Karel Chmelík, Stanislav Mišák
Technical University of Ostrava, Ostrava

ANALYSIS OF WIND POWER PLANT RUNNING WITH INDUCTION GENERATORS

ANALIZA PRACY ELEKTROWNI WIATROWYCH Z WYKORZYSTANIEM GENERATORÓW INDUKCYJNYCH

Abstract: wind power plants are classified such as perspective and ecologic sources of electric energy. The problems of wind power plants running with induction generators is solved within partial target of research project. Presentation of results from measuring running states at selected wind power plants for different type of switching to distributive network is assumed within the manuscript. In the concrete, the analysis of switching transient phenomena, the analysis of power flow and the determination of a back influence on the distributive network are described in detail.

Streszczenie: Pola elektrowni wiatrowych są uznawane za perspektywistyczne i ekologiczne źródła energii elektrycznej. W artykule omówiono problematykę elektrowni wiatrowych, w których zastosowano generatory indukcyjne. Zaprezentowano wyniki pomiarów elektrycznych dokonanych podczas normalnej pracy wybranych elektrowni wiatrowych, w których zastosowano różne sposoby podłączenia generatorów do sieci dystrybucji energii. Przede wszystkim przedstawiono analizy zjawisk przejściowych, występujących przy podłączaniu elektrowni wiatrowej do sieci energetycznej, analizę rozpływu energii oraz przedstawiono sposoby określania negatywnych wyników oddziałujących na sieć energetyczną, a związanych z przyłączaniem i pracą w tej sieci elektrowni wiatrowych.

Introduction

Wind power plants are classified from power aspect to small sources of electric energy. These sources are scattered at variety kind of localities. The economical and technological aspect is necessary to reflect at realization build-up of the new wind-power plant. The economical aspect is described only marginally within this manuscript; more attention is applied to problem of transient phenomena for using induction generators as a source of electric energy. The maximum utilization of the wind energy is dependent on variety of factor. The first factor is selection of acceptable location for build-up of the new wind-power plant. That means location with high-level average velocity of wind and percent occurrence of wind and steady direct of convection. The second aspect is selection of acceptable wind-motor characteristics and last but not least, the selection of suitable generator for wind-power plant. Major parts of the electric machines are modified with change of nominal power machine value, with revolution per minute, with design and so on. When choosing a type of generator it is necessary to take a decision on using drive with gearbox or using generator with multi-pole. The power factor, efficiency and weight of generator nut also costs of investments are necessary to reflect too.

1. The Power Theorem of Electric Machine

For the apparent inner power reads

$$S_i \approx \mathrm{D} \cdot \mathrm{l} \cdot \mathrm{n} \cdot \mathrm{N_{S1}} \cdot I_1 \cdot B_\vartheta \cdot \mathrm{k_V} \cdot \mathrm{m} \qquad (1)$$

Where D, l – inner diameter and stator length, n – number of revolution per minute, B_υ - induction in air-gap, I_1 – stator current, k_V - winding factor, k_B - waveform factor, N_{S1} –number of conductor per one phase in series, m – number of phases.

Dependence of machine size and machine weight on nominal machine power is evident from equation (1).

Therefore:

- For keeping constant value of machine power but with lower revolution per minute, it is needful to increase the capacity of active iron material. Respectively, with constant capacity of active iron material, the machine power decreases with the increasing of number of poles.
- The specific weight decreases with the decreasing of machine nominal power.

- Multi-poles machines are heavier in comparison with less-pole. The machine must have larger capacity of magnetic circuit for constant power and lower revolution per minute.
- The superior will be windings (with higher winding factor $\underline{k_v}$), the saturation of magnetic circuit or density of current can be decreased for keeping constant value of machine power.
- The keeping constant value of machine power energetic indices increasing size of capacity of active iron material, so by increasing capacity of magnetic circuit and increasing of conductor cross-section for. Total losses are decreased after realization above mentioned conditions.
- For $\underline{k}$-multiple increasing part of machine, the efficiency $\underline{\eta}$ is increased according to formula introduced in a literature [1].

$$\eta_k = \frac{k \cdot \eta_0}{1 + \eta_0 (k-1)} \quad (2)$$

Where, $\underline{\eta_0}$ is efficiency of machine with original size. This dependence is given by increase in nominal power proportional to $\underline{k}^4$, and with increase in proportional to $\underline{k}^3$.
The machine surface is increased with $\underline{k}^2$. Therefore, the better thermal utilization of machine is possible with grow up of size.

- And so on.
  The total power efficiency is influenced by:
- value of load,
- time interval use,
- number of starting-ups,
- value of nominal voltage and by voltage divergence,
- value of distortion factor in current and voltage (harmonics contribution),
- maintenance and revision.

2. Induction Generator as a Sources of Electric Energy at Wind Power Plants

Most of wind-power plants are equipped with induction generator. The generator mode of induction machine is possible with over-synchronous revolution per minutes. And next, induction machines (motors and generators) have need of source of reactive power for creation of rotary magnetic field. The source of reactive power is represented by distributive network. The power factor is higher with lower need of reactive power. Requirement of a source of reactive power is disadvantage of using induction generator as a source of electric energy.
The requirement of reactive power is given by:

- the constructive form of machine (size of air-gap, shape of slots, exciting current, dispersion and others),
- number of poles,
- the kind of used rotor,
- load,
- voltage at terminal.

Induction machines can have squirrel-cage rotor or wound rotor. Induction machines with switching number of poles are also possible to be used. Induction generators with wound rotor are used more and more at the present time. The possibility of double feeding is its advantage.
The machine with squirrel cage rotor has higher power factor in comparison with wound rotor.
Windings in wound rotor have to be put into open slots, thereby the size of air-air gap is increased and the consumption of reactive power is increased too. The size of reactive power for load is given by formula

$$Q_M = Q_o + Q_Z \quad (3)$$

Where $\underline{Q_0} = I_0 \cdot U_N \cdot \sin\varphi_0$ is reactive input power for no-load state,
$\underline{Q_Z} = m \cdot X_\sigma I_2^{2'}$ is size of reactive input power depending on load $\underline{X_\sigma}$ (total scattered reactance of stator and rotor windings) and $\underline{I_2^{'}}$ (value of rotor current seen from stator).

The power factor decreases for the case when the load decreases too by virtue of influence of exciting current. The power factor is increased with increasing of nominal power and on the contrary, the power factor is decreased with number of poles (see Fig. 1.)
The power factor is decreased with increasing of terminal voltage.
Effective losses, which are caused by reactive component of current, are necessary to be reflected also for determination of electric consumption. The power factor of machine is decreased, losses are increased and therefore, the efficiency of machine is decreased.
Next: A) most of reactive power is consumed on excitation of magnetic field. The size of air-gap in the rate of nominal power is decreased. Therefore, machines with higher nominal power have consumption of reactive energy lower in comparison to machines with smaller nominal

power. B) Multi-poles machines have bigger weight for identical nominal power.

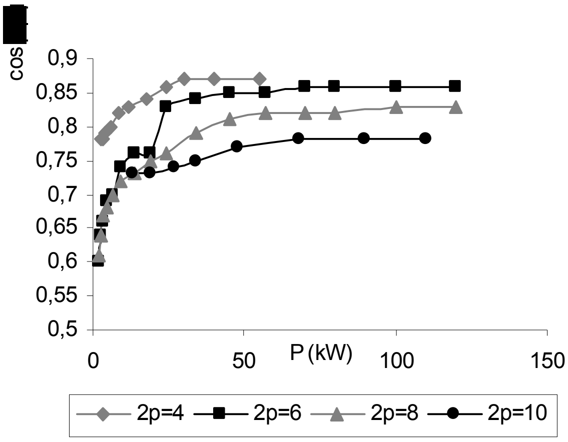

Fig. 1. The course of power factor versus nominal power of induction machine with wound rotor

Hence, multi-poles machines need greater reactive power for identical size. C) The change of reactive power is caused by fluctuating voltage. The power factor is decreased with load smaller than nominal load, the efficiency is decreased too and losses at distributive network are increased.
Problems of choice generator for wind-power plant are solved within chapter two. Analysis of wind-power plant running with the squirrel cage and wound rotor induction generator will be described in chapter three. Selected back negative influence of theirs running on distributive network will be introduced in the concrete.

3. Analysis of Wind-Power Plants Running with Induction Generators

Although value of power of wind power plant achieving to MW, wind-power plants will still be classified as source of small energy in comparison with power plant on fossil fuel. Wind-power plants are not connected to distributive network directly, but over transformer LV/HV. Wind-power plants with nominal power unit till tens of kW are connected to low voltage distributive network. Wind-power plants with nominal power hundreds till thousands of kW are connected to high-voltage electric network. Conditions of theirs running are directed by competence of local Distributive company. The licence of the connection new source of electric energy is directed by codex of the law individual distributive network. The codex of the law is certified Energetic Regulation Office. The importance is finding compromise between requirement of operator distributive network and operator of individual wind-power plant. Profit is a priority for operator of wind-power plant. As least as possible negative back influence by wind-power plant running, stabile supply of electric energy and so on are priorities for operator of distributive network.

3.1 Back influence of wind-power plants running on distributive network

More than four tens of wind-power plants are operated at sixteen localities in area of Czech Republic (with nominal power over 100 kW). Thence c. 65% of wind-power plants are operated with squirrel cage induction generators (with nominal power till 250 kW. The simplified block diagram of system with squirrel cage induction machine is introduced in Fig. 2.

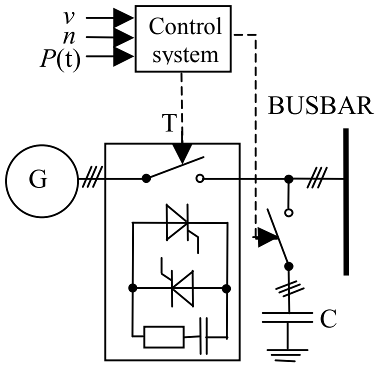

Fig. 2. The simplified block diagram of system with squirrel cage induction machine

The controlling and driving system of wind-power plant evaluates information about direction and velocity of wind. The gondola of wind-motor is yawed according to control system and brakes of wind-motor are released if the velocity of wind is over limit. The connection generator of wind-power plant to distributive is realized if the velocity of wind is over second limit and exceeding of limit takes required interval. The connection of generator to distributive network is realized over the thyristor drive (soft-start) for reduction of current surge at first. The thyristor drive is by-passed after response of transient phenomena and the generator is connected to distributive network directly. The connection of compensation battery follows after set interval. Courses actual values of voltages (V) across generator terminal and current (A) for the case of generator connection to distributive network are shown in Fig. 3. Nominal parameters of generators are: nominal power 150/30 kW, revolutions per minute 758/1012 min^{-1}, nominal voltage 400 V, frequency 50 Hz and delta connection. Deformation of voltages courses is evident for a case of connection of generator to distributive network from Fig. 3.

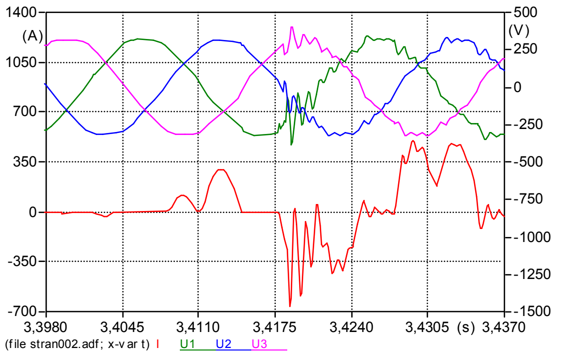

Fig. 3. Actual courses values of voltages (V) across generator terminal and current (A) for the case of generator connection to distributive network.

Inception of short-period voltage's drop is evident from Fig. 3 for moment of wind-power plant connection to distributive network. This voltage's drop is to value c. 221 V; it is percentual change of voltage 4,3%. For direct connection of generator to distributive network the percentual value of voltage drop is c. 4,2%, but time interval of voltage drop is longer than two periods.

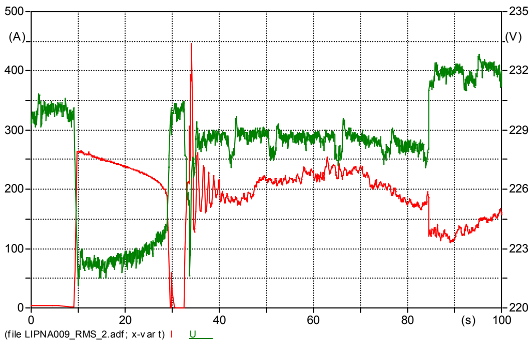

Fig. 4. Effective courses of phase to neutral voltage (V) and current (A)

Induction generator with wound rotor belongs to next type generator as a source of electric energy. Indirect frequency converter with DC inter-circuit, AC inverter and pulse width modulation (see Fig. 5) is used most often. This system with cascade connection is specified by high-energetic efficiency and regulation characteristics. Slip electric power of wound rotor is returned over rectifier, inverter and transformer to distributive network. The reactive power is obtained from distributive network for initialization DC voltage in DC inter-circuit. The gondola of wind-motor is yawed according to values direct of wind of control system. The optimal usage of electric energy is achieved by change of speed-torque characteristic of main frequency converter regulator. The connection of wind-power plant to distributive network is possible to realize for lower velocity of wind and corresponding revolutions per minute of generator. The connection of generator to distributive network so is not limited exceeding synchronous revolutions per minute.

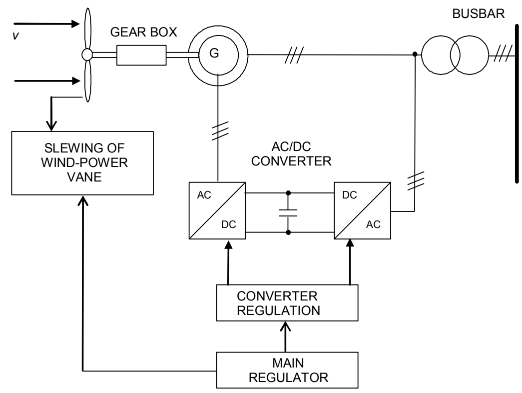

Fig. 5. Simplified block diagram of system with induction machine with wound rotor and frequency converter

The connection of induction generator with wound rotor and frequency converter to distributive network is not executed by surge current and voltage drop (see Fig. 6).

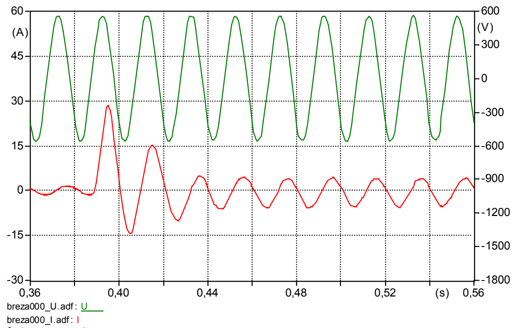

Fig. 6. Actual course of phase to neutral voltage (V) and current (A)

Interaction between wind-power plant and distributive network is determined in the so-called point of common connection (PCC). More consumer and production devices are possible to connection to PCC.

Consumer devices are designed on condition that the supply distributive network has constant parameters (effective value of voltage, frequency). For another case, the supply of energy is not quality. Drop voltage, frequency of voltage, interference of centralized telecontrol (of loads) and emission-flicker is necessary to monitor. [2].
The flicker is fluctuation of luminous flux luminous source in consequence of periodical voltage drop in area of subharmonic frequency. The flicker is perceivable by human eye. These changes of voltages are generally caused by changes of customer load or by change at generation of power. Influence of wind blast and influence of wind power plant tower are by two of cause of flicker creation. Influence of wind blast is possible to eliminate by self-momentum of rotary wind-power plant parts. Influence of strong wind blast is reduced by power controlling of turbine. Influence of wind power plant tower is possible to eliminate much worse. The tower presents for fluctuant wind block and the wind convection is decelerated. The power of wind-power plant is decreased at the moment shutter of turbine and tower. The voltage drop is caused by periodically power drop (active and reactive power drop)

$$\Delta U = \frac{\Delta PR + \Delta QX}{\sqrt{3}U_N} \qquad (4)$$

Where ΔU is voltage drop on impedance of distributive network (V), ΔP, ΔQ active and reactive change of power (W, V·Ar), R, X resistance and reactance of distributive network (Ω) and U_N is nominal voltage of distributive network (V). The change of voltage causative flicker is not dominant in distributive network with inductive character (see Eq. (4)). Changes of active power, which is dominant in comparison with change reactive power, are irrelevant on the low reactance of distributive network. For relative voltage drop is possible to obtain formula respecting short-circuit power:

$$\frac{\Delta U}{U_N} = \frac{\Delta S}{S''_k}\cos(\psi + \varphi_f) \qquad (5)$$

Where Ψ is angle of distributive network impedance $\psi = arctg\frac{X}{R}$, φ_f is relevant angle of flicker $\varphi_f = arctg\frac{\Delta Q}{\Delta P}$,
S_{kV} short-circuit power point of common connection (PCC).
The voltage drop causative flicker is not used as a parameter determining flicker. Emission of flicker, or strictly speaking rate of flicker perception characterized flicker.
Rate of flicker perception is distinguished as short term P_{st}, measured or calculated in interval 10 min, and P_{lt}, measured or calculated for interval pro interval 2 hours. Generally reads, the more of screw blade wind-power plant has, so the emission of flicker is smaller. Systems with frequency converter have smaller of emission of flicker in comparison with system of squirrel cage induction generator. Time interval and frequency voltage drop are another parameters for determination back influence of wind-power plants running. These parameters are independent on character of distributive network and generator. These are specified only by constructive design of devices. The frequency of voltage drop in distributive network is derived by revolution of turbine and number of screw blade. The frequency passage through of screw blade by shutter of tower is given by

$$f_f = a \cdot \frac{n_t}{60} \qquad (6)$$

Where f_f is frequency (Hz), a is number of screw blade and n_t are revolutions per minutes (min^{-1}). The human eye is able to sensible changes of luminous flux from frequency 0,5 Hz to 25 Hz; mostly sensitive is for frequency about 9 Hz. It is important to eliminate revolutions of turbine from this area of 9 Hz frequency of voltage. Unfortunately, it is not possible, because turbine has revolutions from 30 to 50 min^{-1} in generally with corresponding frequency of voltage from 2 to 3 Hz. Any constructive design of wind-power plant can reduced inception of flicker but can not flicker dispatch. The time interval of voltage drop is affected by also size of tower (diameter of tower); see Fig. 6.

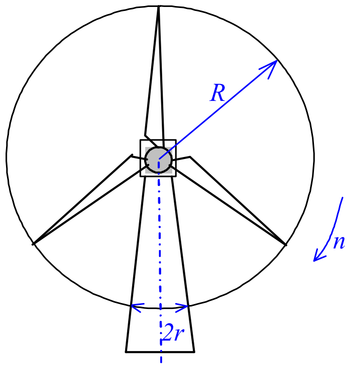

Fig. 6. Scheme for definition interval of voltage drop

If there characteristic parameter of turbine is diameter $\underline{R}$, it can be denoted radius $\underline{r}$ as characteristic parameter of tower. The average diameter of tower is used for calculation by virtue of conical form of tower. Interval $\underline{t}$, (transit of blade about tower) is defined by tip velocity of tip of blade $\underline{v_R}$ and diameter of tower $\underline{2r}$. For tip velocity reads

$$v_R = \omega \cdot R \tag{7}$$

Where $\underline{R}$ is radius of turbine, $\underline{\omega}$ is angular speed

$\omega = \frac{2 \cdot \pi \cdot n_t}{60}$ and $\underline{n_t}$ revolutions of turbine (min^{-1}).

The time interval of voltage drop is given by

$$t = \frac{1}{\omega} \cdot \frac{2r}{R} \tag{8}$$

The rate $\underline{R/2r}$ is characteristic number, which with revolutions of turbine defined the time interval of voltage drop.

Three values, amplitude, frequency and time interval of voltage drop, influence inception of flicker. Influence of individual values is very problematic. But on the other side, reduction of any values takes effect in restriction of flicker.

With respect to last mentioned results is possible to defined next thesis:

- wind-power plants have not connection to local distributive network with small short-circuit power,
- wind–power plants with induction generator and directly connection have connection in the PCC, where the angle of impedance is near 70°,
- turbine revolutions should have been rather lower than higher,
- the rate $\underline{R/2r}$ should have been at maximum.

4. Conclusion

From realized measurement on wind-power plant is possible to say follows: the system with directly connection to distributive network is less financial costingness. But on the other side, problem of voltage drop is typical for mentioned system with squirrel cage induction generator. The system with induction generator with wound rotor and frequency converter is specified by high-energetic efficiency and regulation characteristics. The connection of wind-power plant to distributive network is not limited by exceeding synchronous revolutions per minute. The power utility in the rate of nominal power (-) for system with frequency converter and average velocity of wind ($m \cdot s^{-1}$) are shown in Fig. 7.

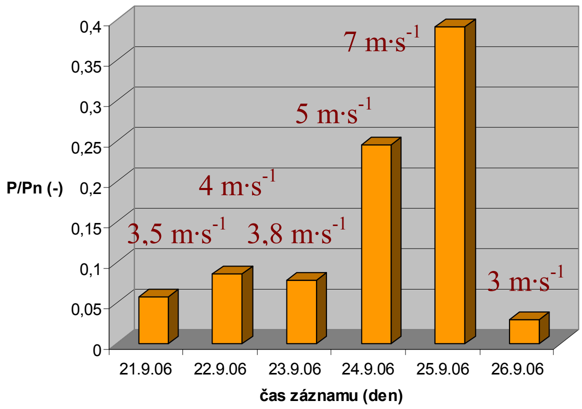

Fig. 7. The power utility in ratio of nominal power for system with frequency converter

7. Bibliography

[1]. Kade F.: Die Wachtungesetze des Induktionmotors ETZ-A Bd. 73 1952 H. 19.

[2]. Kyncl J., Lyčka Š., Sýkora T., Tlustý J. Vybraná hlediska provozu větrných elektráren, Energetika 12/2004, ISSN 0375-8842.

Authors

Doc. Ing. Karel Chmelík, Ing. Stanislav Mišák
Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Electric Machines and Apparatus, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic; e-mail:karel.chmelik@vsb.cz, stanislav.misak@vsb.cz