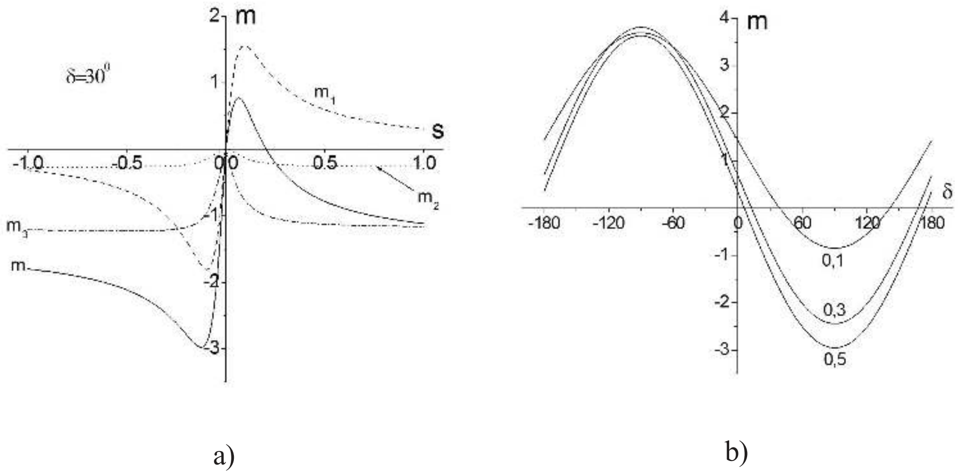
Solving the voltage and flux equations (11), (12), (13) and (14), taking into account assumptions (15), (16) and (17), yields expressions for characteristic quantities of a doubly-fed asynchronous generator in the synchronous operating regime. Operational characteristics are plotted for an asynchronous generator with 200 kVA nominal power, for which the parameters from the equivalent scheme, expressed in relative units, are: r_s=0.022 *p.u.*, r_r=0.026 *p.u.*, x_{sy}=0.14 *p.u.*, x_{ry}=0.14 *p.u.* and x_m=3.4 *p.u.*. Voltage and frequency of the stator remain constant, while rotor quantities change, with a constant ratio of rotor voltage and frequency u_r/f_r=*const.* Since s=f_r / f_s, in relative units u_r =s.

Electromagnetic torque

General expression for the electromagnetic torque of a doubly-fed asynchronous generator is:

$$m_{em}=\frac{u_s^2}{k_1^2+k_2^2}(sr_rx_m^2-u^2r_sx_m^2)+ \\ +\frac{u_s^2}{k_1^2+k_2^2}ux_m\left[-(r_sr_r+sx_sx_r-sx_m^2)\sin\vartheta+(sr_sx_r-r_rx_s)\cos\vartheta\right] \tag{18}$$

Figure 3. a) Dependence *m* = *f*(*s*); b) Dependence *m* = *f*(*δ*).



Expressed as a function of the load angle the electromagnetic torque is:

$$m_{em}=\frac{u_s^2}{k_1^2+k_2^2}(sr_rx_m^2-u^2r_sx_m^2+ux_m\sqrt{a^2+b^2}\cdot\sin\delta)=m_1+m_2+m_3 \tag{19}$$

where: $k_1=r_sr_r-s(x_sx_r-x_m^2)$, $k_2=sr_sx_r+r_rx_s$, and $u=u_r/u_s$.

The torque consists of three components. The first two (m_1) and (m_2) are asynchronous, while the third (m_3) is a synchronous component that corresponds to the angular torque of the synchronous generator to whose rotor voltage u_r is applied. Fig. 3.a) shows the three components of the torque, as well as the resultant torque, versus the slip angle, for a load angle of δ=30°. Owing to the presence of the synchronous component, the resultant torque is at its maximum for δ=π/2 regardless of the slip, as shown in Fig. 3.b).

Stator and rotor powers

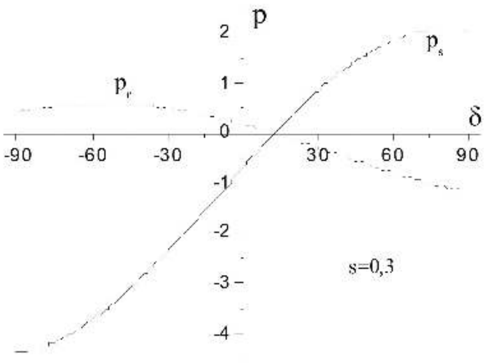
Final expressions for stator and rotor active power are, respectively:

$$p_s = \frac{u_s^2}{k_1^2 + k_2^2}\left[(r_r k_1 + s x_r k_2) - u x_m (k_2 \cos\vartheta + k_1 \sin\vartheta)\right] \tag{20}$$

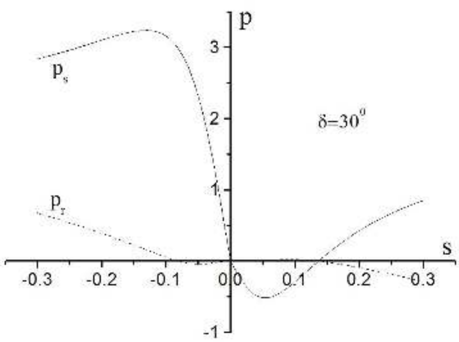
$$p_r = \frac{u_s^2}{k_1^2 + k_2^2}\left[u s x_m (k_1 \sin\vartheta - k_2 \cos\vartheta) + u^2 (r_s k_1 + x_s k_2)\right] \tag{21}$$

Dependences of active power (equations (20) and (21)) on the load and the slip angle are presented in Figs. 4. a)...b) for both stator and rotor, while reactive power curves (based on expressions (22) and (23)) are shown in Figs. 5. a)... b).

Figure 4. a) Dependence $p = f(\delta)$; b) Dependence $p = f(s)$.



a)



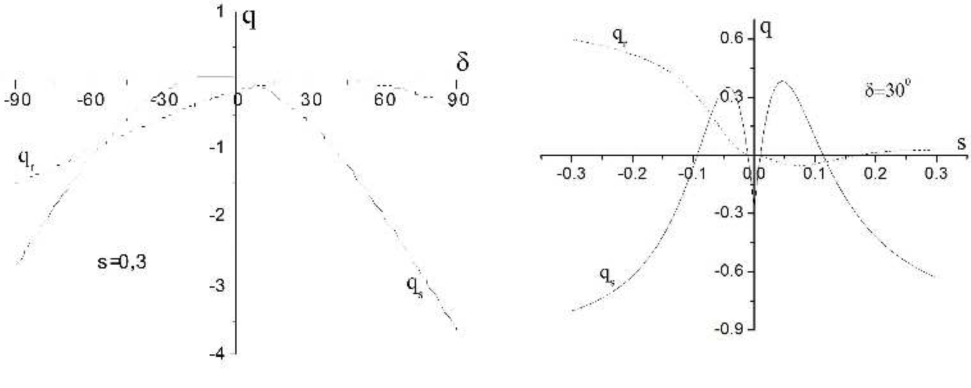
b)

The equations for stator and rotor reactive power are:

$$q_s = -\frac{u_s^2}{k_1^2 + k_2^2}\left[(s x_r k_1 - r_r k_2) - u x_m (k_1 \cos\vartheta - k_2 \sin\vartheta)\right] \tag{22}$$

$$q_r = -\frac{u_s^2}{k_1^2 + k_2^2}\left[u^2 (x_s k_1 - r_s k_2) - u s x_m (k_1 \cos\vartheta + k_2 \sin\vartheta)\right] \tag{23}$$

Figure 5. a) Dependence $q = f(\delta)$; b) Dependence $q = f(s)$.



a) b)

Analysis of characteristics shown in the figures provides insight into a specific power flow in the doubly-fed asynchronous generator. When the generator works with speeds that are lower than the synchronous speed (positive slip), active power is transmitted to the load at stator side, while rotor consumes active power from the grid. However, in the supersynchronous regime ($s < 0$), both the stator and the rotor supply the grid with active power. This is a great advantage, because double feeding can lead to an operation mode with a power higher than nominal, since total active power equals the sum of active powers from both the stator and the rotor.

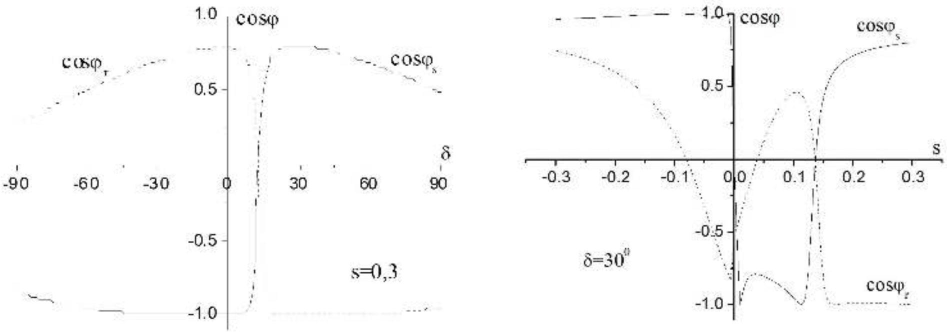
Stator and rotor power factors

In order to meet specific needs of electric power systems, a doubly-fed asynchronous generator, intended for producing active power, in some cases also has to produce reactive power, i.e. it has to work with a desired stator power factor. Figs. 6. a)…b) show the dependences of the power factor on the load angle and slip, respectively. It can be inferred from these graphs that by setting an appropriate rotor voltage change, constant power factor operation can be achieved.

$$\cos\varphi_s = \frac{(r_r k_1 + s x_r k_2) - u x_m (k_2 \cos\vartheta + k_1 \sin\vartheta)}{\sqrt{(k_1^2 + k_2^2)\left[(r_r^2 + s^2 x_r^2) + u^2 x_m^2 - 2u x_m (s x_r \cos\vartheta + r_r \sin\vartheta)\right]}} \tag{24}$$

$$\cos\varphi_r = \frac{u(r_s k_1 + x_s k_2) - s x_m (k_2 \cos\vartheta - k_1 \sin\vartheta)}{\sqrt{(k_1^2 + k_2^2)\left[s^2 x_m^2 + u^2 (r_s^2 + x_s^2) - 2u s x_m (x_s \cos\vartheta - r_s \sin\vartheta)\right]}} \tag{25}$$

Figure 6. a) Dependence $cos\varphi = f(\delta)$; b) Dependence $cos\varphi = f(s)$.



a) b)

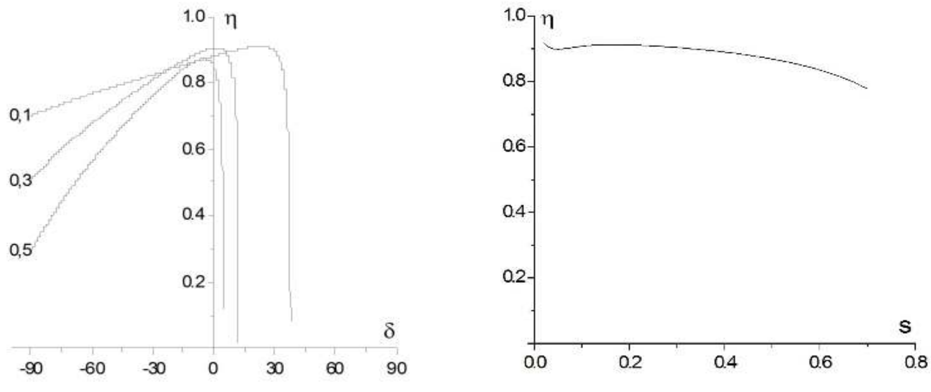
Efficiency

The main indicator of how economic the operation of a doubly-fed asynchronous generator is, comes from analyzing the characteristics of its efficiency, Figs. 7. a)… b), obtained from expression:

$$\eta = 1 - \frac{r_s i_s^2 + p_{Fe_s} + r_r i_r^2 + s p_{Hk_r} + s^2 p_{Fk_r} + p_{fv_n}(1-s)^{\frac{3}{2}}}{m_{em}(1-s) + p_{fv_n}(1-s)^{\frac{3}{2}}} \tag{26}$$

Comparison with characteristics that correspond to standard operation reveals a slight decrease of efficiency, caused by the presence of higher harmonics in stator and rotor currents, which results in the appearance of additional losses and additional torques. An appropriate change of the applied rotor voltage can insure operation with minimal losses.

Figure 7. a) Dependence $\eta = f(\delta)$; b) Dependence $\eta = f(s)$.



a) b)

Conclusion

Considering the operational characteristics presented in the paper, it can be concluded that the doubly-fed asynchronous generator can be efficiently used in wind power stations, for converting wind kinetic energy into electrical energy. The synchronous working regime, when rotor frequency is set independently, allows stable generator operation in a wide range of speeds, typically within ±30% of the synchronous speed.

Efficient energy conversion can be achieved in this way, which means that conversion proceeds with maximum exploitation of the wind turbine (for every wind speed there is a specific speed of the wind turbine, and its efficiency is at a maximum).

For obtaining the desired change in the voltage fed to the rotor, semiconductor based energy converters (thyristors, IGBTs, etc.) are included into the rotor circuit. Since the flow of energy in the rotor changes direction in different regimes, energy converters need to enable energy to flow from the grid to the rotor, but also vice versa. At speeds higher than the generator synchronous speed, transformed energy is conveyed to the grid from both the stator and the rotor. The doubly-fed asynchronous generator can, therefore, work at an energy higher than the nominal.

Because the power transmitted through the rotor is proportional to the slip, the power of the energy converter is proportional to the regulated speed, typically within 30% of the nominal wind generator power. This is the main advantage of a doubly-fed asynchronous generator over other wind generators, in which the power of the energy converter corresponds to the full (nominal) power.

Another advantage of a doubly-fed asynchronous generator is the possibility of controlling its reactive power. Modern wind generators can work with the power factor of $\cos\varphi = \pm 0.9$, whereby active and reactive powers it generates can be controlled independently. Naturally, the generated reactive power causes an increase of the energy converter’s nominal power.

Apendix

p – differentiating operator
Π – number of pole pairs
r_r, r_s – stator, rotor resistance per phase
$x_{s\gamma}$, $x_{r\gamma}$ – stator, rotor leakage reactance
x_m – magnetizing reactance
x_s, x_r – stator, rotor reactance per phase
L_s, L_r – stator, rotor inductance
L_m – magnetizing inductance
i_s, i_r – stator, rotor current
u_s, u_r – stator, rotor voltage
f_r, f_s – stator, rotor frequency
Ψ_s, Ψ_r – stator, rotor magnetic flux
δ – load angle
ϑ – the angle between stator and rotor voltage vectors (phasors)
s – slip
n – rotor speed
ω – rotor angular velocity
ω_s – synchronous angular velocity
m_{em} – electromagnetic torque
p_s, p_r – stator, rotor active power
q_s, q_r – stator, rotor reactive power
p_{fvn} – mechanical losses at rated speed
p_{Fes} – stator core losses
p_{Hkr} – hysteresis losses in rotor core (at locked rotor)
p_{Fkr} – eddy current losses in rotor core (at locked rotor)
η – motor efficiency
$\cos\varphi_s$, $\cos\varphi_r$ – stator, rotor power factor

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KARAKTERISTIKE DVOSTRANO NAPAJANOG ASINHRONOG GENERATORA PRIMENJENOG U VETROELEKTRANAMA [6]

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Sažetak

U radu je definisan matematički model asinhronog generator sa dvostranim napajanjem primenom teorije prostornih vektora, u odnosu na referentnu osu vezanu za stator. Izvedeni su izrazi za karakteristične veličine, nacrtane su pogonske karakteristike za moment, aktivne i reaktivne snage, faktor snage i stepen iskorišćenja, na osnovu kojih je izvršena analiza rada u uslovima sa različitom brzinom obrtanja. Na osnovu toga ukazano je na mogućnosti i prednosti primene asinhronog generatora sa dvostranim napajanjem u vetrolektranama, za dobijanje električne energije iz energije vetra.

Ključne reči: *obnovljivi izvori, vetrogeneratori, održivi razvoj.*

6 Rad je deo istraživanja u okviru projekta broj. TR 33016 – Istraživanje, razvoj i primena programa i procedura energetske efikasnosti u elektromotornim pogonima, 2011-2018, finansiran od strane Ministarstva za Obrazovanje, nauku i tehnološki razvoj Republike Srbije. Period projekta: 2011-2018.

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