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System for the Safe Operation and Stabilisation of the Rotational Rate of Small Wind Turbines

Abstract: The article presents the nearly 30-year evolution of the design of a range of small wind turbine units having power restricted within the range of 3 kW to 100 kW (known under the commercial name of ZEFIR). The evolution was primarily triggered by difficulties in achieving the operational safety of the above-named machines without compromising the simplicity of design. The article also discusses the role of PM synchronous machines in achieving previously assumed safety parameters and satisfying the postulate of "fail safe philosophy design".

Key words: safety of small wind turbine units, PM synchronous motor in the safety system of a small wind turbine sets, safety as a priority in the design of small wind turbine units

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1. Introduction

Because of their location, small wind turbines use wind with low-energy parameters. As a consequence, in order to achieve low production and operating costs, most of the small wind turbines offered on the market are designed to give priority to energy efficiency and structural simplicity.

Wind turbines are located near dwelling houses and their unshielded rotors often operate above people's heads. Taking into account that the tips of the rotor blades move at speeds exceeding 200 km/h, the absolute design priority must be the safety of their operation, even at the expense of energy parameters or production costs.

In the mid-1990s, the first wind turbine unit with a rotor having a diameter of 6 m was developed. The turbine set was similar to the turbine sets of this size commonly offered today. The concept of such simple turbine sets is presented in Figure 1.

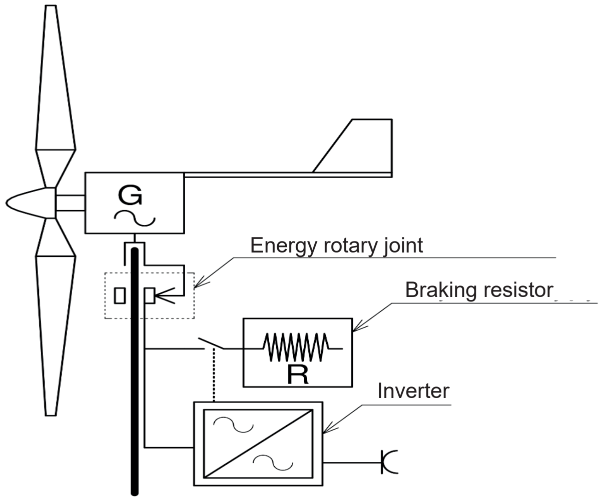

Fig. 1. Schematic diagram of a simple small wind turbine set

The wind turbine rotor, most often of fixed geometry, is mounted directly on the shaft of a low-speed generator or a multiplier with a generator. This assembly, mounted in a rotary manner on a vertical axis, is oriented to the wind by a rudder. Electrical energy is discharged from the generator via the power-signal rotary joint, whereas the rotational rate is limited by an additional resistive load on the generator.

However, the turbine set uses a rotor with a controlled blade angle of attack and a spring-loaded mechanism for moving the blades to the emergency stop position.

The use of this design scheme resulted from research on the current state of technology in this area and the recognition that the simplicity of the design increases the chance of work safety, reliability and low production costs. This is how the turbine set with the commercial name ZEFIR 6A was created (Figure 2).

Fig. 2. ZEFIR 6A wind turbine set

2. First structural modification

The second year of operation saw serious failures, i.e. rotor blade breakage in two turbine sets. Analysis of these failures led to the unequivocal conclusion that they resulted from the system of rotor orientation to the wind (i.e.

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rudder) and excessively optimistic assumptions regarding the size of crosswind gusts and adopted design loads according to [1, 3]. If the wind turbine power plant is located near buildings, structures or even larger trees, it is only a matter of time before violent side gusts appear at full rotor speed, which, in turn, entails significant gyroscopic loads on the rotor blades. However, if the calculations involve assumptions of extreme and theoretically possible side gusts, such an approach leads to unacceptable sizes of hubs and rotor blades as well as the bearings on which the blades are mounted to the hub.

Related analyses led to the conclusion that in terms of wind turbine sets with rotors having diameters of several meters or more, the use of a simple rudder for wind orientation was practically impossible for safety reasons. Even more dangerous was combining the rudder with the rotational rate limitation system, i.e. breaking the rudder or using an additional lateral rudder deflecting the turbine axis from the wind direction.

To limit the speed and angular acceleration of the wind orientation system, one can use the damping of the rudder movements or an active wind orientation system. In order to have full control over the operating parameters of the system as well as to remove the rotating electrical connector of the turbine power output from the structure, the latter solution was chosen.

The introduction of the above-presented modification was followed by the appearance of problems with the noise emission level of the commercial gear-motor and necessitated the use of a special gear-motor with a low-speed PM synchronous motor (Fig. 3). The gear-motor drove a special sliding slewing bearing at the top of the tower.

The active system for orienting the turbine set to the wind provided full control over the gyroscopic loads of the rotor blades. The change also enabled the removal of the problematic rotary joint, provided the possibility of programme-based rotation of the turbine set sideways to the wind and made it possible to set the turbine set in a position convenient for service activities. However, all this was at the cost of structural simplicity. The turbine set took the form as presented in Figure 4, i.e. similar to that characteristic of most large wind turbine sets.

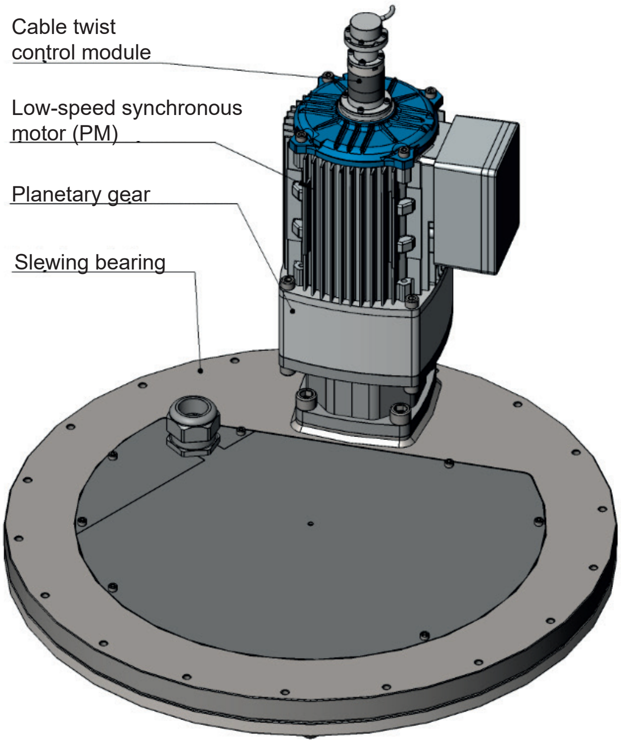

Fig. 3. Rotator of the wind orientation system of a small wind turbine set

Fig. 4. ZEFIR 6A turbine set after the first modifications

It was also necessary to expand the control cabinet and provide additional software for the PLC controller supervising the operation of the turbine set. Other “additional” elements included a second PM synchronous machine, rotator gear-motor and necessary electrical equipment for controlling the motor.

3. Second structural modification

Limiting the turbine rotational rate by loading the generator was theoretically simple. However, ensuring the reliability of such a system proved very difficult. Reference publications on the subject discuss various attempts undertaken to increase such reliability. Damage to the power rotary joint, burnout of braking resistors or even simple loss of continuity of the connection in the electrical terminals between the generator and braking resistors is the shortest way to a catastrophic failure. One of the solutions could involve moving the braking resistors to the turbine set nacelle or mounting them on it. As a result, the resistor control system would have to be moved near the resistor, which created additional, i.e. service-related difficulties. In addition, the implementation of such a system would necessitate the use of a generator with significant long-term overload capacity, which would translate into higher costs.

Limiting the power and rotational rate of a rotary machine by changing the angle of attack of the rotor blades is a proven although rather complicated and expensive solution. The main complication is connected with the need to ensure the reliable operation of the mechanism, preferably without using an external power supply within a wide range of machine operating temperatures, particularly in emergency conditions.

The simple spring mechanism used in the first approach, aiming at moving the blades to the stop turned out to be unstable at low temperatures, especially when the rotor hub was icy. The experience and reference publications [4] revealed that the moment necessary to move the rotor blades in icing conditions can be between ten and twenty times greater than that needed in normal turbine operating conditions. Since the problem concerned the safety of the machine operation, it was necessary to look for a more reliable design-related solution. The solution to the above-presented problem involved the development of a screw-lever mechanism driven by a low-speed PM synchronous motor integrated with a wind turbine generator. The concept (taken from the patent application [6]) of the solution is presented in Figure 5.

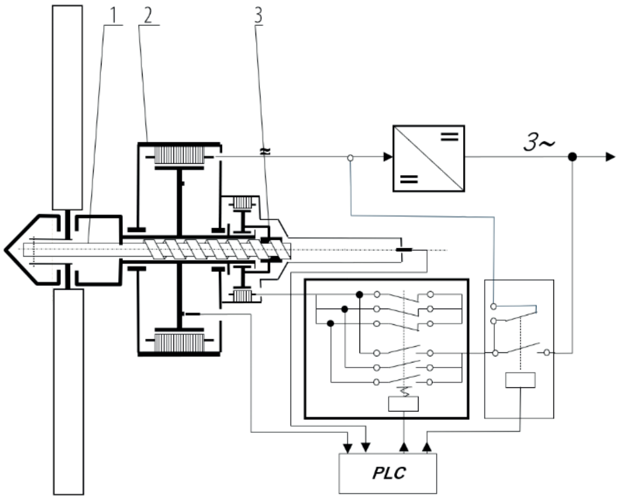

Fig. 5. Modified rotor blade attack angle control system

The main shaft of the generator (2) was provided with a screw actuator (1, changing the position of the rotor blades through a lever mechanism in the hub. The nut of the screw actuator (3) was driven by a synchronous motor PM (3), characterised by the same nominal rotational rate as the turbine generator.

The screw actuator motor operated in the following modes:

- network-based powering for the gradual acceleration and deceleration of the wind turbine,
- turbine generator-based powering aimed at maintaining a constant position of the blades in the wind turbine rotor at power below nominal,
- network-based powering for a constant rotational rate equal to or greater than the nominal rotational rate of the turbine set,
- short circuit with a normally closed contactor located in the terminal box.

The above-presented solution enabled the obtainment of reliable mechanical feedback stabilising the rotational rate of the turbine set. When the turbine set control system detected that the nominal rotational speed was exceeded, the system switched the motor power supply from the turbine set generator to the network. The motor rotated at the nominal rate intended for the wind turbine. Depending on whether the turbine rotor rotated faster or slower than the screw actuator engine, the rotor blade angle of attack increased or decreased. As a result, the mechanism stabilised the rotational rate of the wind turbine. In an emergency state, it was enough to disconnect the power supply from the motor, whereas the contactor in the terminal box short-circuited its terminals. The motor switched to generator mode, generating a large short-circuit moment, stopping the screw actuator nut. Consequently, the wind turbine rotor rotating the screw generated a very large torque in the blade angle control mechanism. The energy required to stop the turbine set came from the wind turbine. The solution satisfied the postulate of the “fail-safe philosophy design” project. Intentional or failure to disconnect the power supply to the rotor blade angle control mechanism led to the stooping of the turbine set, regardless of the icing degree or extreme wind speeds. At the same time, the process of stopping the wind turbine was gentle as the angular speed of the blades in the hub was proportional to the rotor speed and lasted a few seconds.

In spite of introducing another PM synchronous machine to the turbine set, the diagram of the operation of the rotor blade attack angle control system presented in the figure remained simple. Regrettably, the technical implementation, after adding a disc brake, a tight hub with a lever mechanism, non-contact measurement of the rotor blade angular positions and redundant measurements of operating parameters important for safety, was quite complex (as presented in Figure 6, taken from the technical documentation of the turbine set).

Assuming safety as an absolute priority, it was difficult to ensure safety using a single safety system. The redundancy of solutions was necessary. As a consequence of such a perception of the safety issue, it was necessary to equip the ZEFIR series turbine sets with a second turbine set stop system. The system was a normally braked double-calliper disc brake on the wind turbine shaft (see

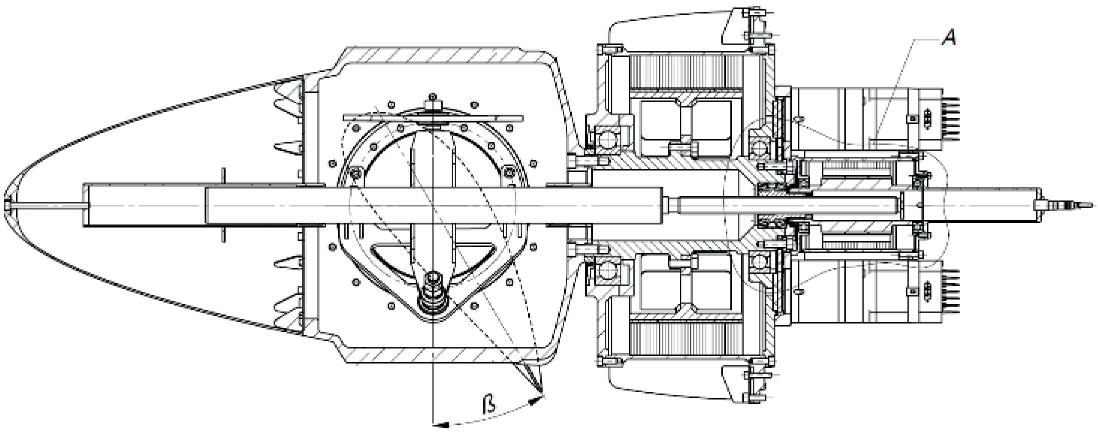

Fig. 6. Technical implementation of the idea presented in Figure 5

Figure 6). The spring-loaded brake callipers were pneumatically released by compressed air from a microcompressor located in the turbine set control cabinet. The brake generated a braking torque more than twice as high as the nominal torque of the wind turbine. The release state was maintained by a few-watt electromagnet in the normally open pneumatic distributor. Such a safety brake also satisfied the requirements of the "fail-safe philosophy design" project postulate. A failure in the pneumatic or electrical supply activated the brake and led to the turbine unit stop.

The implementation of the above-presented modifications was possible, yet required a radical change in the shape and dimensions of the nacelle in order to accommodate the additional components (Fig. 7).

Fig. 7. Wind turbine set after the second modification

4. Third structural modification

Small wind turbines are usually installed in areas designated for residential development. The solution for stabilizing the rotational rate presented in item 3 unexpectedly helps to meet one of the conditions resulting from the location restrictions for such power plants. The legal requirement stating that the maximum noise level at the property boundaries of single-family houses should not exceed 50 dB during the day and 40 dB at night is easier to satisfy if the rotational rate of the turbine set operating at night is reduced accordingly. Since all power plants of the presented series are PLC-controlled, the satisfaction of the above-named requirement became possible, yet it was necessary to use a frequency converter-based power supply for the motors controlling the angle of attack of the rotor blades. In the above-presented way, the nominal rotational rate of the turbine set could be programmed according to the real-time clock, reducing the noise level at night or in cases where the noise level is exceeded at a selected point in the area.

5. Master emergency stop system

The analysis of risks required to issue the EC Declaration of Conformity necessitated the use of a master PLC-independent system for generating a signal of exceeding the permissible turbine rotational rate.

The hardware and software complexity entailed a probability (difficult to estimate) that the emergency stop system might not be activated by the PLC in time or that the command would not be executed due to a failure. It should be noted that during nominal power operation combined with the loss of turbine load, the time of doubling its rotational rate is less than 1 second. Rotor blade manufacturers allow a maximum of 50 % increase in the momentary rotational rate in relation to the nominal one.

A simple master emergency stop system (regardless of the PLC controller operation) disconnects the turbine generator power supply from its own needs when a signal appears from the sensors not being part of the turbine generator control system, leading to a quick stop of the turbine generator. Restarting requires the operator's intervention.

6. Conclusions

Small wind turbines are specific power machines designed to use winds with low energy parameters. As a result, manufacturers tend to compensate for this deficit with a proportionally larger rotor than that used in large power plants. It is therefore difficult to control the rotor at high turbulent wind speeds in relation to low load power. In addition, such machines are operated in a "from-failure-to-failure" system, particularly after the expiry of the guarantee period.

The vast majority of catastrophic and environmentally dangerous failures of wind turbines involve the so-called wind turbine overspeeding and damaging the surroundings with projectiles (i.e. rotor blades). Despite this, reference publications concerning small wind turbine sets usually focus on energy efficiency and methods of increasing it by using appropriate blade profiles, or, e.g. MPPT systems. The tempting structural simplicity of small wind turbine sets fabricated in accordance with the idea presented in Figure 1 (to which the Authors also succumbed at one time) gives a false hope for safe and reliable operation and low production costs. This is probably the reason why such solutions are so common in market offers.

The order of priorities used by the Authors when designing wind turbine sets has always been as follows:

- safety for surroundings,
- quiet operation,
- reliability,
- aesthetics,
- recyclability,
- economic efficiency.

In spite of the above-presented order of priorities, it took several years to break free from the schematic diagram presented in Figure 1 and develop small wind turbine sets in relation to which no dangerous failures have been recorded for nearly 10 years.

Design-related problems can be solved in many ways and it might be possible to develop a safe wind turbine set in accordance with the idea presented in Figure 1. However, the Authors of the article have not found such a solution.

It could be said that (as was the case with large wind turbines) it was the evolutional approach to the design which paved the way for introducing an active wind direction tracking mechanism, an advanced rotor blade angle control system, a hierarchical safety system and a dedicated SCADA system. As the wind does not distinguish between large and small turbine sets, similar problems have been solved using similar ideas.

The satisfaction of requirements concerning safety, quiet operation and reliability raises questions about the possibility of achieving high economic efficiency of such power plants. Large-volume production and the resultant reduction of costs could help in this area. Because, for obvious reasons, the highest economic efficiency is achieved for the largest turbine sets in this class, it can be expected that the market development will begin with the use of such systems in sewage treatment plants, waste storage and recycling plants, water intakes, pumping stations, small manufacturing plants, etc. However, as of today, it is possible to observe the opposite trend, i.e. from the smallest to larger systems, which is hardly a reason for optimism as regards the development of small wind power engineering.

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