TRANSNAV
http://www.transnav.eu

the International Journal
on Marine Navigation
and Safety of Sea Transportation

Volume 18
Number 3
September 2024

DOI: 10.12716/1001.18.03.24

Discrete Laws of Capacitor Control of Asynchronous Generator Voltage

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ABSTRACT: In this article, the authors analysed the voltage stabilization system of an electrical installation with an asynchronous generator and capacitor excitation. The properties and tuning parameters of the discrete-pulse switching laws of three-phase sections of excitation capacitors of an asynchronous generator are considered. The analysis is carried out and recommendations for the use of the described digital controllers are given.

1 INTRODUCTION

The efficiency of the ship's power plant depends on the rational use of energy for the movement of the vessel and the provision of internal needs. The main source of energy at present is natural fuel, the price of which is significant. The composition and structure of the ship's power plant are optimized by the developers for the most efficient and complete use of the expended fuel resources [1, 2].

The use of various types of fuel, the disintegration of the power of the ship's power plant, effective control of energy flows has led to the emergence of multi-generator power plants with various types of drive engines (diesel generators, shaft generators, turbo generators) and alternators (synchronous, asynchronous, with permanent magnets), [3].

Obviously, it is possible to combine all types of energy used on a ship by converting it into electricity, which has led to the widespread use of ships with electric propulsion [4].

Different characteristics of drive motors and many power plants operating in parallel in the traditional use of synchronous generators on ships creates problems with the stability of multi-generator power plants, [5]. The rigid geometric connection of the magnetic flux of a synchronous generator with its excitation winding increases the oscillatory properties of the system of power plants operating in parallel.

An alternative solution to the problem of increasing the stability of multi-generator ship power plants can be the wider use of asynchronous generators (AG) with a squirrel-cage rotor.

The advantages of asynchronous generators are widely known [6, 7]. The AG has smaller dimensions and weight, the design of the squirrel-cage generator rotor is simpler, there are no rotating windings, sliding contacts and semiconductor elements, there is no current insulation on the rotor, which increases the limiting heating temperature and ensures high limiting rotor speeds. The high efficiency of the generator due to the low value of the active resistance of the rotor ensures its higher economical characteristics. The AG has a sinusoidal shape of the curve of the generated voltage, as well as the symmetry of the three-phase voltage with uneven load distribution.

The small time constant of the generator leakage circuits, the rapid decay of inrush currents and short circuit currents ensures the safety of short circuits for the generator. Regulation of the AG excitation through the stator circuit makes it possible to create high-speed and invariant voltage stabilization systems. Simplicity and safety of switching to parallel operation, absence of rotor oscillations with significant load changes ensure the stability of parallel operation in multi-generator power plants.

Such significant advantages explain the interest in the developments of asynchronous generator sets.

Scientific and technical problems that hinder the widespread use of capacitor-excited asynchronous short-circuit generators in ship electrical installations can be grouped into the following areas.

1. Excitation of the AG with additional reactive power.
2. Choice of optimal design parameters of an asynchronous machine operating in a generator mode.
3. Creation of a controlled source of reactive power with good technical and economic indicators.
4. Efficient control of a ship AG electrical installation modes.

2 ANALYSIS OF DISCRETE CONTROL LAWS FOR THREE-PHASE SECTIONS OF AG EXCITATION CAPACITORS

This article discusses technical solutions for the third problem: an analysis of several discrete control laws for three-phase sections of AG excitation capacitors is carried out. The authors of the article consider the further development of the previously described controller [8, 9], which implements the integral discrete-pulse law of voltage stabilization of the AG with capacitor excitation.

The diagram of a capacitor control device with N three-phase sections of capacitors C_0,C_1-C_N in a ship electrical installation is shown in Fig. 1. Stabilization of the AG voltage when the AG load or the drive engine (DE) speed changes is performed by connecting capacitor sections in appropriate combinations. The switching of capacitors is carried out by thyristor switches depending on the deviation of the generator voltage U_g from the set value U_0: $\Delta U=U_0-U_g$.

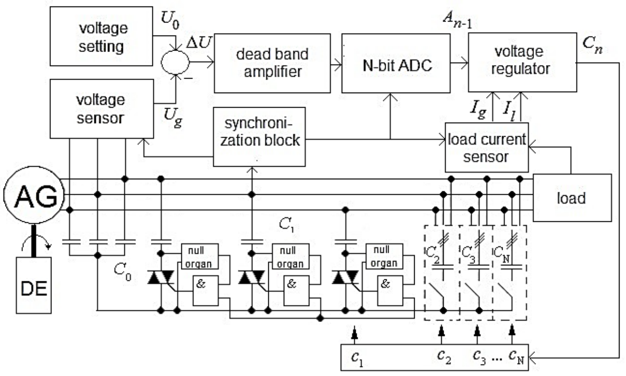

Figure 1. AG electrical installation with a discrete capacitor voltage stabilization system: DE – drive engine, AG - asynchronous generator

The AG excitation current is generated by the connected capacitor sections. The initial excitation of the generator is provided from a permanently connected block of capacitors when the generator is rotated by the drive motor. The capacitance value of the permanently connected block of capacitors provides the specified voltage of the AG at idle at the rated rotation speed of the drive motor.

In this circuit, the sampling value of the control action corresponds to the minimum capacitance of the capacitors $\Delta C=C_1$, which is the level quantization interval. The level quantization interval ΔC is determined by the accuracy of generator voltage regulation at a constant current frequency.

The number of discrete values of the connected capacitance n depends on the choice of individual capacitor sections capacitances.

The minimum number of discrete value levels that differ in the quantization interval ΔC will be minimal if the section capacitances are the same. The maximum number of discrete levels is achieved if the ratio of the capacitor sections capacitances is determined by the weights of the digits of the binary number system:

$$C_1 : C_2 : C_3 ... C_N = 1:2:4...2^N ; N \le n \le 2^N$$

The capacitor device shown in Fig. 1 is discrete not only in terms of level, but also in time, i.e. is impulsive. It belongs to the class of digital automatic control systems with a limited number of bits N. The quantization of the control signal in time is due to the physical properties of capacitors and the technical characteristics of semiconductor switches.

Uncoordinated capacitors inclusion leads to their overcharging by pulsed currents, which can lead to breakdown of switching elements and significant electromagnetic interference. Therefore, the capacitors inclusion in AC circuits is carried out when the voltage on the key is zero, Fig. 1. The capacitor disconnection from the network occurs when the current through the capacitor stops. Because the capacitance current leads the voltage by a quarter of a period, so the capacitor is disconnected from the network at its maximum charge.

The agreed switching times of the capacitors in each phase do not coincide in time. Therefore, the switching control period of a three-phase capacitor section takes at least half of one period of the AC network. Otherwise, bump less switching will become impossible.

The average value of the generator three-phase voltage U_g is measured by a voltage sensor during each period of the generated current, [10]. At the end of the measurement period, the voltage U_g is compared with the set voltage U_0. To eliminate voltage modulation caused by switching sections of capacitors, a dead zone is introduced into the system U_z.

If this difference $|\Delta U|=|U_g-U_0| > U_{zis}$ outside the set dead zone U_z, then the deviation from it is converted into an N-bit binary number A_n depending on the voltage U_{ud}, which determines the discreteness of the voltage deviation (controller sensitivity) by level:

$$A_n = Round\left\{\left(\left|\Delta U\right| - U_z\right) / U_{ud}\right\}. \quad (1)$$

If the generator voltage is in the dead zone $U_0 - U_z \le U_g \le U_0 + U_z$, then the number A_n is zero.

The discrete number A_n (1) is proportional to the voltage deviation in the n-th period. A control binary number C_n is used to control the number of capacitor sections connected. Each digit c_i of the binary control number C_n controls the corresponding switches that switch one of the three-phase capacitor banks. If, c_i=1 then the switches connect the i-th block of capacitors to the stator windings of the generator, and if c_i=0, then the switches disconnect the i-th block of capacitors.

Depending on the use of numbers A_n and C_n it is possible to realize several discrete laws of AG voltage control. Comparing their effectiveness is the purpose of this article.

In works [8, 9], an integral discrete-pulse control law is described, in which the binary number C_{n+1}, which controls the switching of capacitor sections in each current period $n + 1$, is determined by the sum of binary numbers in the previous control period n:

$$C_{n+1} = C_n + A_n \quad (2)$$

Transient processes in an electrical installation with a system of discrete capacitor voltage stabilization AG were studied on computer and physical models created by the authors [9].

Let us consider the form of the main transient processes and the influence of the tuning parameters of a discrete-pulse voltage regulator on the dynamic characteristics of an installation with an AG (the main parameters of AG are presented in relative units: $R_s = 0.03$; $R_r = 0.18$; $L_s = 0.0173$; $L_r = 0.11$; $L_{mo} = 3.3$
)

On Fig. 2 shows the dynamic processes of current, voltage, capacitance, and frequency in relative units in an asynchronous electrical installation when 50% of the active-inductive load is turned on with $cos\varphi$=0.8 . Here, in the four-digit integral voltage regulator (2), the dead zone U_z=±0.05 and the discreteness level U_{ud}=0.01 of the regulator are set. The voltage enters the dead zone, and the stabilization process ends in a quarter of a second.

The tuning parameters of the integrated discrete-pulse controller are the number of discharges and the number of switched sections of capacitors N, the dead zone U_z and the controller sensitivity U_{ud}. The capacitance C_1 switched by the first digit of the control number C_n must be matched to the dead band U_z.

On Fig. 3 shows the processes of voltage regulation when the generator load is turned on with different levels of the regulator discreteness (sensitivity) U_{ud}.

The controller sensitivity U_{ud} significantly affects the response rate to voltage deviation and reduces the transient process time to 0.1 ... 0.2 seconds. When U_{ud}<0.005 the system loses its stability.

The voltage stabilization accuracy in the system is set by the value of the dead zone U_z. On Fig. 2 and Fig. 3 U_z=±0.05, so the stabilization accuracy is ±5%. Doubling the static stabilization accuracy requires halving the capacitance of the least significant bit and increasing the number of bits and capacitor sections per unit. This significantly increases the cost of the regulator.

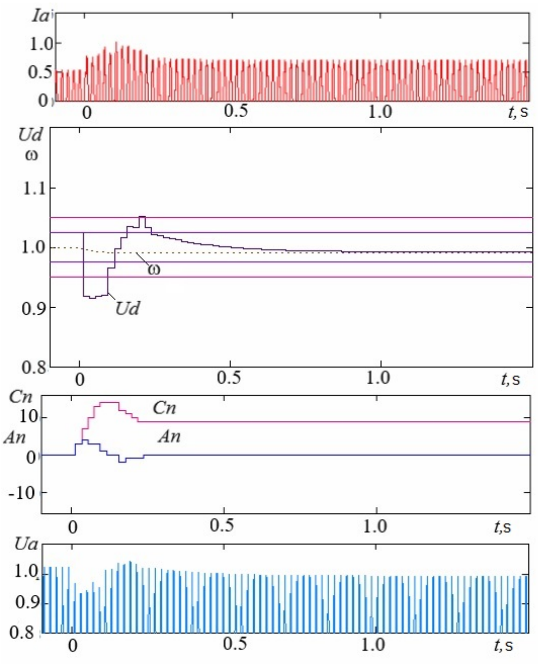

Figure 2. Switching on 50% resistive-inductive load with cos(φ)=0.8: I_a - generator phase current; U_d - voltage sensor output; ω - drive engine frequency rotation; C_n - the number that controls the capacity; A_n - capacity addition; U_g - generator phase voltage

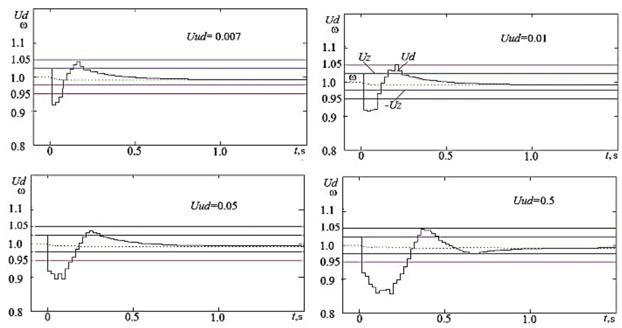

Figure 3. Switching on 50% active-inductive load with cos(φ)=0.8 at different levels of controller sensitivity U_{ud}=0.007...0.5

If the change in the generator voltage with an increase in the excitation capacitance by the value of the least significant bit C_1 is greater than the dead zone, then self-oscillations occur in the system relative to the dead zone ±U_z, Fig. 4.

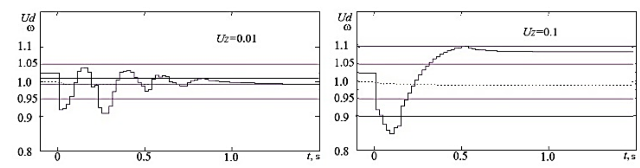

Figure 4. Decreasing and increasing the dead zone of the controller U_z

On Fig. 5 shows the dynamic processes of voltage establishment for various switched loads in a system with an integral control law $C_{n+1}=C_n+A_n$.

The dynamic deviation when switching 25% of the load is 6...7%, when switching 50% the deviation is approximately 10...12%, and at 75...100% - about 14...16%. The time for the AG voltage to enter the dead zone does not exceed 0.3 seconds.

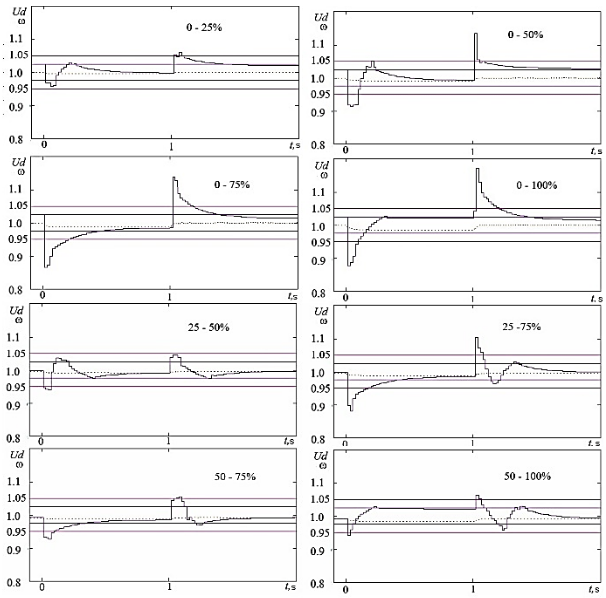

Figure 5. Switching of various active-inductive loads with cos(φ)=0.8 in a system with an integral control law $C_{n+1}=C_n+A_n$

The moment of switching the load is random, and the control is synchronized with the network. The difference of these moments Δt lies within the network period: $\Delta t=0\ldots T_0$. The voltage transient depends on Δt, Fig. 6.

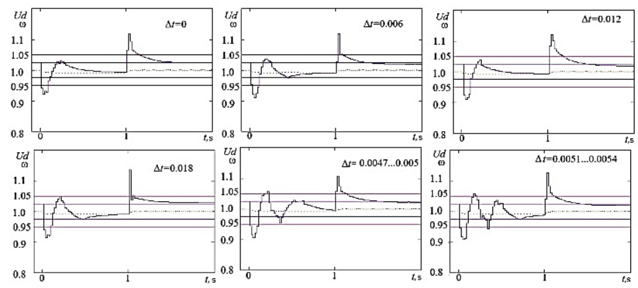

Figure 6. The moment offset of applying the perturbation

The difference in the regulation processes manifests itself in the unsaturated section of the AG iron magnetization curve, i.e. when the load is turned on and the voltage is reduced. The oscillations number can be from one to three.

The desire to speed up the stabilization process when switching large loads and voltage dips leads to forcing control by a non-linear increase in the addition of capacitors, i.e. numbers A_n in the control law (2). The acceleration of the stabilization process with forcing is shown in Fig. 7. Here in the four-digit controller A_n=8 with ΔU<-4U_{ud} and A_n=12 with ΔU<-6U_{ud}.

The rate of the perturbation change is considered by introducing a derivative into the control law. In the discrete case, the rate of deviation ΔU change can be considered by introducing the deviation difference on adjacent control cycles into the law, for example:

$$C_{n+1} = C_n + 2A_n - A_{n-1} \tag{3}$$

The law (3) implements the integration and differentiation of the voltage deviation. The switching processes of the active-inductive load of the AG with control (3) are shown in Fig. 8.

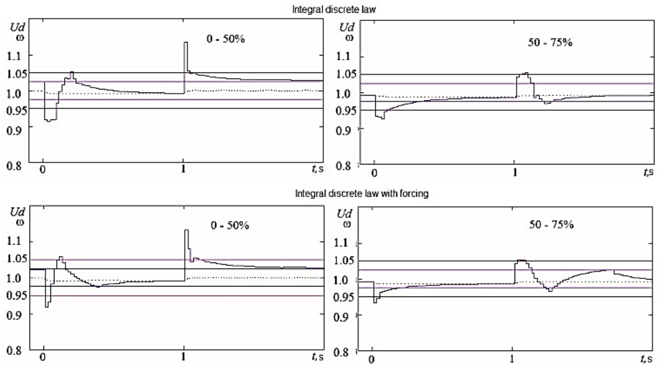

Figure 7. Forcing control

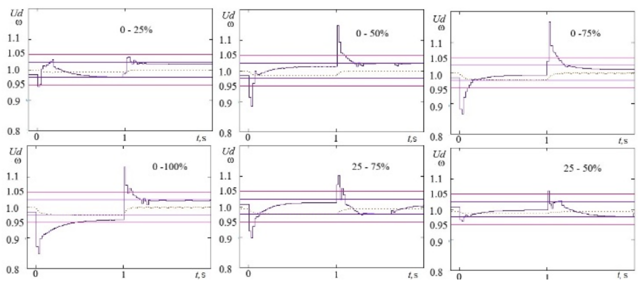

Figure 8. Digital integral-differential control law $C_{n+1}=C_n+2A_n-A_{n-1}$

Comparison of switching processes of 75% active-inductive load using control laws (2) and (3) is shown in Fig. 9.

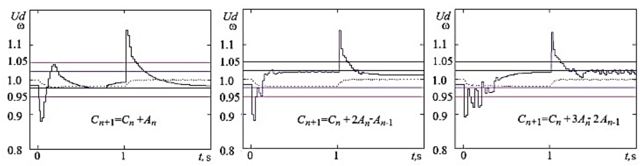

Figure 9. Comparison of discrete control laws (2) and (3)

An increase in the differential component in the law $C_{n+1}=C_n+3A_n-2A_{n-1}$ leads to unacceptable oscillation of the transient process, Fig. 9.

The application of the combined control principle based on the deviation of the controlled parameter (voltage) and perturbation (load) requires an additional measurement of the load current during one voltage period T_0, Fig. 1. The effect of active I_g and inductive I_l load current on the generator voltage U_g is different. A resistive load causes the armature to react, while an inductive load demagnetizes the generator. Therefore, separate measurement of active and reactive load is necessary.

The combined voltage control law of the generator has the form:

$$C_{n+1} = C_n + A_n + \mathrm{Round}\left\{K_g\left(I_{gn} - I_{g(n-1)}\right)\right\} + \mathrm{Round}\left\{K_l\left(I_{ln} - I_{l(n-1)}\right)\right\} \quad (4)$$

where K_g, K_l-adjustment coefficients for active and reactive current.

Comparison of the switching processes on the load of the AG with control by deviation and with the combined control law is shown in Fig. 10.

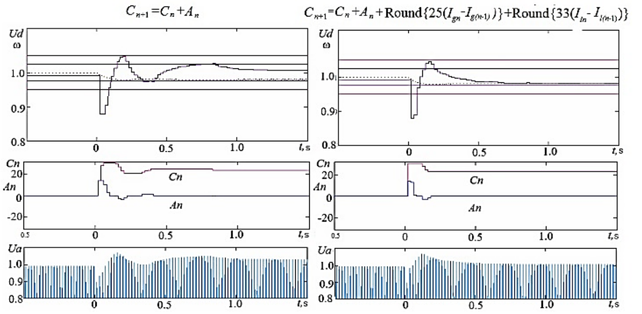

Figure 10. Integral and combined control law. Switching on 75% active-inductive load with cos(φ)=0.8

The complication of the control law by considering the switched load slightly improved the dynamic properties of the system.

3 CONCLUSIONS

1. The discrete-pulse law (2) implements the integral control of the generator voltage deviation. The correct choice of its tuning parameters provides the requirements of regulatory documents for the dynamic properties of the ship's electric power plant (voltage dip less than 15%, transient duration less than 0.5 sec.), [11].
2. When choosing the tuning parameters of the voltage regulator, it is necessary to analyse the processes with possible changes in the load (Fig. 5, Fig. 8) and shifts in the moments of its switching (Fig. 6). Digital integration of the sensor signal of a three-phase circuit and the formation of a synchronizing pulse allows you to optimize the ratio of the analogue and digital parts of the sensor according to the ease of implementation criterion.
3. Improving the dynamic properties of the AG voltage stabilization system with the control law (2) is achieved by introducing excitation forcing at large deviations (Fig. 7) and control by the deviation change rate (3), (Fig. 8 and Fig. 9). The complication of the implementation of these changes to the law (2) is insignificant and does not require additional equipment.
4. The implementation of the combined principle of control by deviation and disturbance (4) does not lead to significant improvements in the dynamic properties of the stabilization system (Fig. 10), but requires additional measurements and controller settings.

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