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DETERMINATION OF CAPACITIVE CHANGE PATTERNS OF CAPACITOR EXCITER WITH VARIABLE TOPOLOGY FOR INDUCTION GENERATOR

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The object of the study is an autonomous induction generator equipped with a capacitor exciter with a variable topology. Neglecting the influence of the generator rotor rotational frequency and load level on the required exciter capacitance, as well as the difficulties with its regulation over a wide range, leads to fluctuations in the output voltage. This is the reason for the decrease in the quality of power supply to consumers. This problem is solved by identifying the relationship between the required exciter capacitance, on the one hand, and the rotation frequency and load power, on the other. Also, by using a capacitor circuit, the topology of which can be changed, implementing different ways of connecting capacitors. The direct dependence of the required exciter capacitance value on the load power and the inverse dependence on the rotational frequency have been confirmed. The insignificant influence of the linear interaction of such factors on the required capacity has been established. The width of the fuzzy interval of coefficient at the relative power value is 0.01, for the coefficient at the rotational frequency – 0.36. This causes a significant increase in the uncertainty of estimating the required capacity as the rotational frequency increases. The possibility of maintaining the generator output voltage within the limits permitted by EN 50160 using a capacitor exciter with a variable topology has been confirmed. The exciter circuit allows to adjust the capacitance within the adjustment range according to a monotonic rising characteristic. The proposed method of controlling the capacitive excitation current allows generating an order of magnitude more current levels compared to analogues due to the use of parallel, series, and mixed connections of capacitors. The obtained results can be applied in the construction of control system for capacitor exciter with a variable topology for an autonomous induction generator

Keywords: induction generator, voltage stabilization, fuzzy range, variable topology, capacitive exciter

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1. Introduction

Microgrids have been widely developed in the context of modern global trends towards reducing fossil fuel consumption and wide developing renewable energy sources. Such localized power systems include, in addition to consumers, photovoltaic, wind, biogas installations, electricity storage systems, and, if possible, small hydroelectric power plants etc. Microgrids can operate in energy exchange mode with a centralized power system, or autonomously. The global microgrid market in 2025 was estimated at 99.76 billion USD, with a compound annual growth rate of 19.7% [1].

One of the main renewable sources in the microgrid, along with solar power plants, is wind power plants. The electric generators used in such installations can be divided into the following types. Type I – induction short-circuit generators that are directly connected to the network, are characterized by high reliability and low cost, but require a constant speed. Type II – induction generators with a wound rotor, allow a change in rotation frequency of about ±10%. Type III – doubly fed induction generators, allow variations in speed within ±30%, are the most common (in 2024 – 55.3% of the global market [2]). Type IV – generators with a power semiconductor converter that stabilizes the frequency of the output current, there are no restrictions on the frequency of rotation, synchronous and inductions machines are used [3]. Induction short-circuited generators (type I) are characterized by the highest reliability and lowest cost. Compared to synchronous machines, such generators are characterized by smaller dimensions and higher efficiency [4]. Unlike synchronous machines with an excitation winding on rotor, the operation of induction machines when the excitation is lost is not accompanied by overvoltages. Compared to permanent magnet synchronous generators, the manufacture of induction machines does not require the use of rare earth metals. The global market for induction generators is estimated to be worth 3.08 billion USD in 2025. The market is expected to reach 3.30 billion USD in 2026 [5]. However, the widespread introduction of type I generators is hampered by two main drawbacks: the need to use a mechanical gearbox to stabilize the rotor speed; the need for a regulated source of reactive power. The need to regulate the reactive excitation current of an induction generator is due to the dependence of the output voltage on the magnitude of such current. The generator voltage is also significantly affected by the rotor speed and the power of the electrical load. Most existing technical solutions have a limited range of capacitive current regulation and do not take into account changes in generator operating conditions, which reduces the quality of the output voltage. For regulating the excitation of an induction generator, a capacitor exciter circuit with a variable topology appears to be effective over a wide range [6]. The principle of operation of the exciter is based on changing the total capacitance by controlling the number and connection scheme of capacitors. However, the question of the influence of external disturbances on the required exciter capacitance remains open. This determines the direction of this study – identifying the patterns of change in the capacitance of a capacitor exciter with a variable topology to maintain the nominal value of the output voltage of an induction generator.

Thus, the need to stabilize the output voltage level of an induction generator under the influence of external disturbances determines the relevance of the disclosed scientific issues.

2. Literature review and problem statement

Previous studies have established a significant influence of the rotor rotational frequency of an induction generator and the load power on the output voltage. In particular, in [7] it was found that the generator voltage depends directly proportionally on the load power and inversely on the rotation frequency. The need to change the exciter capacitance is indicated, but no practical ways of implementing such an approach are outlined. In work [8], an exponential dependence of the magnitude and frequency of the output voltage of a self-excited induction generator on the load resistance was established. Experimental results show that the root mean square voltage value can change almost twice as much when the load impedance changes. However, the generator rotor rotational frequency is considered as a value dependent on the load resistance, which does not always correspond to the generator operating conditions. The dependence of the generator voltage on the load resistance is proposed to be described by a third-order polynomial [9]. In the same work, a quadratic dependence of the generator voltage on the exciter capacitance was established. However, [9] does not consider the influence of the rotor rotational frequency on the functioning of the generator. Research [10] found that increasing the load resistance increases the generator voltage frequency and reduces the output power. The calculation of the required exciter capacitance using the metaheuristic optimization algorithm is carried out only for the nominal rotor rotational frequency and does not take into account the change in such a factor. Linear dependences of the magnitude and frequency of the generator output voltage on the load power under symmetrical and significantly asymmetrical loading were obtained in [11]. However, in this work, the influence of the generator rotor rotational frequency on the characteristics of the latter was not revealed. To maintain the voltage within permissible limits during self-excitation of an induction generator, it is recommended to adhere to the following requirements [12]. The capacitance of the capacitors should be within ±0.05% of the rated value, the rotational frequency should be within ±0.008%. However, the dependence of the generator voltage on the ratios of these two factors has not been established. At the same time, in work [13] the recommended range of capacity change when changing the generator load is ±50–60% of the rated value. In [14] it is shown that the optimal exciter capacitance increases nonlinearly with increasing load current, and also decreases nonlinearly with increasing rotor rotational frequency. However, the effect of the combination of such factors on the required exciter capacitance value has not been investigated. A known scheme [15] of a capacitor exciter for a three-phase induction generator, the stator windings of which are connected in a delta circuit. It is proposed to connect two variable and one constant capacitor in a star, which allows powering a significantly asymmetrical, in particular single-phase, load. The complexity of the practical implementation of this excitation method is due to the need to use variable capacitance capacitors. A known scheme [16] for stabilizing the generator voltage magnitude and frequency using an impedance controller that controls a transistor PWM capacitive current converter. The disadvantages of this approach include the deterioration of the harmonic composition of the generator output voltage.

Analysis of the literature [7–16] allows to establish the existing problem: insufficient efficiency of the functioning of an induction generator with self-excitation. Neglecting the influence of the rotor rotational frequency and load level on the required exciter capacitance, as well as the difficulty in adjusting the latter parameter over a wide range, leads to fluctuations in the output voltage. This, in turn, is the reason for the decrease in the quality of power supply to consumers of the autonomous microgrid.

All this allows to state that it is advisable to conduct a study dedicated to determining the patterns of change in the capacitance of a capacitor exciter with a variable topology for an induction generator.

3. The aim and objectives of the study

The aim of the study is to increase the efficiency of the operation of an induction generator as part of an autonomous microgrid by using a capacitor exciter with a variable topology. This will allow regulating the capacitive excitation current in a wide range under the influence of external disturbances, in particular, load parameters and generator rotor rotation frequency. The RMS value of the generator output voltage will be thereby maintained within acceptable limits.

To achieve the aim, the following objectives must be solved:

– to determine the rated exciter capacitance for an autonomous induction generator;

– to assess the influence of external factors on the required value of the exciter capacitance to maintain the permissible output voltage of an autonomous induction generator;

– to estimate the range of adjustment of the exciter capacitance, in which the permissible output voltage of the autonomous induction generator is maintained, when using a capacitor exciter with a variable topology.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of the study is an autonomous induction generator equipped with a capacitor exciter with a variable topology. The generator rotor rotates with a wind turbine at a frequency ω, Fig. 1. A three-phase capacitor exciter (delta scheme) is connected to the generator stator terminals. The principle of operation of the exciter is based on changing the total capacitance by controlling the number and connection scheme of capacitors [16]. An exciter with the number of capacitor groups $m = 3$, and each group includes $p = 2$, capacitors was selected for modeling. The control system generates signals to control the keys of each phase of the exciter in accordance with the value of the specified capacitance C_{set}. The load Z is powered from the terminals of the stator winding through the switching device Q.

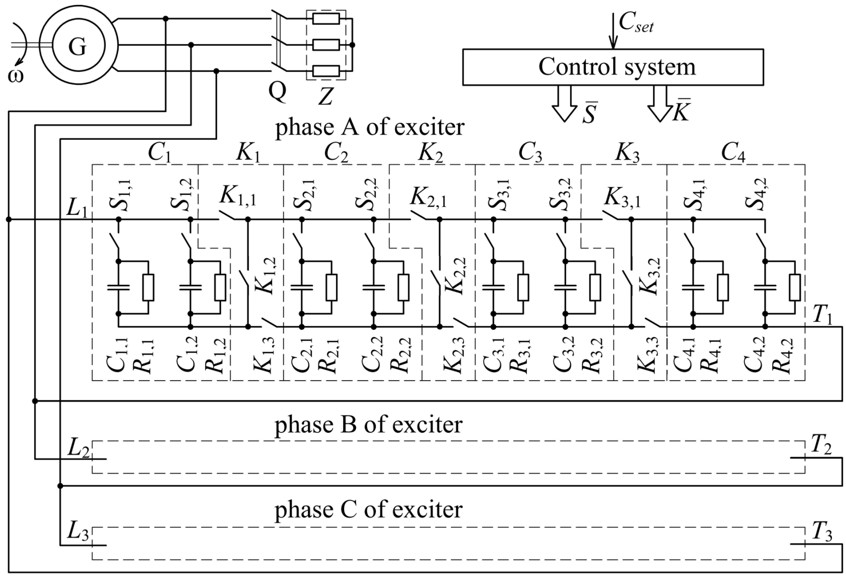


Fig. 1. Schematic electrical diagram of an autonomous induction generator equipped with a capacitor exciter with variable topology

The subject of the study is the dependence of the output voltage of a self-excited induction generator on the load power, rotational frequency, and capacitor exciter capacitance.

The main hypothesis of the study is the possibility of maintaining the generator output voltage within the permissible limits, according to [17], when changing the load power and rotation frequency. Maintaining the generator output voltage within the permissible range is expected to be carried out by adjusting the capacitance of the capacitor exciter.

During the study, the disturbances acting on the generator vary within the following limits: load power – from 0 p.u. to 1 p.u.; rotation speed – from 0.8 p.u. to 1 p.u. In this case, excitation is provided by a capacitor circuit with a variable topology, the total capacitance of which varies discretely. The exciter circuit allows to change the phase capacitance within the range [$C_{\min 1}$; $C_{\max 1}$]. But it is sufficient to change the phase capacitance within the [$C_{\min 2}$; $C_{\max 2}$] adjustment range, which includes M discrete levels of capacitance change, to maintain the rated output voltage of the generator when changing the values of the factors. Then, for the specified range, a vector of changing relative steps in the phase capacitance of the exciter can be obtained

$$\delta_i = \frac{\Delta C_i}{C_{\max 2} - C_{\min 2}} \cdot 100\%, \quad (1)$$

where $\Delta C_i = C_{i+1} - C_i$ – absolute steps of changing the capacity; $i = \overline{1, M-1}$.

The values of δ_i change from step to step due to changes in the topology of the exciter circuit, and their totality can be considered as a pseudo-random sequence.

It is provided that the limits of the control range belong to the range of change of the exciter phase capacitance:

$$\begin{cases} C_{\min 2} \geq C_{\min 1}; \\ C_{\max 2} \leq C_{\max 1}, \end{cases} \quad (2)$$

the following criterion for testing the main hypothesis of the study is adopted. If in the adjustment range the step change in the exciter capacitance does not exceed $\delta_{\lim} = 2\%$ with a probability of not less than $P_{\lim} = 0.9$, then the main hypothesis is not rejected. This condition corresponds to the fulfillment of the inequality

$$F(\delta_{\lim}) \geq P_{\lim}, \quad (3)$$

where F – the empirical distribution function of relative steps δ.

If inequality (3) is not satisfied, then the main hypothesis is rejected and it is assumed that when changing the load power and rotational frequency, it is not possible to maintain the output voltage within acceptable limits using a capacitor exciter.

The set of assumptions and simplifications of the study is as follows:

1. The induction generator is characterized by electrical and magnetic symmetry, steel saturation is taken into account. The effect of current displacement in the rotor bars is not taken into account.
2. The insulation of the generator windings is considered idealized, i.e. insensitive to overvoltages.
3. The generator load is purely active, i.e. $\cos\varphi = 1$.
4. The S and K power keys in the exciter are ideal, i.e. they provide instantaneous switching without an arc.
5. Since the exciter capacitance can vary discretely at specified levels, the actual capacitance value, if not equal to the set value C_{set}, is the closest to it.
6. The generator output voltage when changing the influencing factors should be within ±10% of the rated voltage, which is determined by the requirements [17].
7. The significance level $\alpha = 0.05$ is adopted for testing statistical hypotheses. The confidence level for fuzzy number analysis is $\lambda = 0.4$.

4. 2. Computer model of an induction generator with a capacitor exciter

The study of the functioning of an induction generator equipped with a capacitor exciter is carried out using a Simulink model (MATLAB software, MathWorks, USA), Fig. 2.

For numerical simulation, an induction generator of the SWT-2.3-101 type manufactured by Siemens (Germany),

Table 1 [18], represented by the block G (Asynchronous Machine), was used. To simulate the saturation of the generator steel, the dependence $U = 134.48 \cdot \ln I - 121.56$ was used.

An active load R_1 with a rated power $P_r = 2.3$ MW is connected to the generator output through the switch Q_1. The capacitor exciter is a source of capacitive current for the generator. The phases C_A, C_B, C_C of the exciter are connected in a delta circuit. The model of each phase, Fig. 3, includes a block C that models a capacitor of a given capacitance, built using a controlled voltage source [19]. The following values of capacities in each phase of the exciter were adopted: $C_{1,1} = 1$ mF; $C_{1,2} = 1.5$ mF; $C_{2,1} = 2$ mF; $C_{2,2} = 2.5$ mF; $C_{3,1} = 3$ mF; $C_{3,2} = 3.5$ mF; $C_{4,1} = 4$ mF; $C_{4,2} = 4.5$ mF. The resistances of the discharge resistors, which are shunted across the capacitors, are 1 MΩ.

The permissible states of the power keys of the capacitor exciter (total number of states $H = 518$) were determined using the CEVT (Capacitive Exciter With Variable Topology) program [16], Fig. 4. The range of phase capacitance changes: from $C_{\min1} = 0.48$ mF to $C_{\max1} = 21$ mF.

The "SK states" subsystem controls the exciter keys, Fig. 5. A given value of the phase capacitance is supplied to the input of such subsystem. The specified value is supplied to the first input of the Prelookup block. A list of discrete levels of the exciter capacitance is supplied to the second input. The specified block, together with the adder and the round block at the output, calculates the index *num* of the exciter closest discrete state to the given capacitance. For each key, the Selector block determines the required key state from the vector of its logical states at the specified index.

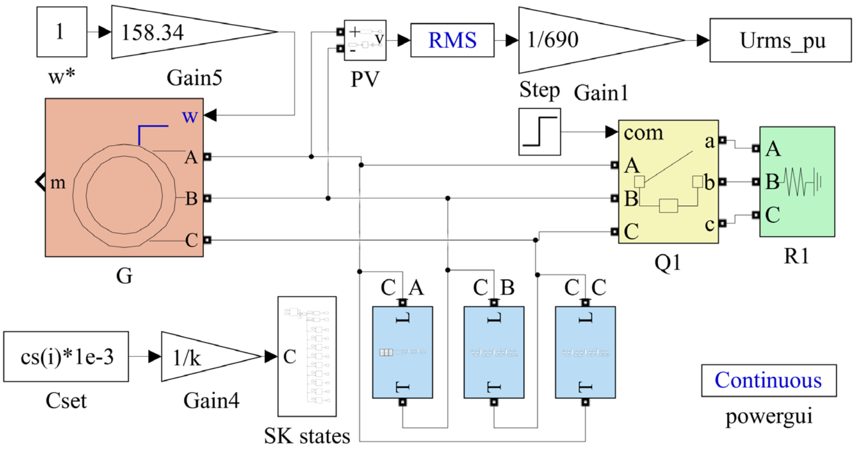


Fig. 2. Computer model of an autonomous induction generator equipped with a capacitor exciter with a variable topology

Table 1

Parameter values of an induction generator SWT-2.3-101 with a squirrel-cage rotor [18]

Parameter	Unit of measurement	Value
Rated output power	MW	2.30
Rated mechanical power	MW	2.3339
Rated apparent power	MVA	2.59
Rated line-to-line voltage U_r	V	690
Rated stator frequency	Hz	50
Rated power factor	p.u.	0.8
Rated rotor rotational frequency	rpm	1512
Rated slip	p.u.	−0.008
Rated mechanical torque	kH · m	14.74
Stator winding resistance	mΩ	1.102
Rotor winding resistance	mΩ	1.497
Stator leakage inductance	mH	0.06492
Rotor leakage inductance	mH	0.06492
Magnetizing inductance	mH	2.13461
Moment of inertia	kg · m^2	1200

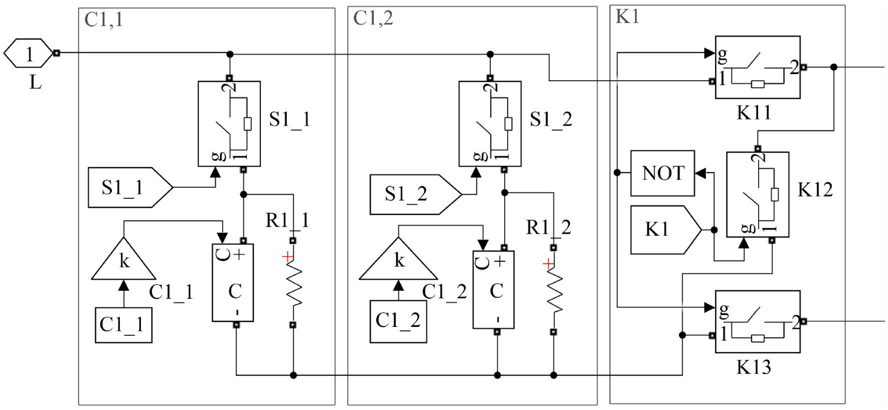
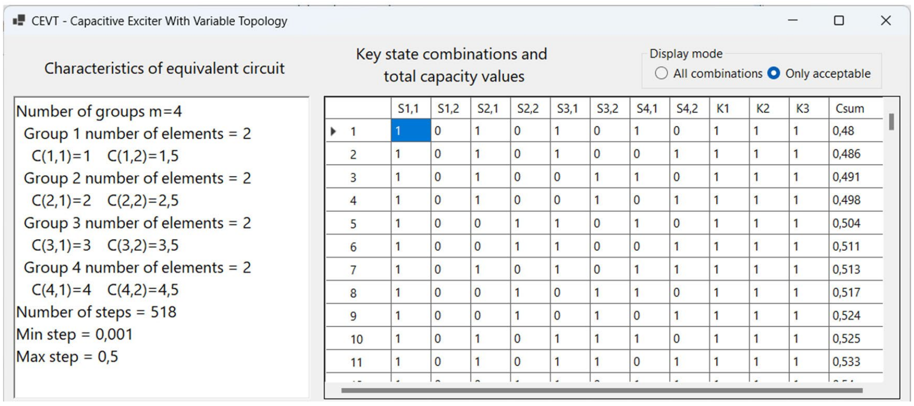


Fig. 3. Model fragment of a phase of capacitor exciter with variable topology



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Number of groups m=4
 Group 1 number of elements = 2
  C(1,1)=1   C(1,2)=1,5
 Group 2 number of elements = 2
  C(2,1)=2   C(2,2)=2,5
 Group 3 number of elements = 2
  C(3,1)=3   C(3,2)=3,5
 Group 4 number of elements = 2
  C(4,1)=4   C(4,2)=4,5
Number of steps = 518
Min step = 0,001
Max step = 0,5
```

	S1,1	S1,2	S2,1	S2,2	S3,1	S3,2	S4,1	S4,2	K1	K2	K3	Csum
1	1	0	1	0	1	0	1	0	1	1	1	0,48
2	1	0	1	0	1	0	0	1	1	1	1	0,486
3	1	0	1	0	0	1	1	0	1	1	1	0,491
4	1	0	1	0	0	1	0	1	1	1	1	0,498
5	1	0	0	1	1	0	1	0	1	1	1	0,504
6	1	0	0	1	1	0	0	1	1	1	1	0,511
7	1	0	1	0	1	0	1	1	1	1	1	0,513
8	1	0	0	1	0	1	1	0	1	1	1	0,517
9	1	0	0	1	0	1	0	1	1	1	1	0,524
10	1	0	1	0	1	1	1	0	1	1	1	0,525
11	1	0	1	0	1	1	0	1	1	1	1	0,533

Fig. 4. Using the *Capacitive Exciter With Variable Topology* program to calculate the permissible states of the power keys of the capacitor exciter

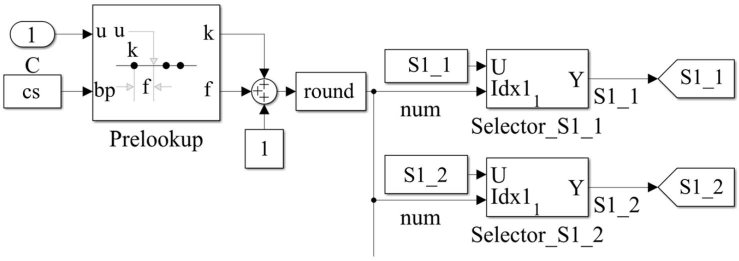

Fig. 5. Model fragment of the exciter power keys control subsystem

The model, Fig. 2, provides a study of the dependence of the RMS value of the output voltage on the load power and the generator rotational frequency.

4. 3. Experiment planning

Two factors influence the object of study: active power P of the load and rotational frequency ω of the generator rotor. The choice of such factors is due to the change in the power loading the generator when operating as part of an autonomous microgrid. When a generator is operating as part of a wind turbine, a change in wind speed over a significant range, despite the presence of an automatic transmission, affects the rotational frequency of the rotor. The values of the factors are set using the windows for specifying the load power and the rotor rotational frequency of the model generator, Fig. 2. A system of relative units is used to evaluate the magnitude of influence factors. The following basic values are accepted: rated load power $P_r = 2.3$ MW; rated rotational frequency $\omega_r = 158.34$ rad/s. The actual values of factors in relative units are calculated according to the dependencies:

$$P^* = P / P_r; \tag{4}$$

$$\omega^* = \omega / \omega_r. \tag{5}$$

The coding of factors, Table 2, was carried out as follows:

$$x_1 = \left(P^* - P_0^*\right) / I_1; \tag{6}$$

$$x_2 = \left(\omega^* - \omega_0^*\right) / I_2, \tag{7}$$

where P_0^*, ω_0^* – the actual values of the main factor levels.

The value of the capacitance C, mF, of the exciter phase, which provides the rated level of the linear voltage of the generator, was chosen as the objective function. The relative voltage value is defined as: $U^* = U/U_r$, where $U_r = 690$ V. The relative value of the phase capacitance of the exciter is calculated according to the relationship: $C^* = C/C_r$, where C_r – the rated phase capacitance of the exciter, mF. In addition, it is planned to estimate the range of exciter capacitance $\left[C_{rl}^*; C_{rh}^*\right]$, the limits of which correspond to the permissible range of generator voltage changes: lower limit $U_{rl}^* = 0.9U_r^*$; upper limit $U_{rh}^* = 1.1U_r^*$. In general, the mathematical model of the object of the study is represented by the function

$$C^* = f\left(P^*, \omega^*\right). \tag{8}$$

A linear mathematical model of an induction generator with a capacitor exciter of variable topology is adopted, which takes into account the influence of individual factors and the effect of their linear interaction

$$C^* = a_0 + a_1 P^* + a_2 \omega^* + a_{12} P^* \omega^*. \tag{9}$$

The estimation of the coefficients a_0, a_1, a_2, a_{12} values of the model (9) is supposed to be carried out based on the results of 2^2 full factorial experiment with a central point. Such an experiment is supposed to be carried out using a computer model of the object of the study, Fig. 2. The experiment planning matrix, Table 3, is composed using the coded values of the factors. The mathematical model (9) for the coded values of the factors has the form

$$C^* = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2, \tag{10}$$

where b_0, b_1, b_2, b_{12} – the coefficients of the mathematical model with coded factor values.

The planning matrix, Table 3, also includes the limits of the range of change in the phase capacitance of the exciter for each experiment.

Table 2

Levels and intervals of factors variation

Parameters	Factors	Factor levels, p.u.			Variation interval I
		−1	0	+1	
P^*	x_1	0	0.5	1	0.5
ω^*	x_2	0.8	0.9	1	0.1

Table 3

Design matrix of 2^2 full factorial experiment with a central point

Experiment No.	x_1 value		x_2 value		Phase capacitance change range, mF	
	Coded	Natural, P^*, p.u.	Coded	Natural, ω^*, p.u.	Low boundary $C_{\min}$	High boundary $C_{\max}$
1	−1	0	−1	0.8	0.774	4.421
2	+1	1	−1	0.8	1.290	7.000
3	−1	0	+1	1	0.480	4.421
4	+1	1	+1	1	0.480	4.421
5	0	0.5	0	0.9	0.480	4.421

Experiment No. 4 corresponds to the operation of the generator set at rated load and at rated rotational frequency. The results of this experiment will be used to determine the rated capacitance of the exciter. The method for determining such a capacity involves modeling the operation of an induction generator in steady-state mode for all possible levels of capacity provided by the exciter. Based on the obtained dependence of the generator output voltage on the exciter phase capacitance, the rated capacitance is determined, which provides the rated output voltage at the rated load power.

4. 4. Estimating model parameter values

During the experiment, it is planned to estimate for each point of the plan the relative values C^*, C_l^*, C_h^* of the exciter capacitance, at which the generator output voltage is equal to, respectively, U_r^*, U_{rl}^*, U_{rh}^*. For each of these cases, it is intended to estimate the values of the parameters of the model (10) using the *fitlm* function available in MATLAB. The specified function performs regression of empirical values. To perform the analysis of variance of the regression model, the *anova* function is supposed to be used. From the known values of the coefficients b, using linear transformations (6), (7), estimates of the values of the parameters a of the model (9) are obtained. In this case, for model coefficient with $k=\{0;\ 1;\ 2;\ 12\}$ index, three values (a_k, a_{lk}, a_{hk}) will be obtained, which correspond to three levels of the generator output voltage: U_r^*, U_{rl}^*, U_{rh}^*.

The fuzzy number apparatus is used to describe the values of the model (9) coefficients. The values of a_k, a_{lk}, a_{hk} coefficients can be considered as parameters of the triangular fuzzy number A_k, Fig. 6.

Then, for a given confidence level λ, the value of the k-th parameter of the model is described by a fuzzy interval $[a_{Lk};\ a_{Rk}]$, the boundaries of which are calculated as:

$$a_{Lk}=\left(1-\lambda\right)a_{lk}+\lambda a_0; \tag{11}$$

$$a_{Rk}=\left(1-\lambda\right)a_{hk}+\lambda a_0. \tag{12}$$

When expressing the coefficients in fuzzy numbers, model (9) takes the form

$$\left[C_L^*;C_R^*\right]=\left[a_{L0};a_{R0}\right]+\left[a_{L1};a_{R1}\right]P^*+ +\left[a_{L2};a_{R2}\right]\omega^*+\left[a_{L12};a_{R12}\right]P^*\omega^*. \tag{13}$$

Estimating the boundaries of fuzzy intervals for a generator set of a specific type makes it possible to estimate the fuzzy interval $\left[C_L^*;C_R^*\right]$ for finding the desired exciter capacitance at which the output voltage will lie within the permissible range.

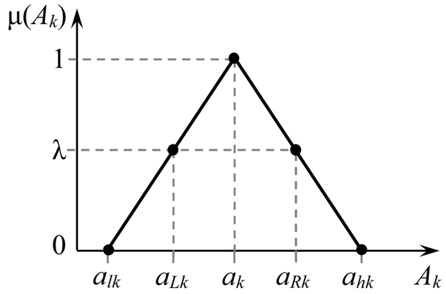

Fig. 6. Membership function μ of the triangular fuzzy number A_k, which describes the value of the k-th parameter of the model (9), and: a_{lk}, a_{hk} – the limits of the membership function; a_k – the value of the k-th parameter closest to the true value; a_{Lk}, a_{Rk} – the left and right limits of the fuzzy number at the confidence level λ

4. 5. Evaluation of exciter characteristics in the capacitance adjustment range

Using dependence (13) for the limit values of the factors from the accepted interval of variation of their values, it is possible to estimate the limits of the adjustment range of the exciter capacitance as:

$$C_{\min 2}^*=a_{L0}+a_{L1}\cdot\min\left[P^*\right]+a_{L2}\cdot\max\left[\omega^*\right]; \tag{14}$$

$$C_{\max 2}^*=a_{R0}+a_{R1}\cdot\max\left[P^*\right]+a_{R2}\cdot\min\left[\omega^*\right]. \tag{15}$$

To evaluate the characteristics of the exciter in a certain adjustment range for the purpose of fulfilling the criterion for testing the main hypothesis, the following procedure can be proposed:

1. Determine the number M of discrete levels of capacitance change based on the list of permissible states of the power keys of the capacitor exciter for the adjustment range $[C_{\min 2};\ C_{\max 2}]$.
2. Check the fulfillment of conditions (2) of the limits of the adjustment range belonging to the range of capacity change.
3. Obtain the vector of relative steps (1) of the change in exciter capacitance within the adjustment range.
4. Construct the empirical distribution function $F[\delta]$, for which the *cdfplot* MATLAB function can be used.
5. Check the fulfillment of criterion (3) and draw a conclusion regarding the main hypothesis of the study.

In the adjustment range of capacitance, the exciter is characterized by the number of adjustment steps and the distribution function of the capacitance change step.

5. Results of research into the possibility of maintaining the permissible voltage of an induction generator

5. 1. Rated capacitance of the induction generator exciter

As a result of numerical experiment No. 4, Table 3, the dependence of the output voltage of the induction generator on the phase capacitance of the capacitor exciter was obtained, Fig. 7.

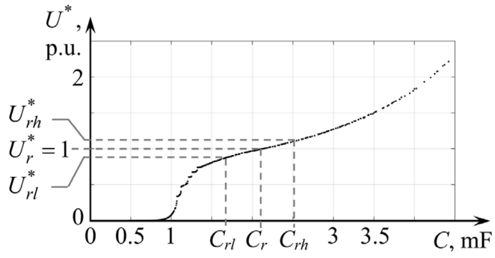

Fig. 7. Dependence of the output voltage U^*, p.u., of the generator on the phase capacitance C, mF, of the exciter at $P^* = 1$ p.u. and $\omega^* = 1$ p.u.: C_r, C_{rl}, C_{rh} – phase capacitances of the exciter, mF, providing the generator output voltage, respectively, $U^*_r = 1$ p.u., $U^*_{rl} = 0.9$ p.u., $U^*_{rh} = 1.1$ p.u.

The rated voltage level $U^*_r = 1$ p.u. at the rated load power $P^*_r = 1$ p.u. and the rotational frequency $\omega^*_r = 1$ p.u. is provided by the phase capacitance of the capacitor exciter $C_r = 2.132$ mF. This value corresponds to a combination number $i = 369$ of the exciter key states when the keys are in the following logical states: $S_{1,1} = 1$; $S_{1,2} = 1$; $S_{2,1} = 0$; $S_{2,2} = 1$; $S_{3,1} = 0$; $S_{3,2} = 1$; $S_{4,1} = 1$; $S_{4,2} = 1$; $K_1 = 1$; $K_2 = 0$; $K_3 = 0$. The limits of the range of change of the exciter phase capacitance at $P^*_r = 1$ p.u. and $\omega^*_r = 1$ p.u., corresponding to the permissible voltage range $[U^*_{rl}; U^*_{rh}]$, for a generator of a given type are: $C_{rl} = 1.75$ mF ($i = 333$); $C_{rh} = 2.5$ mF ($i = 398$).

5. 2. Results of evaluating the influence of external factors on the required exciter capacitance value

Table 4 presents the results of the numerical experiment, namely, the relative values C^*, C^*_l, C^*_h of the exciter capacitance, at which the generator output voltage is, respectively, U^*_r, U^*_{rl}, U^*_{rh}.

As a result of performing regression analysis using the obtained values of the objective function C^*, the coefficients b of the model (10) were estimated, Table 5. For each coefficient, the values of the standard error and asymptotic significance (p-value) were obtained. The regression indicators are as follows: root mean squared error 0.148; R-squared 0.939; adjusted R-squared 0.878.

Table 4

Numerical experiment results

Experiment No.	C^*, p.u.	C^*_l, p.u.	C^*_h, p.u.
1	1.3757	1.1257	1.5807
2	1.8874	1.6346	2.1107
3	0.5188	0.3518	0.6914
4	1.0	0.8208	1.1726
5	1.0	0.7767	1.1937

Table 5

Estimates of the model (10) coefficients b values using the obtained values of the objective function C^*

Model coefficient	Coefficient estimation	Standard error	p value
b_0	1.1117	0.0559	$2.7711 \cdot 10^{-4}$
b_1	0.2482	0.0739	$4.3742 \cdot 10^{-2}$
b_2	−0.4361		$9.7109 \cdot 10^{-3}$
b_{12}	−0.0076		$9.2431 \cdot 10^{-1}$

In model (10), it is possible to neglect the component with the coefficient b_{12}, since for the latter the asymptotic significance p exceeds the accepted confidence level $\alpha = 0.05$. That is, for the coefficient b_{12}, the null hypothesis cannot be rejected using the two-tailed t-test. Then the adjusted mathematical model of the object of the study takes the form

$$C^* = b_0 + b_1 x_1 + b_2 x_2. \quad (16)$$

The results of the analysis of variance (ANOVA) of model (16) are given in Table 6. Estimates of the sum of squared deviations, variance, F-test, and its asymptotic significance are determined for the factorial (intergroup) variance that arises under the influence of two significant factors.

Table 6

Results of the analysis of variance for regression model (16)

Type of dispersion	Sum of squares of deviations	Number of degrees of freedom	Mean square (estimate of variance)	F-criterion	p value
Total	1.0728	6	$1.7881 \cdot 10^{-1}$	–	–
Model	1.0071	2	$5.0355 \cdot 10^{-1}$	30.641	$3.7544 \cdot 10^{-3}$
Residual	$6.5736 \cdot 10^{-2}$	4	$1.6434 \cdot 10^{-2}$	–	–

The mathematical model (16) for the natural values of the factors is as follows

$$C^* = a_0 + a_1 P^* + a_2 \omega^*, \quad (17)$$

where the estimates of the model coefficients obtained taking into account dependencies (6), (7) are given in Table 7.

Table 7

Values of coefficients of regression models (17)–(20)

Model coefficient	Index k of coefficients			Model
	0	1	2	
a_k	4.7884	0.4964	−4.3610	(17)
a_{lk}	4.2225	0.4889	−3.9692	(18)
a_{hk}	5.1641	0.5056	−4.5685	(19)
a_{Lk}	4.4489	0.4919	−4.1259	(20)
a_{Rk}	5.0138	0.5019	−4.4855	

According to model (17), contour lines C^* were obtained, Fig. 8, which correspond to the rated level of the generator output voltage when changing the load power P^* and the rotor rotational frequency ω^*.

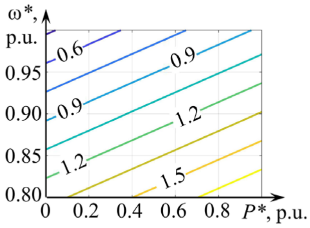

Fig. 8. Contour plot containing isolines of phase capacitance C^*, p.u., in coordinates P^*, p.u., and ω^*, p.u. according to model (17)

The dependences of the lower and upper limits of the allowable capacitance providing the generator output voltage, respectively, $U_{rl}^*=0.9U_r^*$ and $U_{rh}^*=1.1U_r^*$, on the values of the factors were estimated as a result of similar regression and variance analysis. The values of C_l^* and C_h^*, obtained as a result of experiments, were taken into account, Table 4. The corresponding mathematical models are as follows:

$$C_l^*=a_{l0}+a_{l1}P^*+a_{l2}\omega^*; \quad (18)$$

$$C_h^*=a_{h0}+a_{h1}P^*+a_{h2}\omega^*, \quad (19)$$

where the estimates of the model coefficients are given in Table 7.

Since the hypothesis regarding the null value of the model component describing the effect of linear interaction of factors was not rejected, a model was obtained from (13) where the coefficients were described by fuzzy intervals

$$\left[C_L^*;C_R^*\right]=\left[a_{L0};a_{R0}\right]+\left[a_{L1};a_{R1}\right]P^*+\left[a_{L2};a_{R2}\right]\omega^*. \quad (20)$$

The values of the boundaries of fuzzy intervals for the coefficients of such a model, obtained on the basis of the membership functions, Fig. 6, according to the dependencies (11), (12), are given in Table 7.

5. 3. Results of characteristics evaluation of the exciter capacitance adjustment range

Based on (20), the dependence of the boundaries of the fuzzy ranges, to which the exciter phase capacitance should belong to maintain the generator output voltage within permissible limits, on the factors was obtained, Fig. 9.

Based on (20), the dependence of the boundaries of the fuzzy ranges, to which the exciter phase capacitance should belong to maintain the generator output voltage within permissible limits, was obtained on the factors, Fig. 9.

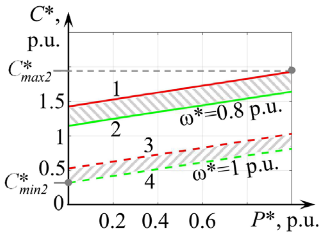

Fig. 9. Fuzzy ranges $\left[C_L^*;C_R^*\right]$ of change of permissible exciter phase capacitances when changing P^* for two levels ω^*: 1, 2 – limits C_R^*, C_L^* at $\omega^*=0.8$ p.u.; 3, 4 – limits C_R^*, C_L^* at $\omega^*=1$ p.u.

The values of the adjustment range limits calculated according to dependencies (14) and (15), Fig. 9, for a generator set of a given configuration are compared with the list of permissible capacitance values. For the lower limit, the nearest smaller standard value $C_{\min 2}^*=0.3222$ p.u. was selected, for the upper limit – the nearest larger value $C_{\max 2}^*=1.9329$ p.u. In this range, the exciter topology provides a change in capacitance at $M=408$ discrete levels, Fig. 10.

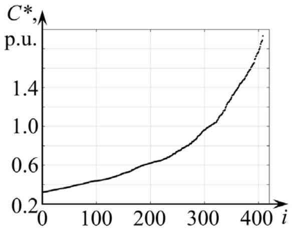

Fig. 10. Graph of possible levels of C^*, p.u., phase capacitance of the exciter in the adjustment range depending on the number i of the state

In the system of relative units, the limits of the range of change of the phase capacitance of the exciter are: $C_{\min 1}^*=0.2251$ p.u.; $C_{\max 1}^*=9.8499$ p.u. Condition (2) is fulfilled for such values, that is, the limits of the adjustment range belong to the range of change of the phase capacitance of the exciter.

According to dependence (1), the values of the relative steps of the exciter capacitance change were obtained, Fig. 11.

The empirical distribution function $F[\delta]$ of relative steps of capacitance change is shown in Fig. 12.

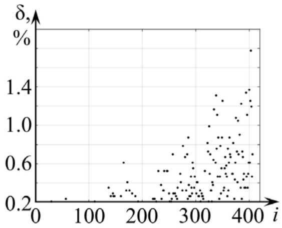

Fig. 11. Graph of relative steps δ, %, changes in exciter capacitance in the control range depending on the number i of the state

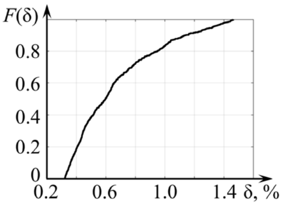

Fig. 12. Empirical function F of the distribution of relative steps δ, %, of the exciter capacitance change in the capacitance adjustment range

From the distribution function, it can be established that for the conditions of the numerical experiment $F(\delta_{\lim})=0.99$. At the limiting probability $P_{\lim}=0.9$, the relative step value is equal to $\delta'_{\lim}=1.45\%$.

6. Discussion of the results of assessment of maintenance allowable voltage possibility of induction generator

Analyzing the dependence of the generator output voltage on the phase capacitance of the exciter in the nominal mode,

Fig. 7, the following can be established. The self-excitation process of the generator of selected type begins at $C > 1$ mF. The rated output voltage level is achieved at a phase capacitance $C_r = 2.132$ mF. It is allowed to change the capacitance from $C_{rl} = 1.75$ mF (voltage is 0.9 p.u.) to $C_{rh} = 2.5$ mF (corresponds to a voltage of 1.1 p.u.). The dependence of voltage on capacitance at $1.3 < C < 3$ mF is practically linear and directly proportional. This is explained by the increase in the magnetic flux and, accordingly, the self-excitation electromotive force of the generator with a decrease in the capacitive reactance, i.e., an increase in the capacitive excitation current.

Analysis of the results of the full factorial experiment, Table 4, allows to establish a significant influence of the load power and rotational frequency on the required capacity value. The transition of the generator at $\omega^* = 0.8$ p.u. from idle mode to rated load (experiments No. 1, 2) requires an increase in capacitance by 0.5 p.u. to maintain the rated output voltage. A similar result occurs at $\omega^* = 1$ p.u. (experiments No. 3, 4). Increasing the rotational frequency from 0.8 p.u. to 1 p.u. in idle mode (experiments No. 1, 3) and at rated load (experiments No. 2, 4) requires a reduction in capacity by 0.9 p.u. From this, it is possible to establish a direct dependence of the required capacitance value on the load power and an inverse dependence on the rotational frequency. The interval of capacitance change, which provides a voltage within 0.9...1.1 p.u., at $\omega^* = 0.8$ p.u. is about 0.47 p.u., and at $\omega^* = 1$ p.u. – about 0.35 p.u. That is, the width of such an interval decreases with increasing rotational frequency. The estimation of the values of the mathematical model (10) coefficients was carried out by regression analysis, Table 5. The values of the coefficient of determination of 0.939 and the adjusted coefficient of determination of 0.878 indicate that the regression is sufficiently accurate. For the coefficient b_{12}, the asymptotic significance of 0.924 significantly exceeds the significance level $\alpha = 0.05$. According to the Student's t-test, this indicates that the component $b_{12}x_1x_2$ of model (10) is insignificant. That is, the linear interaction of factors does not have a significant impact on the objective function. Excluding the insignificant component allows to obtain an adjusted model (16), which reflects the independent influence of factors on the objective function. The results of the analysis of variance of the regression model (16), Table 6, allow to establish the following. The model variance (1.0071) makes a significant contribution to the total variance (1.0728). The significant influence of the studied factors on the objective function is confirmed by the insignificant value of the asymptotic significance of the factor variance $p = 3.7544 \cdot 10^{-3}$ compared to the significance level $\alpha = 0.05$. The degree of influence of each factor on the objective function can be established based on the interpretation of model (16). The coefficient $b_1 > 0$, Table 5, therefore, with increasing load power, the required capacitance value increases. Since $b_2 < 0$, increasing the rotational frequency leads to a decrease in the required capacitance value. Comparing the absolute values of the coefficients, can be established that $|b_2|$ exceeds $|b_1|$ by almost two times. This determines the predominance of the influence of the rotational frequency, compared to the influence of the load power, on the required capacitance value. Similar relationships are preserved when transitioning to models (17), (18), (19) in the full-scale values of factors for voltage levels, respectively, 1 p.u., 0.9 p.u., 1.1 p.u., Table 7. The C^* contours in Fig. 8 are plotted for the rated voltage level and are a practical means of establishing the required excitation capacitance under given generator operating conditions. The use of the fuzzy number apparatus made it possible to estimate the values of the coefficients of the model (20), Table 7. The width of the fuzzy interval of the coefficient at P^* is 0.01, for the coefficient at ω^* – 0.36. This indicates an increase in the uncertainty of establishing the value of the required capacity with increasing rotational frequency.

The width of the fuzzy ranges of changes in the phase capacitances of the exciter, Fig. 9, does not significantly depend on P^* but changes significantly when ω^* changes. In particular, at $\omega^* = 0.8$ p.u. the width of the fuzzy range is 0.275 p.u., and at $\omega^* = 1$ p.u. – 0.205 p.u. The estimated width of the adjustment range of 1.6107 p.u. is divided into 408 levels. The average step of changing the capacitance is $3.95 \cdot 10^{-3}$ p.u. The exciter circuit allows to adjust the capacitance within the adjustment range according to the monotonic rising characteristic, Fig. 10. There is a tendency for the spread of regulation steps to increase with raising capacity, Fig. 11. In particular, at $C^* < 0.6$ p.u. ($i < 200$) step $\delta < 0.4\%$. At $0.6 < C^* < 1.0$ p.u. the step $\delta < 0.8\%$, and at $C^* > 1.0$ p.u. the capacity changes with a step $\delta < 1.4\%$. This is explained by the switching of capacitors of larger unit capacitance in the exciter circuit. The distribution of step sizes is described by an increasing nonlinear function, Fig. 12. From this graph, it can be established that criterion (3) is met, since $F(\delta_{lim}) = 0.99 > P_{\text{lim}}$. In addition, at the limiting probability $P_{\text{lim}} = 0.9$, the step does not exceed 1.45%. This value is significantly less than the specified value $\delta_{\text{lim}} = 2\%$. Therefore, there are no grounds for rejecting the main research hypothesis. From this it can be established that it is possible to maintain the generator output voltage within the limits permitted by EN 50160 using a capacitor exciter with a variable topology.

Unlike [7], in this study the generator rotor rotational frequency is considered as an independent factor determined by the operating conditions of the primary turbine. This approach corresponds to the operating conditions of a wind turbine with an automatic transmission. Compared to the study [9], the proposed model allows determining the required capacitance value when reducing the load power and rotational frequency, and not only for rated conditions. Unlike work [13], this study found that the influence of the linear interaction of factors on the required capacity value is insignificant.

The advantages of the proposed approach to increasing the efficiency of the operation of an induction generator include the use of a discrete capacitance control circuit, a characteristic feature of which is the possibility of using parallel, series, and mixed connections of capacitors. Due to this, with a relatively small number of capacitors (6 per phase in the circuit adopted for the study), it was possible to obtain several hundred steps of capacitance regulation (518 in the case under consideration). The exciter capacitance value estimated by the proposed mathematical model can be provided by such a capacitor circuit with a relative error of no more than 1.45% with a probability of 0.9. That is, the formulated problem is solved by identifying the relationship between the required exciter capacitance, on the one hand, and the rotation frequency and load power, on the other hand. Also, by using a capacitor circuit, the topology of which can be changed, implementing different ways of connecting capacitors. That is, the formulated problem is solved by identifying the relationship between the required exciter capacitance and the rotation frequency and load power and using a capacitor circuit, the topology of which can be changed by implementing different ways of connecting capacitors.

The obtained results can be applied in the design of a system for automatic stabilization of the output voltage of an autonomous induction generator using a capacitor exciter with a variable topology.

The limitations of the proposed approach include the choice of a rather narrow range of rotational frequency changes – from 0.8 p.u. to 1 p.u. During operation of a wind power plant, the generator rotor rotational frequency can vary within much wider limits. However, the estimates of the required capacitance obtained in the work are limited and cannot be extrapolated to a wider range of ω. Separate studies are required to evaluate the generator's performance over a wider range of rotational frequency.

The disadvantages of the proposed approach to maintaining the permissible voltage of an induction generator include the discreteness of the excitation current regulation. Stepped switching of capacitors causes transients, accompanied by overvoltages, in the stator winding of the generator. This reduces the insulation resource. Overcoming this drawback requires the development of a multi-stage switching algorithm with control of overvoltage values.

In the course of further study, it is advisable to conduct laboratory studies of the functioning of an induction generator equipped with a capacitor exciter with a variable topology. This will allow to verify the adequacy of the modeling results with empirical data.

7. Conclusions

1. The rated capacitance of the exciter of an induction generator with a capacity of 2.3 MW in the nominal operating mode is estimated at 2.132 mF. Changing the capacitance from 1.75 mF to 2.5 mF ensures that the voltage is in the permissible range of ±10% of the rated level. The linear nature of the dependence of the generator voltage on the capacitance is established. This is explained by the increase in the magnetic flux and, accordingly, the electromotive force of the generator's self-excitation with a decrease in the capacitive resistance, i.e., an increase in the capacitive excitation current.

2. It has been established that the load power and the generator rotor rotational frequency have a significant impact on the capacity value that provides the permissible output voltage. The impact of such factors is mutually independent. The dependence of the required capacity value on the load power is direct (the coefficient of the linear regression model is 0.4964), and on the frequency – inverse (−4.3610). The frequency has a more significant impact on the required capacity value than the load power. This is explained by the decrease in mechanical power supplied to the generator as the speed decreases.

3. As the rotational frequency increases, the RL-boundaries of the fuzzy interval for estimating the required capacity increase. For a 2.3 MW generator, the width of the capacity adjustment range is 1.6107 p.u. The exciter circuit provides a change in capacity at 408 levels. For the adopted limiting probability of 0.9, the step size of the capacity change does not exceed 1.45%, which is significantly less than the adopted limiting step of 2%. This confirms the main hypothesis of the study about the possibility of maintaining the output voltage within the permissible, according to EN 50160, limits when changing the load power and rotational frequency.

Adjusting the exciter capacitance by using a capacitor circuit, the topology of which can be changed by implementing different ways of connecting capacitors, distinguishes the proposed approach from analogues. The problem of insufficient efficiency of the functioning of an induction generator with self-excitation, in terms of fluctuations in the output voltage, was solved by identifying the regularity of the outflow of external factors and precise regulation of the excitation current.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contribution

Sviatoslav Vasylets: conceptualization, supervision, writing – review & editing; **Kateryna Vasylets**: data curation, formal analysis, validation; **Antonii Zaluzhnyi**: methodology, resources; **Volodymyr Ilchuk**: funding acquisition, investigation, writing – original draft; **Vladyslav Hlushchuk**: project administration, software, visualization.

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