Analysis of Advantages of the Double Supply Machine With Variable Rotation Speed Application in Wind Energy Converters

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1. Introduction

The traditional version system of wind energy converters (WTGS) with asynchronous generator, connected strictly to an electric grid, and stall-control of wind power has found a wide dissemination between producers in Denmark and Germany such as Micon, Nordtank, Wind World, Bonus, and Nordex [1,2]. Application of this concept was connected first of all with an effort to simplify WTGS construction by limitation of control functions within start-stop functions and orientation by wind direction.
However, an intensive development of industrial electronics and fast mastering of the megawatt class WTGS has led to the necessity of considering the prospects of maximizing the energy production through highly efficient WTGS control system designs. It is assumed that the rise in installation price due to the innovative control systems will be noticeable at the first stage of their industrial introduction only.

2. Wind turbine control system analyses and advantages of their application

Table 1 shows main data of some wind turbines with rated powers between 500 and 1500 kW, built with advanced controls for performance and load optimisation:

Type	Power [kW]	Concept	Regulation	Revolution [RPM]
Enercon-40 (Germany)	500	Synchronous generator with frequency converter, gearless	pitch	18 - 38
Lagerwey 45 (Netherland)	750	Synchronous generator with frequency converter , gearless	pitch	20 - 35
Enercon-66 (Germany)	1500	Synchronous generator with frequency converter, gearless	pitch	10 - 20,3
Genesys 600 (Germany)	600	Permanent excited synchronous generator with frequency converter , gearless	pitch	22 - 32
Wind World W-4500/750 (Denmark)	750	Asynchronous generator with frequency converter	stall	16 -30
Windtec 646 (Austia)	600	Double supplied asynchronous generator	pitch	15 - 33
Südwind N4660 (Germany)	600	Double supplied asynchronous generator	pitch	10 - 35
Zond Z-46 (USA)	750	Double supplied asynchronous generator	pitch	16 - 30
Tacke 1.5 (Germany)	1500	Double supplied asynchronous generator	pitch	14 - 20
Windtec 1566 (Austria)	1500	Double supplied asynchronous generator	pitch	12 - 23,5
Vestas-42 (Denmark)	600	Asynchronous generator with dynamic slip regulation	pitch	30 - 33
Vestas-63 (Denmark)	1500	Asynchronous generator with dynamic slip regulation	pitch	21 - 23

Table 1: Data of new regulated wind turbines.

The following characteristics apply to all the above systems:

- A rotational speed control system (**variable speed system**); it should be noted however that the Vestas system is a near constant speed system

- A wind turbine torque (power) control system (**pitch system**)

The following is a brief analysis of energy production of three different concepts of wind turbine regulations ranging from the traditional Danish concept to the fully regulated system:

- NORDTANK 500kW/41 (stall, constant rotor speed),
- VESTAS-39/500kW (pitch, constant rotor speed),
- ENERCON-40/500kW (pitch, variable rotor speed).

For the calculation of energy production, the data of the power and power coefficient curves (Fig.1) were taken from [2]. Algorithms of the calculation were taken from the European Wind Atlas [3] and [9].

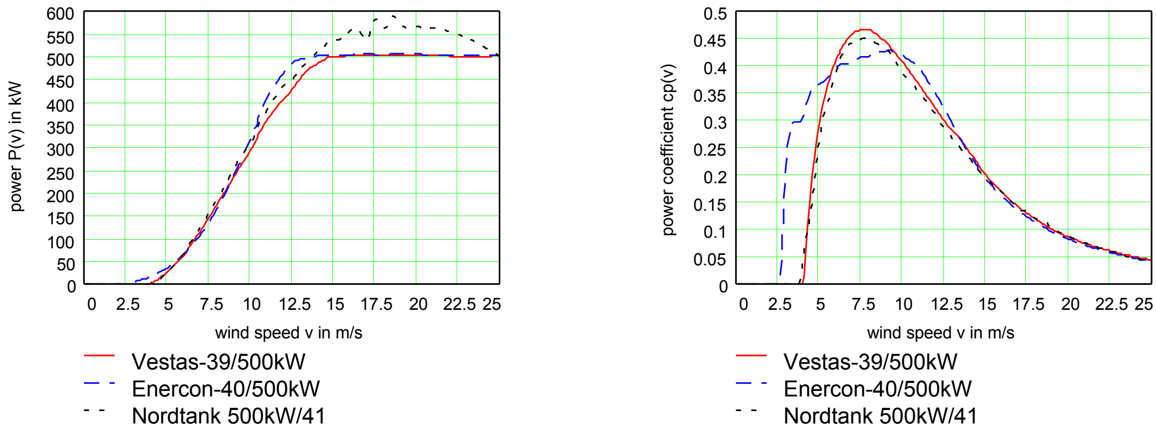


Figure 1: Power- and power coefficient curves.

It is important to note, that the rotor diameters of this WTGSs are different. So it is necessary, for a comparison of these installations, to carry out a correction of their diameters into the same conditions. In the calculations, the 39 m diameter for VESTAS-39/500kW installation has been used as a common basis for the calculation of power production (Fig. 2). The relative productions of the more advanced concepts are compared with the NORDTANK 500kW/41.

Fig. 3 shows the relative energy production rise of the VESTAS-39/500 kW installation over the NORDTANK 500kW/41 installation in dependence of the wind conditions for different sites, as described by the average annual wind speed and wind distribution, which are again characterised by the scale parameter A and the shape parameter k characterising a Weibull-function.

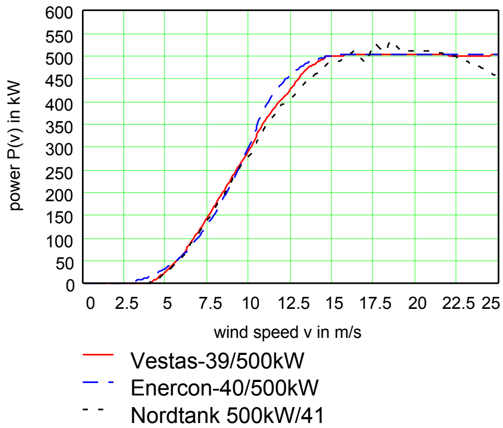


Figure 2: Power curves for corrected diameters.

As can be seen from the diagram, the relative energy production rise of VESTAS-39/500kW with **pitch-regulation** increases the annual energy production of the wind turbine with ca. **3.4 - 4.7 %** depending upon average annual wind speed and wind distribution of the site. In addition it is important to notice, that although the relative energy production rise decreases with the increasing average annual wind speed, the absolute energy production rise will be higher in regions with high average wind speeds.

The same analysis was carried out for the ENERCON-40/500kW with pitch regulation and variable rotor speed. The diagram of relative energy production rise of the ENERCON-40/500kW over the NORDTANK 500kW/41 is presented in Fig. 4.

As would be expected, the data analysis shows that an application of totally regulated installation (**pitch and variable speed**) increases the energy production even more than an application of the pitch system alone. The relative energy production rise constitutes, as can be seen in the diagram, **5.3 - 9.4 %**.

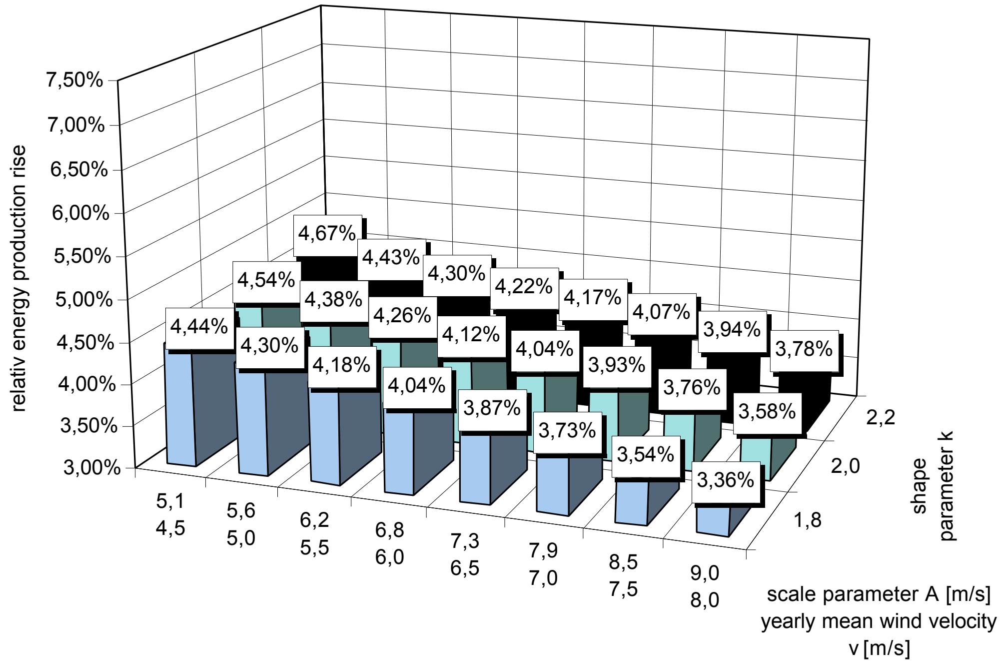


Figure 3: Relative energy production rise of a VESTAS-39/500kW.

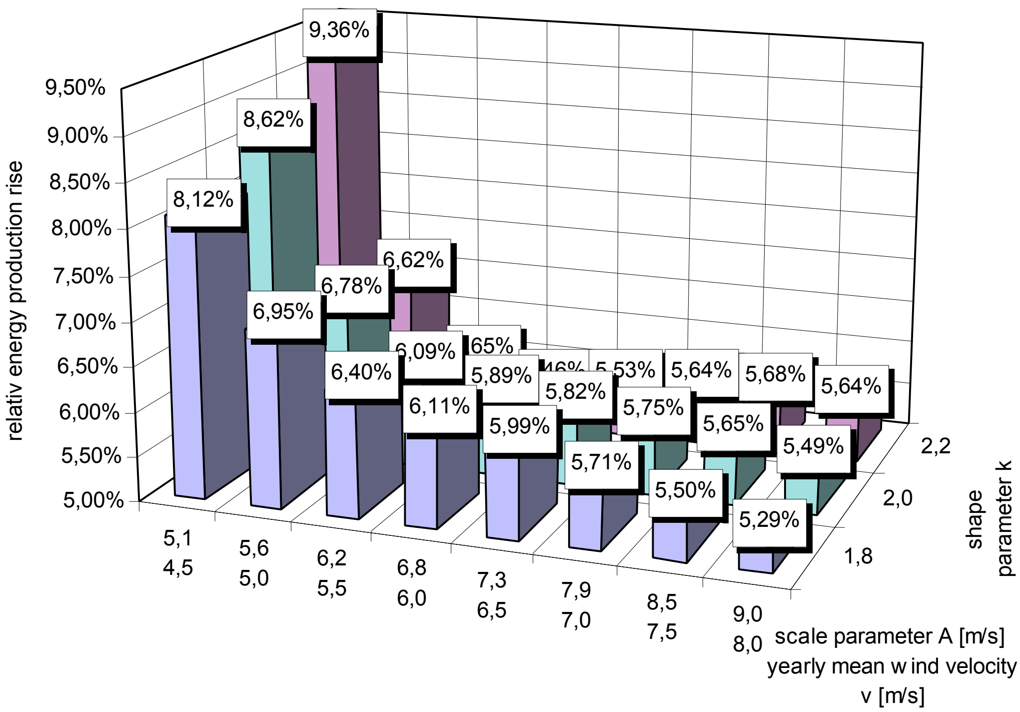


Figure 4: Relative energy production rise of a ENERCON-40/500kW.

As a whole these indices are higher than those presented on the Fig. 3. In this case the substantial relative energy production rise, observed in regions with very low average annual wind speeds of 4.5 - 5.0 m/s, is **6.6 - 9.4 %**. It is explained by best turbine usage ($c_{P,\,max}$) in low wind speed ranges, which is only possible with variable speed regulation. This can be seen directly from the power coefficient curves (Fig. 1); the wind turbine with variable speed starts production at 2.5 m/s, whereas the wind turbines with constant rotor speed start production at 4 m/s. Further the efficiency is far superior up to 6 m/s.

In the average annual wind speed range of 6.0 - 8.0 m/s, the relative energy production rise is in the range of **5.3 - 6.1 %**. This is more than for pitch regulation alone. It is important to note that the variable speed system of ENERCON-40/500kW has a higher overall efficiency, even though the efficiency of the electric power conversion system is lower (cmp. Fig. 1). This means that the energy production can be increased substantially with application of more effective generators based upon permanent magnets [4,5,6], as in the GENESYS-600kW installation, implemented in 1997.

To sum up the analysis presented above, it is possible to conclude that wind turbines with joint usage of **variable rotor speed regulation together with pitch regulation** are promising concepts as compared to stall-systems with constant rotor speed. It is important to note that wind turbines with **variable speed regulation** can be applied not only for integration into a powerful electrical grid, but in **autonomous systems as well, i.e. universal application**.

Further, it appears that variable speed as a single factor is at least as important as pitch regulation and is superior in terms of grid adaptation.

A realistic comparison of sound pressure levels of two wind turbines, one with constant and one with variable rotor speed, must be based upon the same wind turbine size and the same conditions. The following figures are based upon a rotor diameter of 40 m, which is typical for a 500 kW turbine, and a hub height of 50 m. The height of the immission point is assumed to be 5 m at a distance of 100 m. A typical rotational speed of a 500 kW wind turbine with constant rotor speed is 30 RPM, which leads to a constant sound power level of ca. 100 dB(A). A typical speed range of a 500 kW wind turbine with variable rotor speed is 18 - 38 RPM. At nominal power, which is reached at ca. 12.5 m/s, the rotational speed is 38 RPM. The dependence of the sound level on the power of the wind turbine is neglected, since this influence comes from the noise sources generator and gearbox and depends thus on the construction. With these assumptions it is possible to calculate the sound power levels of both wind turbines in dependence on the wind velocity. And the sound pressure level be calculated with the VDI norm 2714 [7] (Fig. 5).

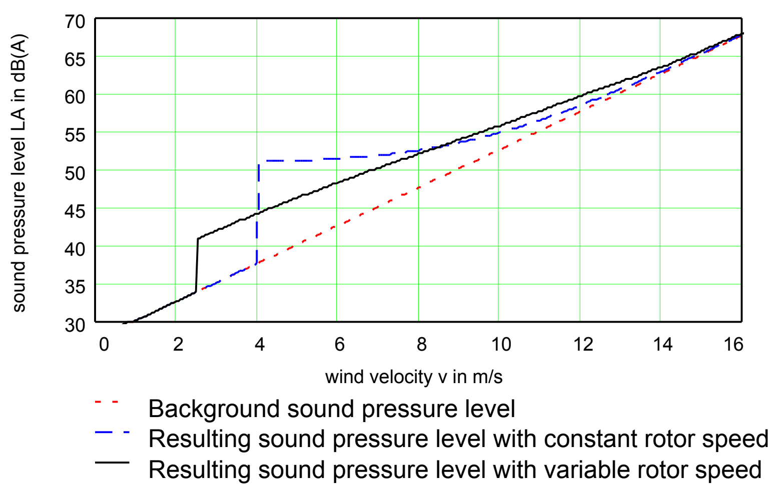


Figure 5: Resulting sound pressure levels in the distance of 100m

For the judgement of the noise immissions it is necessary to see the sound pressure levels of the wind turbines in relation to the sound pressure level of the background sound, which is also shown in Figure 5. From the diagram it can be seen, that the resulting sound pressure levels of the wind turbines approach that of the background with increasing wind velocity. This means that the noise of a wind turbine is overlaid with the background noise at high wind velocities. Thus the main influence through the noise of a wind turbine is in the range of low wind velocities.

It can be seen from Figure 5 that the resulting sound pressure level of a wind turbine with variable rotor speed is lower than with a constant rotor speed in the low velocity range till **8 m/s**, which is also the most frequent range at real wind conditions. In the distance of 100 m the maximum difference is ca. **7 dB(A)** at starting wind velocity of **4 m/s**. Thus, the rotational frequency control application has also advantages in this regard.

In addition the following advantages of WTGS with full regulation (pitch, variable speed) may be noted [5,6,8,9,10]:

- possibility of cosϕ control at the grid side;
- electric power fluctuations reduction;
- mechanical loads reduction;
- the WTGS are getting more universal for the application at different electric supply systems/ applications (parallel work with grid; wind-diesel systems, and stand-alone systems).

3. A short review of the WTGS with the variable rotation speed technical solutions

Presently, the wind turbine ENERCON 40/500 kW, where gearless multipole generator with electromagnetic excitation and frequency converter at the stator circuit are applied, has found a wide industrial dissemination. It should be noted that the absence of the gear as a mechanical energy converter and service works connected with it forms an additional advantage.

Similar technical solutions are applied for the ENERCON 66/1500kW and LAGERWEY 45/750 kW installations (See table 1).

As a principally new technical solution it is necessary to recognise the WTGS GENESYS 600 kW created in 1997, where gearless multipole generator with permanent magnets (Nd-Fe-B-based) and frequency converter at the stator circuit is applied. The increased efficiency due to absence of excitation losses and its contactless version implies further advantages. However, the application of the gearless version generators for WTGS find nonuniform assessment among producers, first of all on account of novelty of these technologies. Many firms are conservative because the standard solution has proved inexpensive and reliable.

The simplest way to obtain frequency control is to apply a frequency converter at the asynchronous generator stator's circuit. However, a wide dissemination of this concept is ruled out by a significant price of the frequency converter at the stator circuit, being proportional to its installed power (by the first approximation it is possible to assess the frequency converter price as 1000,- DKK/kW) and by additional losses reducing application efficiency. High price of the frequency converter has led to the appearance of intermediate solutions, as in the Wind World 250 kW and Wind World 750 kW power installations (see table 1), where the **stall** system with **variable rotation frequency** of turbine is applied. In these cases the frequency converter, having lower power than in the asynchronous generator case, plays electric power damping role (reduction of the voltage pulsation i.e. flicker) when the load for installation is close to nominal, and at the reduced wind speeds regimes it supplies a variable rotational frequency of turbine, reducing power pulsation as well.

A promising technical solution of the gear version WTGS with variable rotation frequency is the application of a double supply machine (see table 1), which has the frequency converter at the rotor's circuit. Interest for this machine is the prospect of a frequency converter with much lower power application and lower price. Taking into account nominal installation power rising permanently, this factor can be decisive in the choice of the WTGS future design concept.

It has to be noted, that the double supply machines and also the control systems for them are mostly in the research phase. Quite detailed analyses of AC machines for WTGS of different types was done in a work [11], where their prospects in the brushless version especially, that increases machines durability, was noticed. At the same time it was noticed, that nonstandard versions, i.e. special designs due to the placement of the exciter at the machine's rotor, constitutes a disadvantage. As double supply machines have just been introduced to the wind industry, it is worth carrying out some analysis of their technical abilities.

4. Analysis of the double supply machine advantages for WTGS

First of all, the main requirements, applied for the double supply machine for the WTGS 500-1500 kW power, may be formulated:

- The range of the rotation frequency is to constitute ca. (0.5-1.0)$\mathbf{n}_{\mathbf{nom}}$.
- High machines efficiency (close to the efficiency of asynchronous generator with corresponding power).
- Exciters power should not exceed 30-40 % of nominal generators power.

- Brushless machines version.
- The electric energy quality has to satisfy the European norms.

Data, presented in [11], show that with a brushless version the double supply machine is able to have exciters power up to 30% of nominal generator power with rotation frequency regulation depth (0.6-1.0) $\mathbf{n_{nom}}$. Efficiency values for the double supply machine 1MW power with sleep range +- 15% is a little inferior to asynchronous generators and constitutes about 94% at full generator load [8]. These data give evidence quite convincingly about prospects of the double supply machine for the WTGS of gear version with variable rotation frequency application from the point of view of technical characteristics. The prospects of double supply machines may also be assessed from the electric power pulsation damping and the reduction of the voltage pulsation (flicker) points of view.

The calculation diagram for which the research was carried out, contained double supply generator, working through external grid with short-circuit resistance X_{sc} on the powerful electric system. On the mathematical modelling the transitional processes and active resistance at the stator circuit were not been taking into account. Allowing for the above, the equations for the double supplied machine before its terminals with voltage U_1 at the axes, connected stiffly with synchronous axes **ds**, **qs** of the grid, may be written in the following form [12]:

$$X I_{ds} + E_{qs} = U_{1,qs}; \qquad X I_{qs} - E_{ds} = U_{1,ds};$$

$$T_{d0} \frac{d\psi_{f,qs}}{dt} = U_{f,qs} + E_{ds} - T_{d0}\,\omega_0\, s\,\psi_{f,ds};$$

$$T_{d0} \frac{d\psi_{f,ds}}{dt} = U_{f,ds} - E_{qs} - T_{d0}\,\omega_0\, s\,\psi_{f,qs};$$

$$\psi_{f,ds} = \frac{X_a^2}{X_f} I_{ds} + E_{qs}; \quad \psi_{f,qs} = \frac{X_a^2}{X_f} I_{qs} - E_{ds};$$

$$T_J \frac{ds}{dt} = M_w - M_{el}; \qquad M_{el} = E_{ds} I_{ds} + E_{qs} I_{qs},$$

where I_{ds} , I_{qs} , $U_{1,ds}$, $U_{1,qs}$, E_{ds} , E_{qs} - current in the stator circuit , voltage U_1 and e.m.f. of E excitation projection on to axes **ds** , **qs** ; $U_{f,ds}$, $U_{f,qs}$ - voltage projections at the excitation windings; $y_{f,ds}$, $y_{f,qs}$ - projections of the flux clutches of rotors contours on to **ds** , **qs** axes; M_w - moment of wind turbine; M_{el} - electrical moment of generator; s - generators slipping; X , X_f - synchronous resistance of the stator circuit and the resistance of the double supplied machine excitation winding; X_a - interinduction resistance; T_{d0} - the time constant of the longitudinal and horizontal excitation windings.

The external circuit equations with short-circuit resistance X_{sc} at the electric system's splint vector of voltage U combining together with **qs** axis are :

$$U_{1,qs} + X_{sc} I_{ds} = U;$$

$$U_{1,ds} - X_{sc} I_{qs} = 0.$$

The double supplied generator control law on the splint voltage of an infinite power, combined with **qs** - **ds** axes, choosing as its orientation axis, is presented by form [12]:

$$U_{f,qs} + T_E \frac{dU_{f,qs}}{dt} = (1 + k_E)\left(U_{f,qs,0} + k_{0s} s + k_{1s} \frac{ds}{dt}\right) + k_E E_{ds} - T_E U_{f,ds}\,\omega_0\, s;$$

$$U_{f,ds} + T_E \frac{dU_{f,ds}}{dt} = (1 + k_E)\left(U_{f,ds,0} + k'_{1s} \frac{ds}{dt}\right) - k_E E_{qs} + T_E U_{f,qs}\,\omega_0\, s.$$

where k_E - coefficient of stiff negative reverse connection by rotor currents or proportional e.m.f. E_{qs} , E_{ds} ; k_{0s} , k_{1s} , k'_{0s} , k'_{1s} , k_E - adjustment coefficients; T_E - equivalent time constant of the excitation regulator.

The wind wheel torque modelling was carried out in account of two main components of the excitation effect on the wind wheel torque, noticed in [14]: wind speed oscillations and tower passage effect. By the data [8,15] the wind wheel torque pulsation amplitude on the blade passing the wind turbine tower was accepted to equal 20% of nominal installation power on its work in the regime close to nominal (Fig. 6).

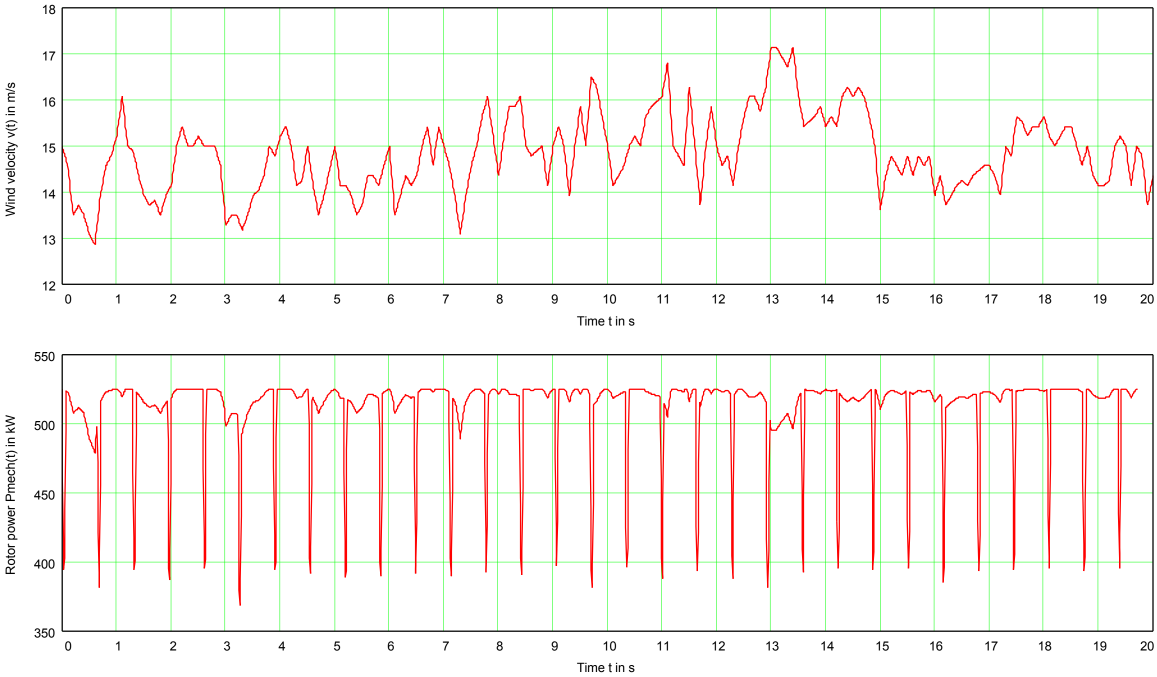
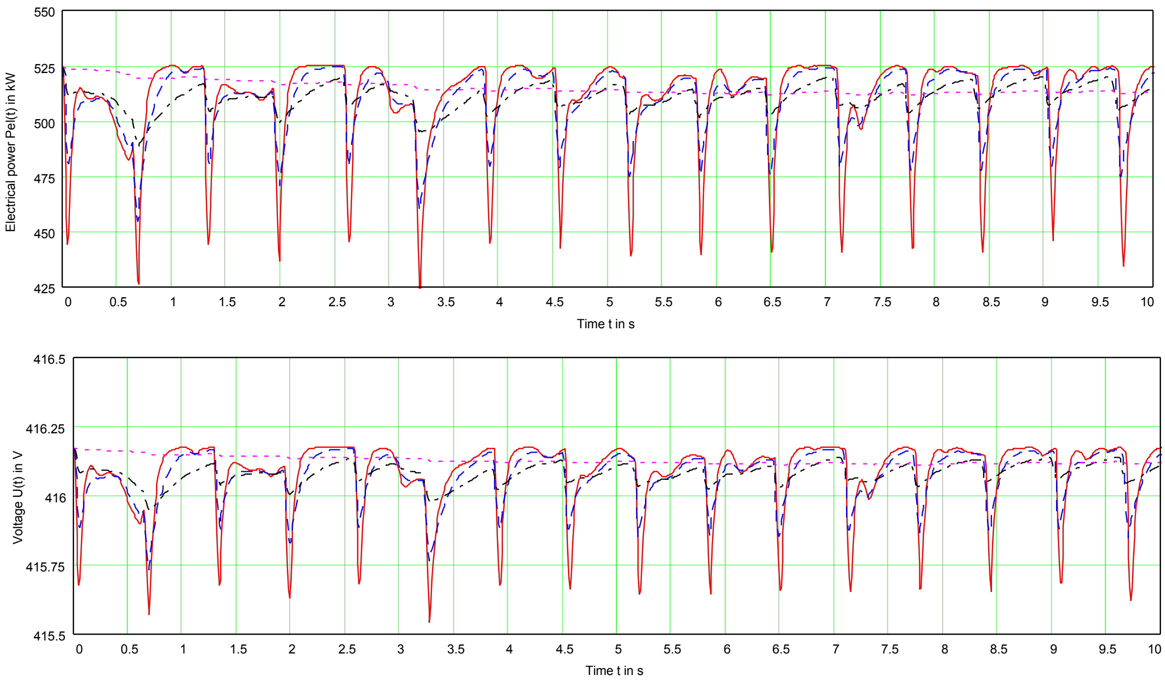


Figure 6: Wind velocity and rotor power.



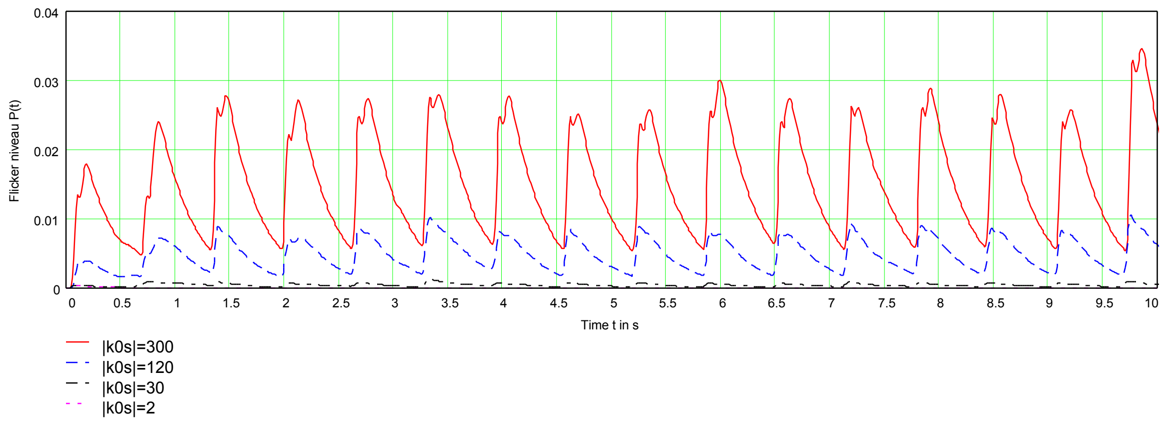


Figure 7: Electrical power, voltage and flicker of double supplied generator.

In accordance with presented mathematical description the algorithm and programme of transition processes of the wind electric double supplied generator at a gust wind were compiled and the calculation researches were carried out.

The main double supplied generator's parameters: X_a =0.8 - inductive resistance of the stator and rotor winding interinduction; X_{sf} = 0.2 - longitudinal and horizontal excitation winding diffusive resistance; T_{d0} =0.1s -the time constant of the excitation windings; T_J =10s - inertia constant of the aggregate corresponds to the average value for wind electric installations of 525 kW Hanstholm wind turbine [13]. The external short-circuit resistance X_{sc} was assumed to be 0.12, i.e., quite stiff conditions of the wind energy installations with electrical system connection were regarded. Aerodynamical characteristics of wind wheels corresponded to the Hanstholm Wind turbine airfoil profile [13]. At the initial regime the wind speed were assumed to equal the calculated value; the generator rotation frequency equalled to the synchronous one (slipping s=0); an active power of generator P equalled P_{nom}. The reverse circuit amplification coefficient by rotor current k_E equalled 50; T_E = 0.02s -the time constant. The adjustment coefficient k_{0s} -the wind turbine behaviour depending upon gusts was varied in a wide range. Results of calculations of the transition processes at a gust wind are presented on Fig. 7 at several amplification coefficients k_{0s} .

An analysis of the processes shows the pulsation of all regime parameters- generator's electric power, the voltage at the point of connection with the electrical system are defined by k_{0s} , characterising a stiffness of double supply machine characteristics. At small amplification coefficients $|k_{0s}|$ =2-10, corresponding to a gentle characteristic $M_{el}(s)$ and sufficient reduction of pulsation of all regime generator's parameters due to the diffusion of wind turbine torque excitations in its rotation masses of wind turbine with some accelerating-slowing down.

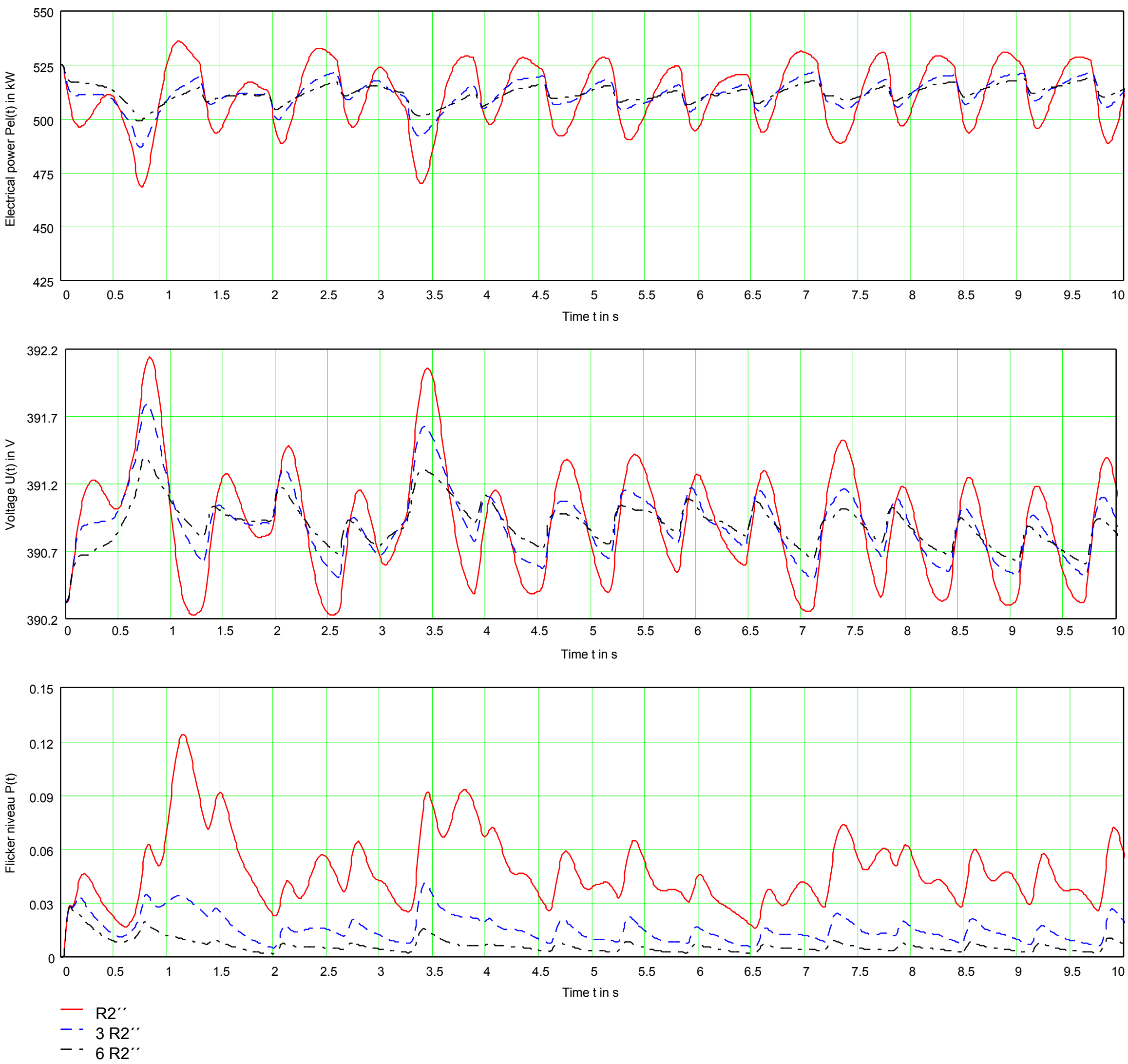


Figure 8: Electrical power, voltage and flicker of standard asynchronus generator.

In addition the flicker value P_{st}, calculated in accordance with [16,17] at the connection with system point (in this case at the terminals of machine) constituted P_{st} = 0.11; 0.06; 0.02; 0.01 at $|k_{0s}|$ = 300; 120; 30; 2 correspondingly. Thus, at small stiffness of moment characteristic of double supplied machine ($|k_{0s}|$ =2-10) the flicker problem is excluded.

Analogous effect of the process parameters pulsation and flicker reduction for asynchronous generators is possible by reduction of the characteristic's $M_{el}(s)$ steepness by an introduction of an additional resistance in the rotor circuit [8].

As an illustration in Fig. 8 processes of the standard asynchronous generator for the Hanstholm Wind Turbine with s_{nom} = 0.7% are presented. An assessment of the rotor resistance on a regime parameters pulsation influence the processes with increased rotor resistance R_2'' by 3 and 6 times were calculated.

As it can be seen from graphs, pulsation of all parameters are reduced sufficiently, in addition the value P_{st} = 0.19; 0.11; 0.08 versus $R_2'' = R_2''$; $R_2'' = 3R_2''$; $R_2'' = 6R_2''$ constituted correspondingly.

Returning to the small amplification coefficients $|k_{0s}|$ = 2-10 usage advantages (nonstiff characteristic of double supply machines) it is important to notice, that it is expedient to reach the highest agreement of the machine characteristic $M_{el}(s)$ with torque line, thus keeping close to the wind turbine maximum power, being defined as $\mathbf{C_{p,max}}$.

In this case not only full exclusion of the regime parameters pulsation will be obtained, but maximum energy production ($C_{p,max}$) will occur in a wide range of wind speed changes due to natural changes of rotation frequency, defined by a gentle characteristic $M_{el}(s)$.

5. Literature

[1] S. Heier : Anschluß von Windkraftanlagen an das öffentliche Netz. Windkraftanlagen, Marktübersicht 1997, IWB, S. 95-100.

[2] Windkraftanlagen, Marktübersicht 1997, IWB.

[3] Ib Troen , Erik Lundtang Petersen : European Wind Atlas. 655 pp., Risø National Laboratory, Roskilde, 1989.

[4] B.Johnsen : Generatorkonstruktionsregeln auf den Kopf gestellt. Wind Energie Aktuell, No.3, 1997 , S. 36-37.

[5] N. Vilsbøll, A. Pinegin, J.Bugge : Zur Weitere Entwicklung des Konzeptes von vielpoligen direkt-getriebenen Permanent-Magnet-Generatoren für Windkraftanlagen mit variabler Drehzahl. Wind-Kraft & natürliche Energien Journal No. 6, 1996. S.14-19.

[6] N.Vilsbøll, A. Pinegin, D. Goussarov, J.Bugge : The Experience of Designing and Testing a 20kW Multi Pole Permanent Magnet Generator for Wind Turbines. DEWI- Magazin No.9,1996. S. 74-83.

[7] VDI : Schallausbreitung im Freien, VDI 2714, Januar 1988.

[8] E. Hau : Windkraftanlagen. 2. Aufl., Springerverlag Berlin 1996.

[9] R. Gasch (Hrsg.) : Windkraftanlagen. Grundlagen und Entwurf. 2. Aufl., 1993.

[10] Enercon : The Benchmark in Windenergy-Technology. 1995.

[11] B. Hopfensperger, D.J. Atkinson, R.A. Lakin : Kaskadierte doppeltgespeiste Maschinen als drehzahlvariable Generatorsysteme : ein Überblick. DEWEK'96- Tagungsband. 1996.

[12] A.A. Ragozin, A.L. Pinegin : Double-Feed Asynchronized Synchronous Wind Power Generators Operating in Prallel with Network, Elektrichestvo, No.2, pp 8-13, 1997.

[13] N.Vilsbøll, P. Kunwald : Final Report on development and building of DANmark 36, 525 kW windturbine situated at Hanstholm., Project EN3W.0071.DK (EU Commission),Project No. 860588.0 (Danish Energy Agency) of Folkecenter for Renewable Energy, pp. 70.

[14] R. Klosse, F. Santjer, G. Gerdes : Flickererzeugung durch Windenergieanlagen. DEWI Magazin Nr. 10, Februar 1997

[15] D. Moritz : Digitale Simulation netzgekoppelter Windenergieanlagen. DEWI Magazin Nr. 10, Februar 1997.

[16] P. Sørensen, J.O.Tande, L.M. Søndergaard, J.D. Kledal : Flicker Emission Levels from Wind Turbines. Wind Engineering Vol. 20 No. 1 1996.

[17] W.Mombauer : Neuer digitaler Flickermeteralgorithmus. etz Archiv Bd. 10 1988 H. 9, S. 289-294.

[18] International Electrotechnical Commission : IEC Report. Publication 868. Flickermeter. Part 0: Evaluation of Flicker Severity. First edition, Geneva 1991.