ЕЛЕКТРОЕНЕРГЕТИЧНІ ТА ЕЛЕКТРОМЕХАНІЧНІ СИСТЕМИ

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AN INFLUENCE OF A CURRENT COMPOUNDING ON THE BEHAVIOR OF A SYNCHRONOUS GENERATOR WITH A BRUSHLESS EXCITATION SYSTEM DURING A TERMINAL-VOLTAGE VARIATION

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Brushless excitation systems of synchronous generators provide non-contact transfer of the excitation power to the generator rotor in case absence of a commutation in rotor circuit. Such systems have a long response time of terminal-voltage regulation caused by the additional rotating machine (exciter). Using of fast-acting compound circuit allows improving dynamic parameters of terminal-voltage regulation in modes of sharp voltage variation and short circuit in line.

The brushless excitation system of synchronous generator with current-compound circuit implements a combined approach of the terminal-voltage regulation. A disturbance-compensating control is realized by compound circuit with the current source and error-closing control provides by automatic voltage regulator with the voltage source. In other side, there's a currents' redistribution of the brushless excitation system with current-compound circuit in different modes of synchronous generator. The excitation-current increment is not equal to the compound-current increment because the changing the voltage-source current. It's caused by mutual influences between the voltage source and the current source (compound circuit). The compound current is proportional to the stator current of the synchronous generator.

The influence of the compound circuit is essential in modes of the sharp changes of generator variables. To analyze this effect, the paper investigates the modes of the 10 % terminal-voltage reducing and three-phase short-circuit in line. These researches have obtained for different ratio of current transformers by mathematical modeling method. The influence of the compound-circuit parameters (transformer ratio of current transformer) on the system characteristics and the stability of the generator is analyzed. Therefore, the static error of the voltage regulation is reduced by increasing the coefficient of the compound circuit in the terminal-voltage reducing mode. The reducing the the coefficient of the current-compound circuit can lead to the synchronism loss of a synchronous generator in three-phase short-circuit modes, depending on the distance of the short-circuit point from the generator and the value of the terminal-voltage drop.

Key words: synchronous generator; brushless excitation system; current compounding.

Introduction

Excitation systems of synchronous generators (SG) provide terminal-voltage and reactive-power regulation as wall as stability of SG work in power system [1, 2]. Static excitation systems are mainly used, in which the excitation current of the generator is regulated by a controlled rectifier (a thyristor converter). Electromachine excitation systems with exciters are used for the excitation of power synchronous generators. One type of electromachine excitation systems is brushless excitation system, which provides non-contact transfer of the excitation power from exciter to the generator rotor in case absence of a commutation in rotor circuit. Using the exciter in field circuit of generator decreases response time of excitation regulation and requires additional action for its increasing. It should be note, that it requires rapid response time of the excitation regulation in modes of the sharp change of generator variables. Such modes are modes of the voltage drop and the short circuit in line. So, analyze of the compound-circuit influence on the dynamic characteristics of the generator with brushless excitation system is actual task.

Analysis of the recent research

Excitation systems of synchronous generators realize an error-closing control and combined approach of terminal-voltage regulation: a disturbance-compensating control and the error-closing control. The feature of the excitation system with combined approach of voltage regulation is rapid response time of excitation regulation in transitional and emergency modes [3].

The excitation systems of SG with compound circuit implements a combined approach of the terminal-voltage regulation. A disturbance-compensating control is realized by compound circuit and error-closing control provides by automatic voltage regulator. There are two types of excitation systems of SG with compound circuit: current-compounding [1–3] and phase compounding [5, 6].

Controlled rectifiers (thyristor converters) are used for the excitation regulation in current-compound excitation system. The field current of SG is function of the voltage-source current (controlled rectifier) and current of the current source (compound circuit). There’s a currents’ redistribution in the excitation system [7, 8].

The using the compound excitation system of SG improves voltage-regulation quality under sharp load variation and short circuit on SG terminals [9].

The compound-circuit influence on the characteristics of the brushless excitation system under terminal voltage variation and short circuit in a line is not sufficiently investigated.

Research objectives

The research aim is an analyze of the influence of the compound-circuit parameters on the electromagnetic process in SG under sharp terminal-voltage variation, which is caused by the voltage drop and short circuit in line, and also on the dynamic of the field-current regulation.

Presentation of the main material

Electrical power system with SG and brushless excitation system with current compounding consist of two synchronous machines: turbogenerator G and exciter E (Fig. 1). The field current of generator is algebraic sum of voltage-source current (output of the non-controller rectifier 1) and current of current source (compound current). Compound circuit is realized by current transformers (Power CT) and non-controlled rectifier 2.

There are two types of excitation systems: self excitation and independent excitation. In the first case, input voltage of transformer PT is terminal voltage of the generator. In the second case, it’s used independent voltage source for excitation (for example, auxiliaries grid).

The error-closing control provides by automatic voltage regulator, which includes field voltage and current regulation loops. This regulator is described in [8].

There’s a currents’ redistribution in brushless excitation system of SG in different modes of SG (Fig. 2). It’s caused by the mutual influence of the voltage source and current source.

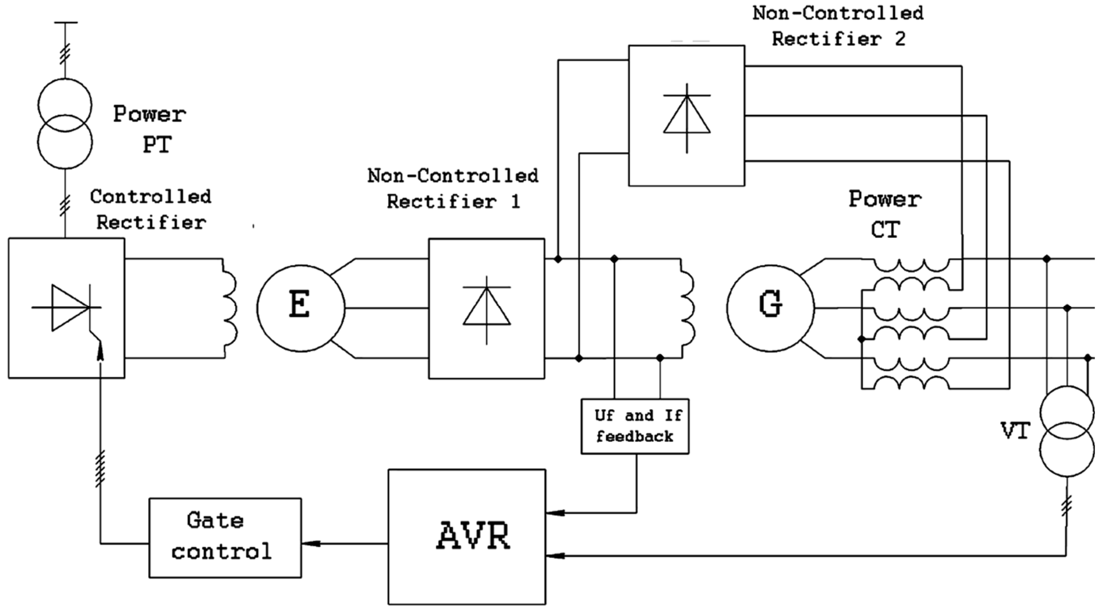


Fig. 1. Brushless excitation system of SG with current compounding

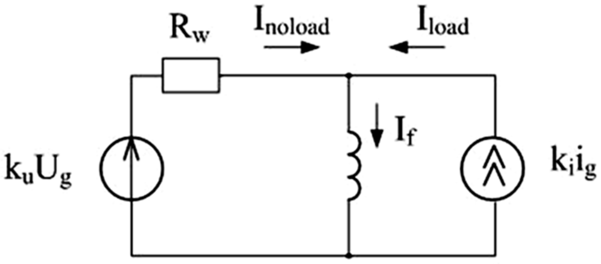


Fig. 2. Equivalent circuit of self-excitation system of SG with current compounding

According to the equivalent circuit of excitation system of SG with current compounding (Fig. 2) [7] an increment of the field current ΔI_f and voltage-source current ΔI_{noload} in steady-state mode are defined by the following equations:

$$\Delta I_f = \frac{\dfrac{k_u \Delta U_g}{R_w} + k_i \cdot \Delta I_g}{(1 + \dfrac{R_f}{R_w})}, \tag{1}$$

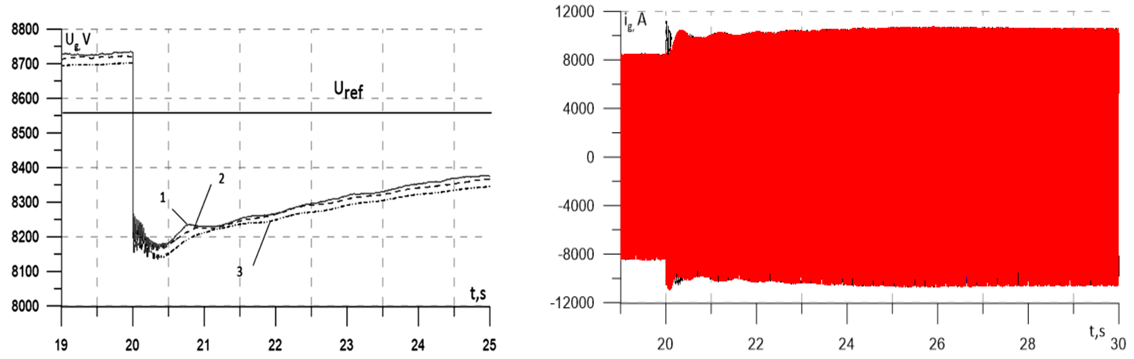
$$\Delta I_{noload} = \frac{\dfrac{k_u \Delta U_g}{R_f} - k_i \Delta I_g}{(1 + \dfrac{R_w}{R_f})}, \tag{2}$$

where $\Delta I_{load} = k_i \Delta I_g$ – the increment of the current-source current (compound current); k_i – coefficient, which takes into account transformer ratio of current transformer and coefficient of the non-controlled rectifier 2; ΔU_g – the terminal-voltage increment; ΔI_g – the stator-current increment; k_u – coefficient, which takes into account transformer ratio of voltage transformer and coefficient of the non-controlled rectifier 1; R_f – resistance of the excitation winding; R_w – internal resistance of excitation voltage source of SG.

From the equation (2) it follows that the influence of the stator current increment ΔI_g on the excitation current I_f depends on the internal resistance of the excitation voltage source. The increasing of internal resistance R_w will lead to decreasing the current drop at the output of the voltage source ΔI_{noload} and increase the excitation current of the synchronous generator. Thus, in order to increase the influence of the compound circuit on the value of the excitation current, it is necessary to increase the internal resistance of excitation voltage source.

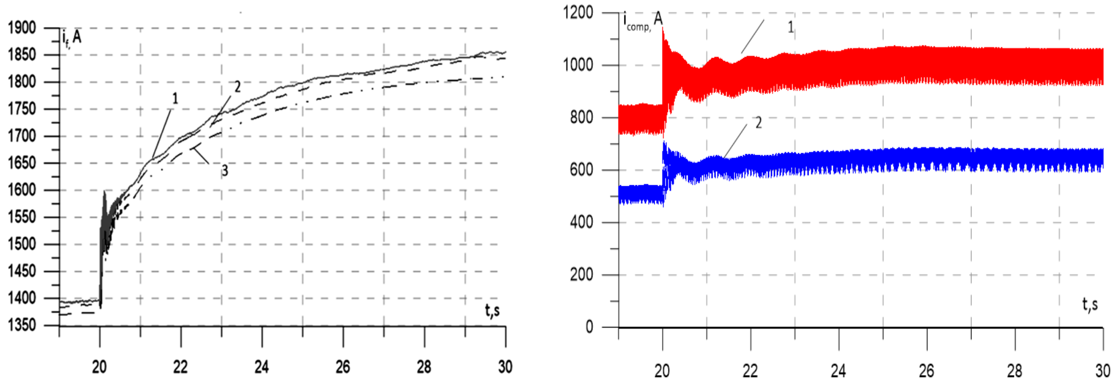
The mathematical model of SG with brushless excitation system and current compounding is used for the investigation of electromagnetic and electromechanical processes. This model is based on the theory of mathematical modeling of electromechanical systems [10] and object-oriented method [11] and widely described in [9, 12]. The features of the model are taking into consideration the nonlinearity of semiconductor converters and synchronous machines. Each gate of semiconductor converters is represented by a branch with resistance and inductance, the values of which are determined by the state of the gate. This allows us to investigate the waveform of voltages and currents in the excitation system. The adequacy of the mathematical model has been proofed in [9] by matching of simulation and physical experiment results, which are obtained on physical model. In particular, the standard deviation between the results of mathematical modeling and physical experiment was 11 % [9]. Parameters of SG: P_n =100 MW, U_n = 10.5 kV, I_n = 6875 A, I_f = 1715 A.

Research results of 10 % terminal-voltage drop (on 20 s) are shown on Fig. 3–4. The stator-current increase (Fig. 3, *a*) provides to additional increase of the field current (Fig. 4, *a*) because of compound-current increase (Fig. 4, *b*). It cases increase of terminal voltage and decrease of the terminal-voltage dynamic error (Fig. 3, *a*).



a *b*

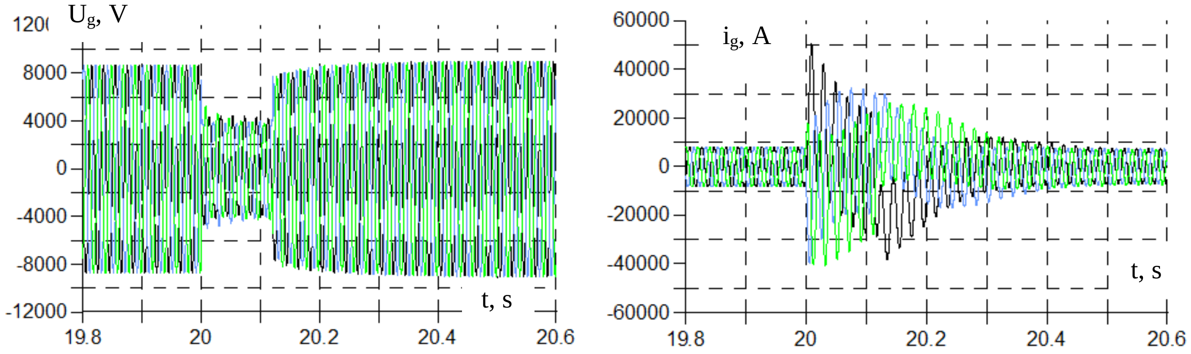
Fig. 3. Phase-voltage amplitude envelope (a) and stator current (b) of SG by 10 % terminal-voltage drop for k_i=0.1 (curve 1), k_i=0.064 (curve 2), k_i=0 (curve 3, without compound circuit)



a *b*

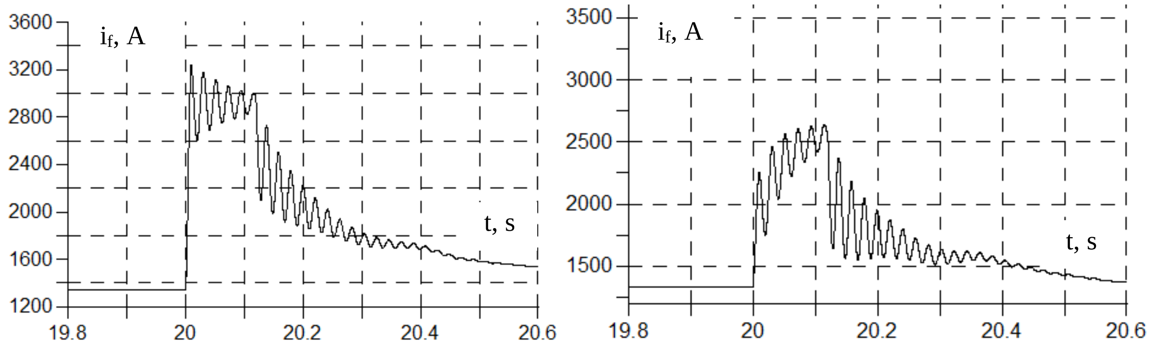
Fig. 4. Field current of SG (a) and compound current (b) of SG by 10 % terminal-voltage drop for k_i=0.1 (curve 1), k_i=0.064 (curve 2), k_i=0 (curve 3, without compound circuit)

Research results of electromagnetic processes for three-phase short circuit in power line are shown on Fig. 5–8. The short circuit begins on 20 s and continues 0.12 s. The value of the terminal voltage decreasing is defined by the distance of the short-circuit point from generator, power line parameters, and is equal 50 % (Fig. 5, *a*). There's increase of the stator current under short circuit. The stator current has fading aperiodic component in transitional mode (Fig. 5, *b*). It must be high-speed excitation forcing for the generator-stability providing in this mode. According to Fig. 6 and Fig. 7 compound circuit has the essential influence on dynamic of the field-current variation and allows increasing the forcing value of field-current by 37 %. The compound-coefficient decreasing reduces compound current and forcing property of the excitation system (Fig. 6, *b*, Fig.7, *b*). The SG losses synchronisms for dedicate parameters of the short circuit in case absence of compound circuit as results are shown. Thus, compound circuit increases the stability of SG under short circuit in line.



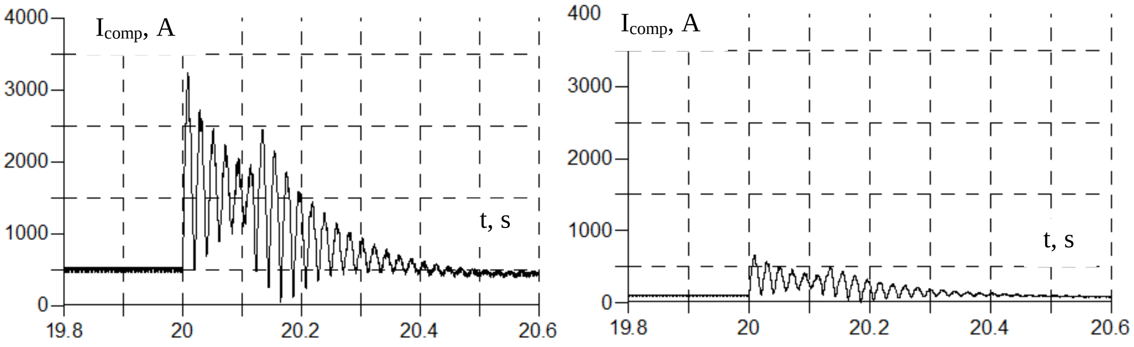
a *b*

Fig. 5. Phase stator voltage (a) and stator current (b) of SG under three-phase short circuit in power line



a *b*

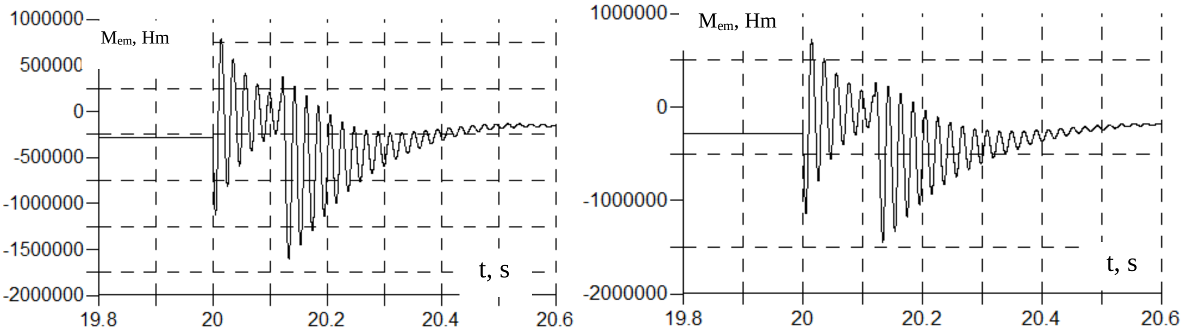
Fig. 6. Field current of SG under three-phase short circuit in power line for k_i=0.064 (a) and k_i=0.013(b)



a *b*

Fig. 7. Compound current under three-phase short circuit in power line for k_i=0.064 (a) and k_i=0.013(b)

The aperiodic component of stator current causes essential pulsation of the field current and electromagnetic torque of SG (Fig. 8). The peak value of electromagnetic torque is 300 % of nominal value, that has negative influence on turbine. It should be note, that compound circuit increases the excitation forcing. It provides to a slight increase (about 5 %) in the throw of the electromagnetic moment.



a *b*

Fig. 8. Electromagnetic torque of SG under three-phase short circuit in power line for k_i=0.064 (a) and k_i=0.013(b)

Conclusions

1. The compound circuit in brushless excitation system of SG has essential influence on forcing property of excitation system by increasing the performance of excitation regulation and the multiplicity of the excitation-current forcing in the modes of a sharp variation of the terminal voltage. Due to this, the dynamic error of terminal-voltage regulation is slightly reduced in mode of the terminal-voltage decrease.

2. The greatest influence of the compound circuit is felt in the case of a significant voltage variation under three-phase short circuit in the network. This effect allows, in particular, to increase by 37 % the excitation-current forcing in case 50 % voltage terminal-voltage decrease, that increases the stability of SG in the power network. The action of the current-compound circuit is decisive for the excitation forcing in the self-excitation system, because the forcing action of the automatic excitation regulator is limited in such system due to the reduction of the thyristor-converter input voltage.

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ВПЛИВ СТРУМОВОГО КОМПАУНДУВАННЯ НА ПОВЕДІНКУ СИНХРОННОГО ГЕНЕРАТОРА З БЕЗЩІТКОВОЮ СИСТЕМОЮ ЗБУДЖЕННЯ ПІД ЧАС ЗМІНИ НАПРУГИ МЕРЕЖІ

Безконтактні (безщіткові) системи збудження синхронних генераторів забезпечують безконтактне передавання потужності збудження на ротор турбогенератора за відсутності комутації в роторному колі. Такі системи інерційні з погляду регулювання напруги, оскільки містять додатковий збудник. Введення швидкодіючого контуру компаундування дає змогу покращити динамічні показники регулювання напруги турбогенератора в режимах різкої зміни напруги та в режимах короткого замикання в лінії.

Безщіткова система збудження синхронного генератора зі струмовим компаундуванням реалізує комбінований спосіб регулювання напруги. Регулювання за збуренням здійснює контур компаундування, а за відхиленням – система регулювання з автоматичним регулятором збудження. З іншого боку, в безщітковій системі збудження з контуром струмового компаундування спостерігається перерозподіл струмів системи збудження в різних режимах роботи синхронного генератора. Тобто приріст струму збудження генератора не дорівнює приросту струму компаундування, оскільки змінюється струм джерела напруги. Це спричинено взаємними впливами між джерелом напруги (випрямлячем) та джерелом струму (контуром компаундування), струм якого є пропорційним до струму статора синхронного генератора.

Досліджено режими 10 % зменшення напруги мережі та режим трифазного короткого замикання в лінії для різних коефіцієнтів трансформації трансформаторів струму кола компаундування методом математичного моделювання. Адекватність моделі підтверджено експериментальними результатами, які отримані на фізичній моделі. Крім того, проаналізовано вплив параметрів контуру компаундування на характеристики системи. Зокрема, статична похибка регулювання напруги зменшується зі збільшенням коефіцієнта контуру компаундування у режимі зменшення напруги. Також зменшення дії контуру струмового компаундування може призвести до випадання із синхронізму синхронного генератора в режимі трифазного короткого замикання в лінії.

Ключові слова: синхронний генератор; безщіткова система збудження; струмове компаундування.