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Self-Excitation System for Synchronous Generator

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***Abstract* – Self-excitation for synchronous generator is described in the paper. The system is based on a buck converter input filter capacitor discharge through excitation winding of the generator. The buck converter is connected to the stator outputs through an uncontrollable diode rectifier, but excitation winding is used as a load. Input filter capacitor of the converter provides initial current pulse which magnetizes excitation system and produces the generator voltage increase, for this reason the capacitor is charged before self-excitation process starts.**

Results of the computer simulation and physical experiment are obtained and presented. These results show that the proposed self-excitation converter in conjunction with an input capacitor pre-charged from a low-power electronic generator actually magnetizes the generator excitation system therefore generator voltage and accordingly excitation current increases. Stabilization of generator output voltage occurs with a voltage surge, though its peak value slightly exceeds the reference one.

The future investigation of the proposed self-excitation system may include definition of mathematical equations which describe transients in the generator's self-excitation mode and development of control methods for purpose of self-excitation process control without voltage peaks. The computer model also should be improved.

***Keywords* – Wind energy generation, AC machines, generators, converters, power transistors.**

I. Introduction

Possibility to utilize the centralized power supply in some regions can be limited to technical or economic aspects, therefore autonomous power supply systems is a topical research point. In conditions of possible natural disasters the centralized power supply can be broken. In this case in some isolated area generation of the electric energy can be realized only by means of local autonomous system.

Many technological processes demand an uninterrupted power supply, and the autonomous system will allow satisfying these requirements in case of network shutdown. Thus, the autonomous power supply system has to have capability to operate with connection to the centralized power grid as well as in independent operation mode.

From the political point of view any energetically dependent country excites possibility of the country-supplier to influence economic and political processes in the dependent country. Autonomous power supply systems can bring the significant contribution to increase the state power independence.

Wind turbines occupy one of the central places among the autonomous power supply systems. Their development can give new possibilities in the utilization of renewable energy sources with the goal to reduce emission of the fossil fuel burning products in the atmosphere, having increased the share of alternative sources in state power industry. In recent years the attention is paid to electric machines which are widely applied in wind turbines – doubly-fed induction generators and permanent magnet synchronous generators.

The project „Wind and Hydrogen Based Autonomous Energy Supply System" within possibility of use of the double fed induction generator [1-3] in the autonomous power supply system's wind turbine was investigated. This type of generators are popular for large wind turbines, since the power electronic converter consumes only 30% of the generator output power, but they have some disadvantages, regarding the construction features [4], and also low generator residual magnetism, which is insufficient to create voltage from the cold start, therefore the use of this type of generators in autonomous power supply system without connection to the power grid is inefficient [5]. It was offered to use combined excitation system which includes electromagnetic excitation and a thin layer of permanent magnets built into the slots of excitation winding. This solution can increase the remanent electromotive force, but it is necessary to make mechanical modernization of the machine, which is an expensive action.

Permanent magnet synchronous generator provides high efficiency and high installed power factor, it may be slightly cheaper [4], but its output voltage is unstable and depends on the rotational speed. The cold start is possible, but there are some disadvantages related to excitation system [6, 7]. Permanent magnets are expensive, excitation is fixed and uncontrollable. Operating temperatures inside the generator must be limited in order to retain magnetic properties, because demagnetization of permanent magnet material is possible.

For the mentioned project the decision to use the double fed induction generator in synchronous generator with independent excitation mode was made.

Unlike the generator with permanent magnets, machine with independent excitation can be controlled. This is especially useful at changeable and sometimes too high wind force. If the generator speed is too high for normal operation the reduction of excitation current value prevents an excess of admissible output voltage level.

Use of the accumulator battery for excitation of generator applied in the mentioned project is irrational, because excitation current value can reach 20 A. For this reason the capacitor activated self-excitation system of synchronous generator was developed [8, 9]. The synchronous generator self-excitation systems described in [10-13] have a lot of disadvantages as, for example, complexity in production and low level of residual magnetism. The capacitor activated self-excitation system was developed to allow self-excitation without generator rebuilding, but the testing of the system showed that it has its own disadvantages which interfere with its use.

First, operation of a control system depends on the form of generator output voltage. It is quite difficult to adapt system for measurement of voltage frequency in the real machine in which non sinusoidal form or distortions are inherent.

Secondly, using this system the excitation current has a pulsing character as in the scheme the current smoothing with filter was not provided.

For these reasons a scheme with the buck topology DC/DC converter was applied for self-excitation of the synchronous generator [14, 15]. The feature of this scheme is the charging of the converter input filter capacitor before the start of system operation. Charged capacitor provides the necessary current pulse to start self-excitation process. In this case generator mechanical modernization is not required, but self-excitation system also allows control of the generator output voltage.

II. Scheme and Operation of the System

A. Functional Scheme of the Self-Excitation System

Unlike the scheme of capacitor activated self-excitation system of synchronous generator with independent excitation described in [8], in scheme (Fig. 1.) with buck converter [14] the excitation winding is connected as a load of buck converter with an input filter and one switching element instead of three thyristors, which were used in the previous configuration [8].

The uncontrollable rectifier consisting of diodes VD1…3 is connected to stator phase outputs. The rectified current is filtered by the capacitor C1 and controlled by the transistor VT1. For a discharge of the excitation winding L_f the parallel diode VD4 is used. The resistor R1 is used to decrease excitation current and as sequence field weakening in case of a system stop to prevent filter capacitor voltage from sharp increase. In a normal operating mode the resistor R1 is shunted by the transistor VT2.

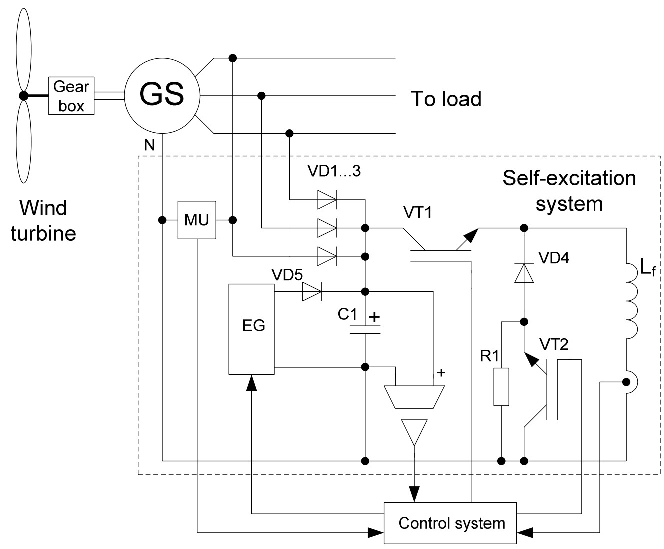

Fig. 1. Self-excitation system with buck converter.

B. Operation of the System

At low speed the remanent electromotive force of the generator is low, but its frequency can be measured by measurement unit (MU) of the self-excitation system [8, 14], thus the generator speed is defined. Self-excitation process can be provided only when generator speed is at proper level [8, 14].

To start self-excitation process the initial current impulse is required [8]. For this purpose at first filter capacitor is charged by a low-power electronic generator (EG). The electronic generator needs an energy source, but in the general scheme of the autonomous power supply system described in the above-mentioned project an accumulator battery is used for the supply of a control system and the electronic generator.

When generator rotation speed is sufficient for normal operation, the control system switches transistor VT1 on. A closed circuit: the charged capacitor C1 – switch VT1 – excitation winding L_f is formed. As a result of a capacitor discharge there is a current pulse which magnetizes excitation system therefore voltage of the generator increases [8]. Further the capacitor C1 is used as the input filter of the converter.

The transistor VT1 is switched with high frequency, thus the duty ratio is selected to provide necessary excitation current. The main task of the control system is generator output voltage regulation provided that excitation current should not exceed some preset value.

In a normal operating mode the transistor VT2 is permanently in on condition, shunting the resistor R1. In this case excitation current flows through VT2 and diode VD4. In case of current value gradual reduction with the subsequent stop of system, the field weakening is not required, but if operation of the system is interrupted suddenly, the current is circulating in the contour: excitation winding – transistor VT2 – diode VD4, causes sharp C1 voltage increase. To avoid it, in this case VT2 is switched off and excitation winding energy dissipates in the resistor R1.

C. Self-Excitation Process

The self-excitation system equivalent scheme [14] can be presented as a series connection of inductances and resistances of windings and voltage source of dependent on circuit's current electromotive force (Fig. 2).

Self-excitation process comprises two stages. During first one previously charged capacitor is discharged through excitation winding L_f. In the applied generator the excitation winding parameters are L_f = 17 mH and R_f = 2 Ω.

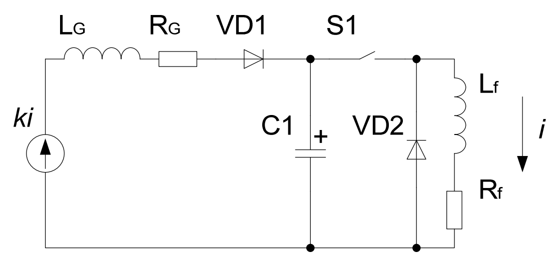

Fig. 2. The self-excitation system equivalent scheme.

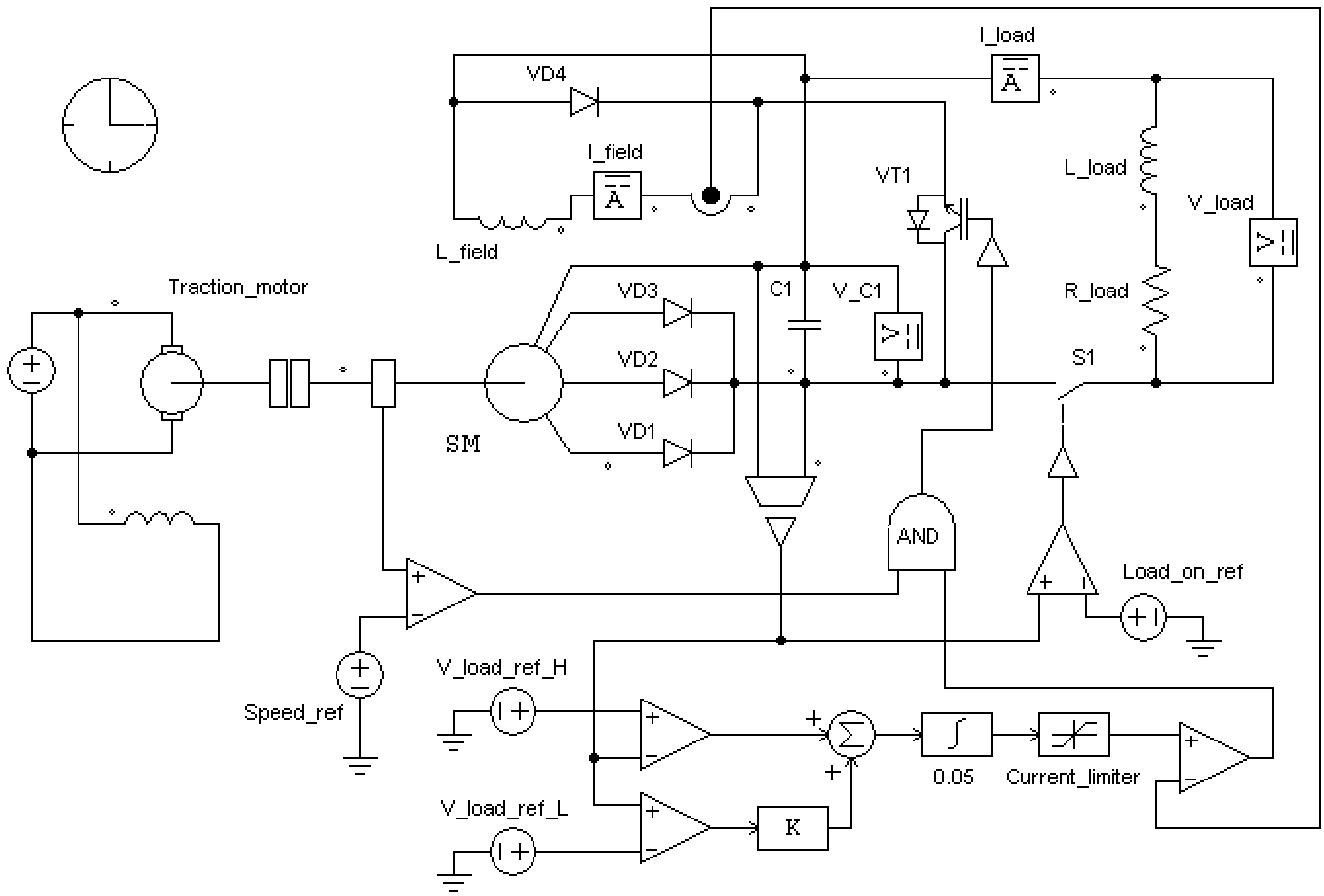

Fig. 3. PSIM model of the synchronous generator self-excitation system.

This stage depends on circuit parameters and capacitor C1 initial voltage U_{C1}:

$$L_f \cdot \frac{di}{dt} + \frac{1}{C_1} \cdot \int idt - U_{C1} = 0, \tag{1}$$

where C_1 is capacity of capacitor C1.

At the second stage the capacitor is used as filter and further self-excitation depends on rise of electromotive force connected with rise of current. The scheme can be described as

$$(L_G + L_f) \cdot \frac{di}{dt} + i \cdot (R_G + R_f - k) + \frac{1}{C_1} \cdot \int idt = 0. \tag{2}$$

The process will be developing only if $k > (R_G+R_f)$. Indicator k characterizes connection between the equivalent electromotive force of generator and current in excitation winding and it depends on rotation speed of generator.

III. SYSTEM'S COMPUTER SIMULATION

A. PSIM Model

Computer simulation of self-excitation process can be realized in PSIM (Fig. 3.). The self-excitation converter and RL load is connected to the generator phases through three-phase half-wave diode rectifier and the neutral wire. A simple control system the task of which is to stabilize load voltage between two nearby located values (*V_load_ref_H* and *V_load_ref_L*) is used. It is necessary to pay attention to relatively high value of integration constant in the control system. Its value strongly influences a form of excitation current and was selected experimentally. Current limiter limits the excitation current, as it can be seen in Fig. 4. The source *Speed_ref* set generator speed at which self-excitation process must be started, the source *Load_on_ref* set the voltage at which the load is turned on by switch S1.

The process will be developing only if $k > (R_G+R_f)$. Indicator k characterizes connection of the equivalent electromotive force of generator with current in excitation winding and depends on rotation speed of generator.

B. Simulation Results

Simulation diagrams are shown in Fig. 4. and Fig. 5. At 0.08 s when generator speed reaches reference speed value the capacitor C1 starts discharging. As a result the excitation system magnetizes and generator voltage increases.

The excitation current raises until the generator voltage reaches the preset value considering excitation current limit.

At 0.7 s when generator voltage is relatively close to the preset value the switch S1 is turned on and RL load is connected to the generator through the mentioned rectifier. Of course, in real conditions sharp load connection is not favorable, but in this simulation load current peaks did not arise.

In this computer model parameters of the generator are approximated to those of the real machine used in physical experiment but more precise calculations are required. The available model quite precisely describes the process of self-excitation realized in the previous experiments [8].

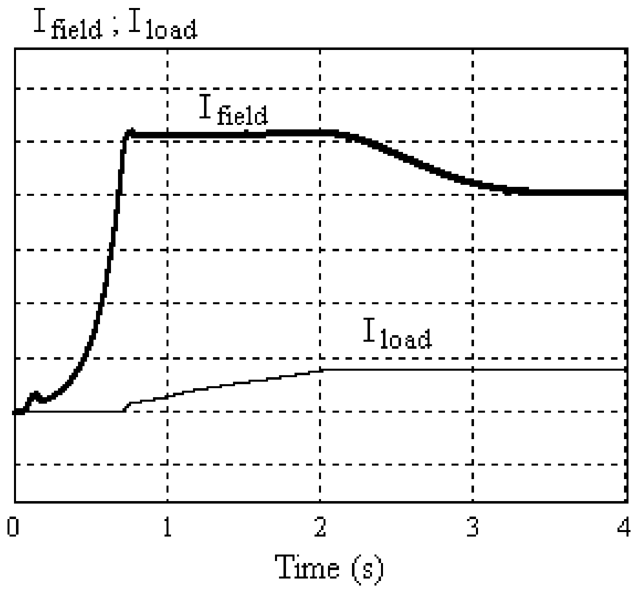

Fig. 4. Currents in excitation winding (I_{field}) and load circuit (I_{load}).

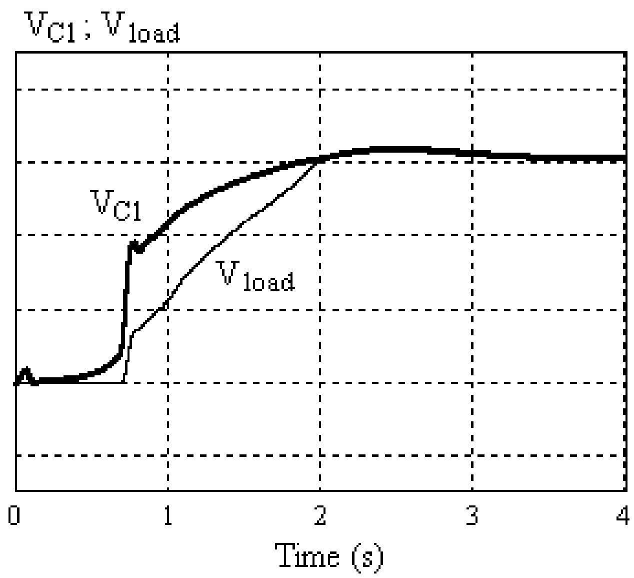

Fig. 5. Capacitor C1 and load voltages.

IV. Experimental Results

A. Experimental Set-Up

Self-excitation system was applied to double fed induction generator working as synchronous generator with independent excitation winding [14].

Experimental scheme is shown in Fig. 6. The generator is mechanically coupled to the AC motor driven by frequency converter. The control unit of the self-excitation system is connected to a 24 VDC power supply which simulates an accumulator battery of the autonomous power supply system mentioned above.

Main parameters of the generator are: stator winding resistance 2 Ω; stator winding inductance 100 mH; excitation winding resistance 2 Ω; excitation winding inductance 17 mH.

The experimental equipment, excepting motor and generator, is shown in Fig. 7.

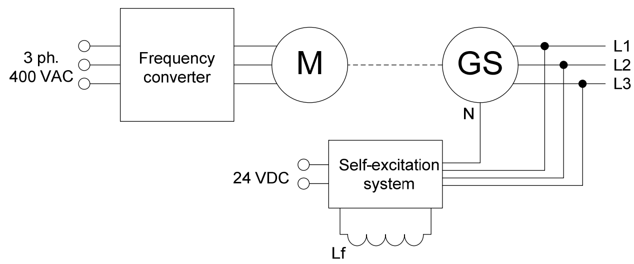

Fig. 6. Experimental scheme.

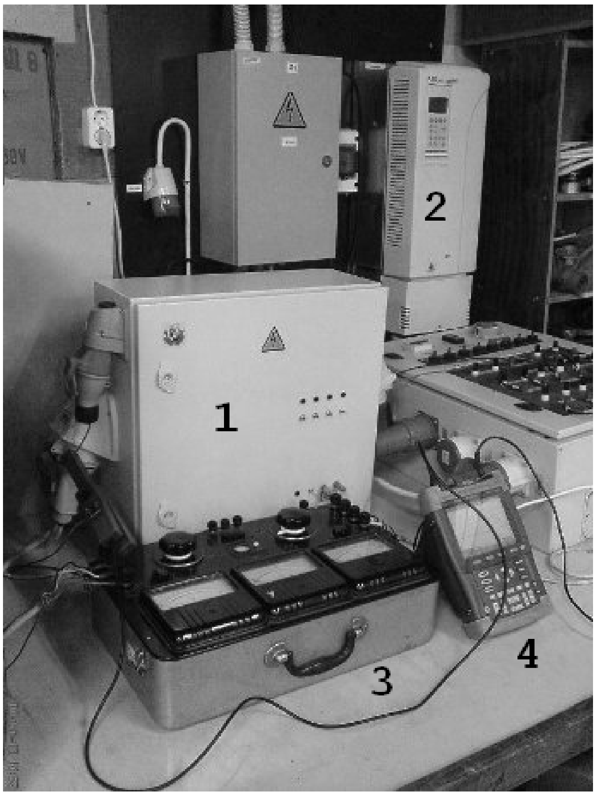

Fig. 7. Experimental set-up: 1 – self-excitation system; 2 – frequency converter; 3 – measurement devices; 4 – oscilloscope.

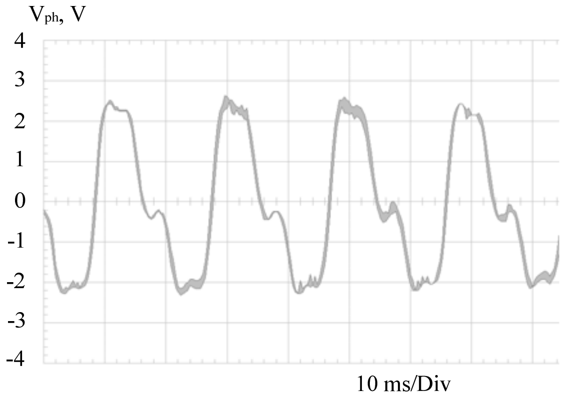

Fig. 8. Generator's phase voltage diagram at 120 rpm without excitation.

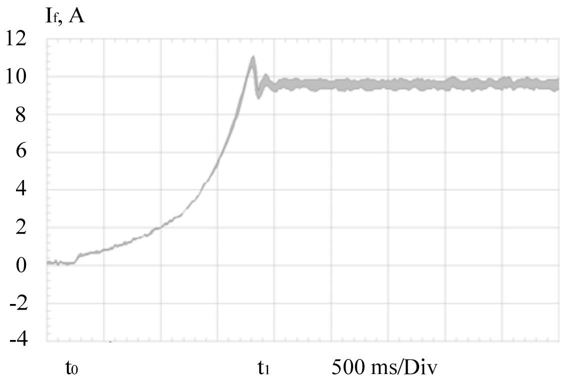

Fig. 9. Excitation current I_f of the generator during the self-excitation process.

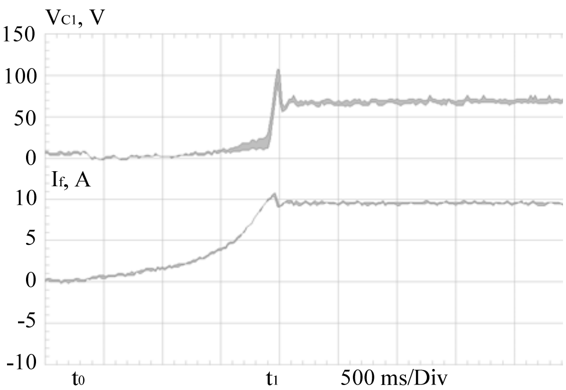

Fig. 10. Voltage V_{C1} on the self-excitation converter input and generator's excitation current If during the self-excitation process.

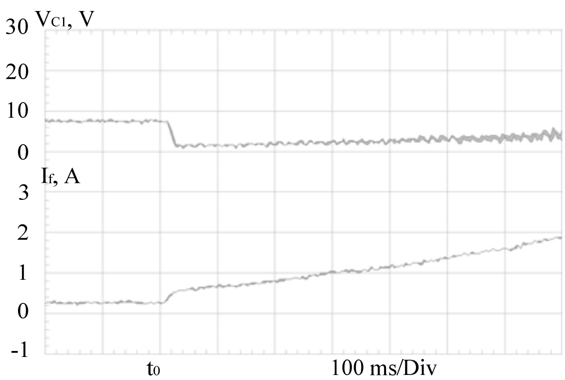

Fig. 11. Capacitor C1 discharge.

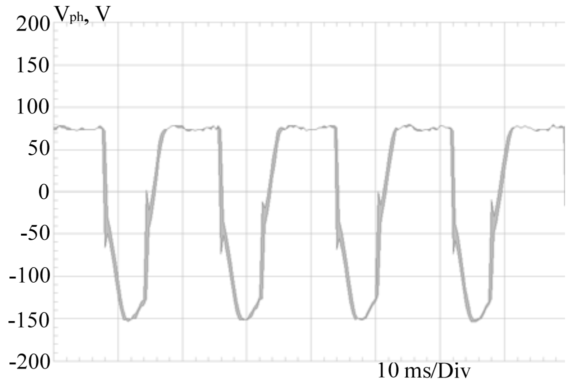

Fig. 12. Generator output voltage.

As it was stated above the remanent electromotive force of the generator is low (Fig. 8.), but its frequency can be measured by the measurement unit.

In the experimental generator, the self-excitation process can successfully proceed at minimum speed 120 rpm corresponding to frequency 52 Hz. The experiment described in this paper was executed at generator speed 130 rpm (56.4 Hz).

B. Experimental Results

The behavior of the generator with self-excitation system is described by experimental diagrams, which confirm the validity of computer simulation. Fig. 9 displays changes of the generator's excitation current I_f since the process beginning until the state of an operating mode with a constant excitation current and constant generator output voltage.

At time moment t_0, when capacitor C1 is charged and generator speed is on necessary level, C1 discharging begins. When the capacitor is discharged, excitation current increases less promptly. At time moment t_1, when voltage reaches maximum preset value, the control system maintains the current within acceptable limits for the purpose of output voltage stabilization.

Fig. 10 demonstrates that capacitor C1 voltage V_{C1} and, respectively, the generator output voltage at the beginning of the self-excitation process increases not so quickly as excitation current but then the surge occurs. In this experiment the control system first of all had to limit excitation current therefore such a power surge was possible. In its turn the excitation current reaches the preset value (9.5 A) rather smoothly.

In Fig. 11 the time moment of a previously charged capacitor C1 discharge is shown. It results in surging of the excitation current I_f (at time moment t_0) which in its turn magnetizes the excitation winding and thus causes the increase in voltage V_{C1}.

Fig. 12 represents generator phase voltage V_{ph} in the stationary operating mode.

The curve of the generator phase voltage is not an ideal sine-wave form because of the influence of higher harmonics, noise of measurement and the 10 kHz filter of the oscilloscope. Influence of higher harmonics is also noticeable in Fig. 8.

V. CONCLUSIONS

The self-excitation system of synchronous generator with independent excitation is realized by the connection of an excitation winding to three stator phase outputs through three-phase uncontrolled diode rectifier, buck converter and neutral wire of the generator.

The computer model of the system is made. The prototype of self-excitation converter is created and simulation results are confirmed by practical experiment. In experiments the double fed induction generator working in synchronous generator with independent excitation mode was used.

Experimental results show that the previously charged from low-power electronic generator input capacitor of the self-excitation converter provides initial current pulse which magnetizes the generator excitation system therefore the generator voltage and accordingly excitation current are increasing. Stabilization of generator output voltage does not happen smoothly but with a voltage surge, though its peak value (100 V) exceeds the preset value only by 30 V, as it is shown in Fig. 10.

The future work includes definition of mathematical equations which describe transients in the generator's self-excitation mode and development of control methods for purpose of self-excitation process control without voltage peaks. The computer model must be improved.

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