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Development and simulation of special rotary transformer – contactless power transmitter and control device for a counter-rotating wind turbine

***Abstract**. In a counter-rotating wind turbine with the vertical axis of rotation (VAWT), a special three-phase transformer was developed for contactless transmission of electric energy from the synchronous generator with permanent magnets (PMSG) and rotating rotor and stator. The half-core of this transformer with primary and secondary windings can rotate relative one to another. One phase of such a transformer was developed, engineered, and studied. According to the results of experimental studies, its computer simulation model was designed. We built and study a general computer model of an autonomous VAWT with a three-phase rotary transformer, the secondary windings of which have taps that are switched by triaks, providing quasi optimal control of VAWT operation. The analysis of necessary amount of taps is conducted for effective work of VAWT on all range of speed of wind.*

Streszczenie.** W przeciwwirującej turbinie wiatrowej z pionową osią obrotu (VAWT) dla bezkontaktnego przekazywania energii elektrycznej od generatora synchronicznego o magnesach trwałych (PMSG) z wirującymi induktorem i twornikiem, opracowano specjalny trójfazowy transformator, którego połowy rdzenia z pierwotnym i wtórnym uzwojeniami mogą obracać się względem siebie. Zaprojektowano, stworzono oraz zbadano jedną fazę takiego transformatora. W wyniku badań eksperymentalnych opracowano jego model stymulacyjny komputerowy. Wybudowano ogólny model komputerowy siłowni wiatrowej z VAWT o prace autonomicznej z trójfazowym wirującym transformatorem, którego uzwojenia wtórne mają placówki przełączane za pomocą triaków przewidując quasioptymalną pracę VAWT. Przeprowadzono analizę ilości placówek niezbędnej do skutecznego działania siłowni wiatrowej na całym zakresie prędkości wiatru. **(Opracowanie i modelowanie specjalnego transformatora wirującego – bezkontaktnego przekaźnika energii oraz regulatora dla przeciwwirującej turbiny wiatrowej)

Keywords: counter-rotating wind turbine, VAWT, PMSG, rotary transformer, FEM, quasi optimal control.
Słowa kluczowe: przeciwwirująca turbina wiatrowa, VAWT, PMSG, transformator wirujący, FEM, quasioptymalne sterowanie.

Introduction

In low annual average wind speeds on the territory of Ukraine and Poland [1], low power VAWTs work better, due to their advantage of stable work in low, rapidly changing winds and because they do not need to follow the direction of the wind [2]. To generate electricity with maximum energy efficiency, PMSG are used in VAWT, and due to the absence of restrictions in such a design on the size of the generator, wind turbines should be gearless, which ensures their high reliability and low starting wind speed [3]. The use of a counter-rotating design of VAWT, where inductor of PMSG is connected with one wind rotor, and armature – with another counter-rotating wind rotor, makes it possible to double the angular velocity of the generator, which decreases its number of poles and significantly reduces the size and cost of the generator [4, 5]. However, in a counter-rotating VAWT there is a problem of transmitting the produced electric energy from the armature of PMSG located on the moving part of the installation. In low-powered autonomous VAWTs produced electric energy accumulates, as a rule, in a storage battery with permanent voltage. Therefore, for effective work of VAWT it is necessary to regulate the electric loading of PMSG.

Development of the Rotary Transformer

For contactless transmission and discrete regulation of produced electric energy from the rotary armature of PMSG, a special transformer with a rotary part was proposed [6]. The functional characteristics of such a transformer, namely the need for the primary winding to rotate with respect to the fixed secondary winding, determine the features of its design – the mutual inductance for each phase of the transformer must not depend on the angle of rotation of its moving parts. Such properties can be provided by the transformer, in which the primary and secondary windings of each phase are embedded in separate steel half-cores, which are laminated in the radial direction and can rotate relative one to another (Fig. 1).

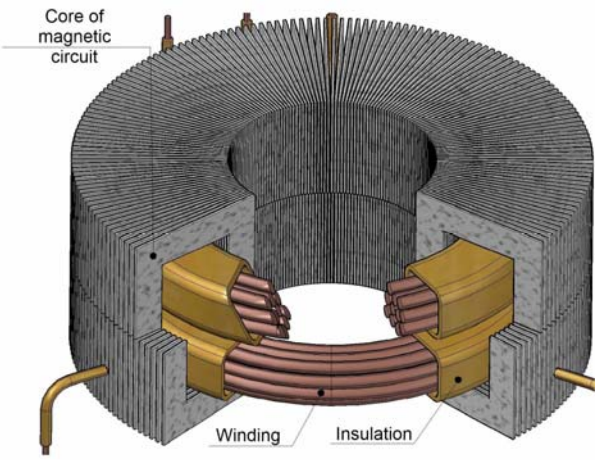


Fig. 1. The sketch of the design of one phase of the rotary transformer

Such a rotary transformer is an atypical object of electrical engineering and electromechanics. This is due, above all, to the presence of an air gap between the half-cores, as well as to the fact that the transformer feeds from the power source (generator), the voltage and frequency of which change within wide ranges. We developed a method of the preliminary calculation of rotary transformer ensured efficiency values not lower than 0.85 for the three ranges of operation: on fixed frequencies 40, 80 and 120 Hz with supply voltages ratio of the primary windings 1:2:3 and power 1:8:27 respectively. For achievement of the put aims, the number of turns and diameter of wire of primary winding was increased during designing relatively to the same parameters of typical transformers of small power. Also a cross-cut to magnetic circuit is chosen on such considerations, that induction in steel was low. Such decision assists of reduction of the magnetizing current, and work on the straight section of the magnetizing characteristic reduces losses in steel. The rotary transformer was engineered coming from the supply voltage of low frequency, as at the increase of frequency the inductive resistance grows, and the magnetizing current diminishes accordingly. One of the features of transformer there is a force of attracting between steel half-cores, what is determined by the Maxwell formula [6]. Adequacy of the proposed method was verified by calculating the steady-state electromagnetic processes in the field model of the transformer (Fig. 2), in which all the factors affecting its performance were also examined.

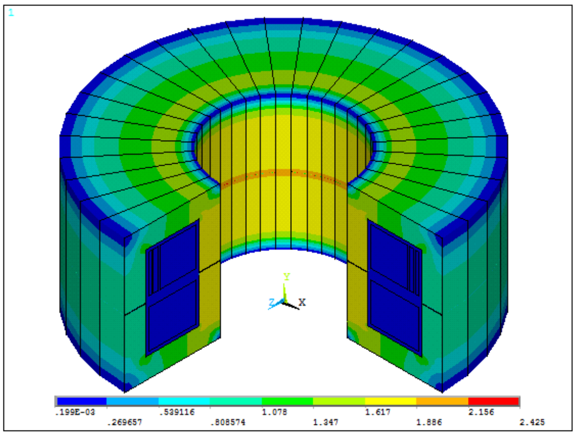


Fig. 2. The distribution of induction of magnetic field in one phase of the rotary transformer

As a result of the design, an experimental model of one phase of the rotary transformer was created, which has maximum output power of 200 VA and three taps in the secondary winding that must operate in the above ranges (Fig. 3).

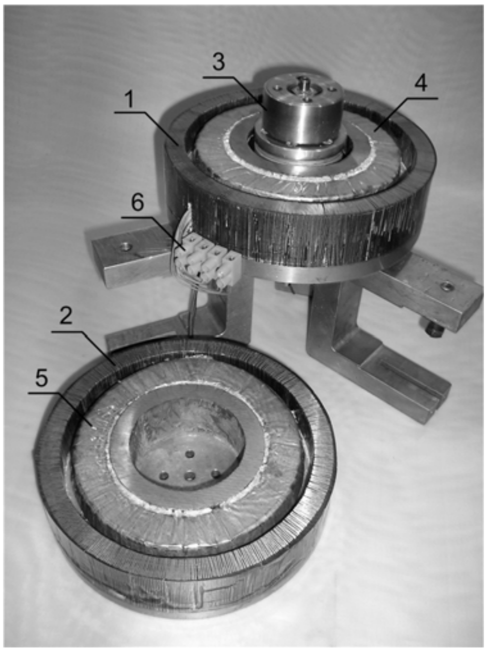


Fig. 3. Model of rotary transformer: 1 – immobile half-core, 2 – movable half-core, 3 – slewing gear, 4 – secondary (immobile) winding, 5 – primary (movable) winding, 6 – taps of secondary winding

On the slewing gear knot 3 is rigidly fixed the immobile steel half-core 1, in which the secondary winding 4 is situated. A slewing gear gives an opportunity to be revolved to the movable half-core 2, in which there is the primary winding 5 connected to armature of generator. By means of the taps 6 of the secondary winding electric energy is transmitted from the movable armature of generator with the necessary adjusting of parameters of output voltage. The slewing gear must maintain a force of attracting between the steel half-cores and provide the air gap at the level of 0.2 mm. The magnetizing current will grow in case of increase of this value, and as consequence – the efficiency of device will diminish. At reduction of air gap a probability of "sealing" of two half-cores increases.

Experimental Studies

The work of the rotary transformer is described by the known equations of the transformer reduced to one winding in the complex form [4]. These equations correspond to the modified T-shaped equivalent circuit. To determine its parameters for a single-phase rotary transformer, a series of experiments on the created experimental model was carried out on different taps and frequencies of voltage: the measurement of active resistances of the windings at DC, the no-load experiments to determine the magnetizing inductance and losses in steel, and the short-circuit experiments to determine the leakage inductances.

For carrying out the aforementioned tests the experimental setting (Fig. 4) was created, which gives an opportunity to change the parameters of voltage in a wide range, and also to conduct the necessary measuring.

Fig. 4. The experimental setting for research of one phase of rotary transformer: 1 – autotransformer, 2 – transformer, 3 – diode bridge, 4 – synchronous generator with driving DC motor, 5 – digital oscillograph, 6 – load resistor, 7 – rotary transformer

Fig. 5 represent the electric circuit of the experimental setting. The rotary transformer 7 feeds from the monophase synchronous generator 5, the value of voltage of which is regulated by excitation current changed by the resistor 6. Voltage frequency is regulated by changing of speed of the driving DC motor 4 by adjusting the voltage added to the armature of motor by means of the autotransformer 1.

On the results of conducted physical experiments and next calculations, the parameters of rotary transformer, which is submitted in the Table 1, are got.

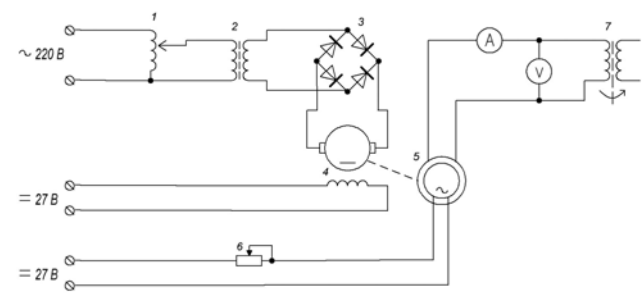


Рис. 5. Electric circuit of the experimental setting: 1 – autotransformer, 2 – transformer, 3 – diode bridge, 4 – driving DC motor, 5 – monophase synchronous generator, 6 – resistor, 7 – rotary transformer

Table 1. Parameters of the equivalent circuit of the rotary transformer, obtained in experiment

Name of parameter	Value
Resistance of primary winding R_1 [Ohm]	0.221
Resistance of first secondary winding R_{21} [Ohm]	0.428
Resistance of second secondary winding R_{22} [Ohm]	0.309
Resistance of third secondary winding R_{23}, Ohm	0.106
Leakage inductances of primary winding and transformed to it first secondary winding $L_{\sigma 11} = L'_{\sigma 21}$ [mH]	1.153
Leakage inductances of primary winding and transformed to it second secondary winding $L_{\sigma 12} = L'_{\sigma 22}$ [mH]	0.782
Leakage inductances of primary winding and transformed to it third secondary winding $L_{\sigma 13} = L'_{\sigma 23}$ [mH]	0.673
Magnetization inductance L_m [mH]	85.7
Iron loss resistance R_{Fe} [Ohm], (f is the frequency of supply voltage)	0.0306 $f^{1.3}$

Computer Modeling of the Rotary Transformer

Based on the T-shaped equivalent circuit and using its experimentally determined parameters, the computer model of the rotary transformer was developed in the software MATLAB/Simulink. The model takes into account the frequency-dependent losses in steel. They are modeled by resistance that is determined after expression:

(1) $$R_m = \frac{P_{st}}{I_\mu^2} = \frac{1.7\rho_{1/50} B_0^2 \left(\frac{f_1}{50}\right)^{1.3} G_{st}}{I_\mu^2}$$

where P_{st} is the power losses in steel, I_μ is the current of magnetizing, $\rho_{1/50}$ is the specific losses in steel at induction of 1 T and frequency of 50 Hz, B_0 is the induction in a core, f_1 is the voltage frequency, and G_{st} is the mass of steel core.

The experimental researches showed that losses in steel are proportional to $f_1^{1.3}$. It is explained by that a transformer works on the straight section of the magnetizing characteristic. The correlation $B_0^2 / I_\mu^2 = \mathrm{const}$ takes place regardless of the mode of operations of rotary transformer and of number of taps, on which it works. Thus, the subsystem of modeling of losses in steel was created on the basis of the expression

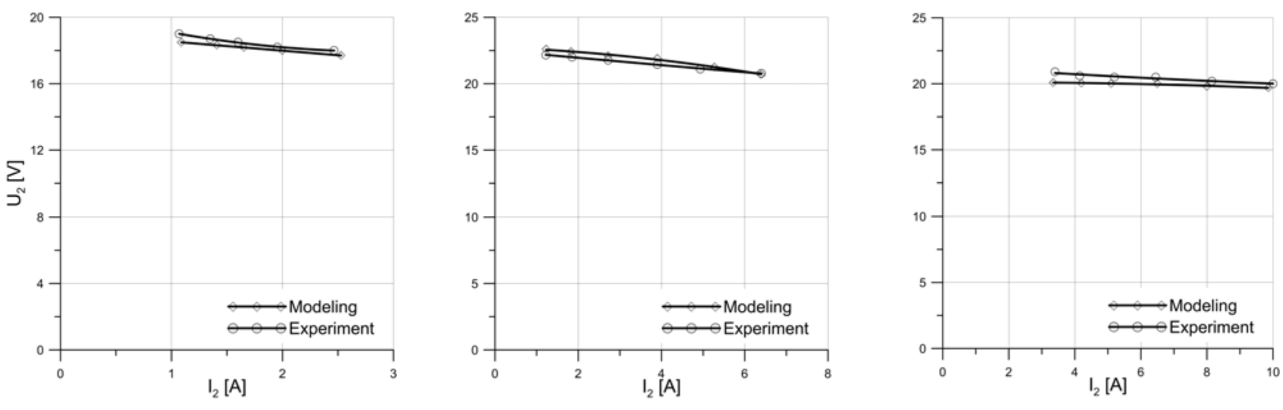
(2) $$R_m = K_m f^{1.3}$$

where coefficient K_m is determined an experimental way and is permanent for all range of supply voltage of rotary transformer:

(3) $$K_m = \frac{1.7\rho_{1/50} B_0^2 G_{st}}{50^{1.3} I_\mu^2} = 3.06 \cdot 10^{-2}$$

The taps of the secondary winding of the transformer are switched in the model by external signals at the transitions of secondary voltage through zero.

A special feature of the model is the use of a cross automatic control system, which provides coordination of real load with the T-shaped equivalent circuit. To verify the computer model, the physical experiments on the experimental model and computer simulation were conducted for the same conditions of supply and load of the rotary transformer. The results of these studies (Fig. 6) showed no difference above 5%.



a) b) c)

Fig. 6. Characteristics of the rotary transformer on three taps of secondary winding at the frequency of supply voltage 50 Hz

Computer Simulation of the Counter-Rotating VAWT with a Rotary Transformer

In order to study the work of a counter-rotating VAWT and choose the optimal mode of its operation, a system was modeled according to the functional scheme shown in Fig. 7. The following options of the counter-rotating wind turbine were selected: rated output mechanical power 540 W at wind speed 10 m/s, the radius of one wind rotor 1.14 m and its swept area 1.29 m^2 (at the height of one wind turbine 1.13 m), maximum value of power coefficient $C_{P\max}$ = 0.351. The options of PMSG: rated mechanical speed 520 rpm, number of poles 12, peak line-to-neutral back emf in no-load 40.3 V, winding resistance and inductance 0.8 Ohm and 3.5 mH respectively. Battery had the voltage of 24 V.

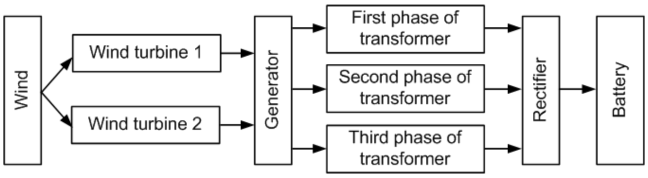
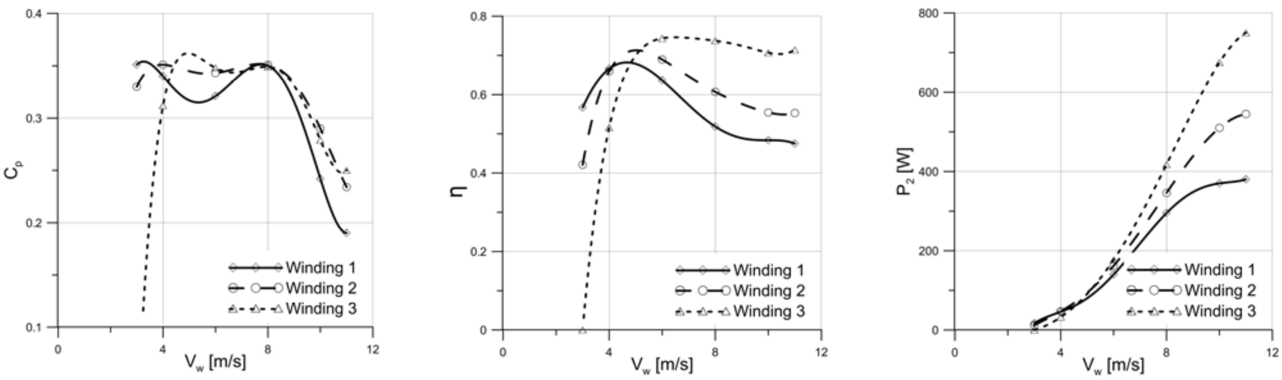


Fig. 7. Functional scheme of the counter-rotating VAWT

The results of computer simulation are shown in Fig. 8. Because wind power is a renewal energy source, an analysis is conducted on considerations of taking off from wind of maximal power for charging of storage battery. Thus, the efficiency of power transfer in all elements of VAWT and also the value of power coefficient C_P digress on the second plan. An analysis shows, that for the efficient operation of VAWT in the entire range of wind speed, just two taps on the secondary winding of the rotary transformer are sufficient: at wind speeds at 3-5 m/s – work on the first tap, and at 5-11 m/s – on the third tap. This provides almost maximum energy extraction from the wind – power coefficient is close to its maximum value $C_{P\max}$. However, the overall efficiency of the system PMSG–rotary transformer–rectifier is relatively low – 0.6 - 0.75 due to energy losses in the electrical circuits of windings, particularly through the reduction. A slight increase in the efficiency can be achieved by incorporating in these circuits capacitors for reactive power compensation.



a) b) c)

Fig. 8. Performance of the tested VAWT at different enabled taps of the secondary windings of the rotary transformer at the different wind speeds: a) power coefficient, b) efficiency of energy transform by system PMSG–rotary transformer–rectifier, b) output power entering to battery

Conclusion

Designed rotary transformer for a counter-rotating VAWT retains the main advantage of PMSG – no mechanical contact between moving and stationary parts, and also serves as a simple and reliable control device. A design technique that takes into account indistinctness of its construction and conditions of use is worked out. One phase of rotary transformer is made and explored. The simulation computer model of rotary transformer and also a model of general system of counter-rotating VAWT are built. The results of computer studies can determine the optimal ranges of wind turbine work on the relevant taps of the secondary winding of the rotary transformer, in order to ensure high energy efficiency of stand alone VAWT.

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