THE OPERATION OF THE EXCITATION AND VOLTAGE CONTROL SYSTEM OF A SYNCHRONOUS GENERATOR IN ASYMMETRICAL STATES

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1. INTRODUCTION

Traditionally, the excitation voltage of static models of thyristor excitation and control systems is described with an equation of the external characteristics of an excitation rectifier with the use of mean values. This method is applied in system analysis. The voltage regulator is selected from the standard IEEE models or custom-designed to meet the goal of the research. The input signals of the voltage regulator, such as currents, voltages and powers are derived directly from the generator model and do not account for the problems related to measurements, digital processing and imperfection of the algorithms adopted for determination of useful current, voltage and power signals. The synchronous generator model is by default the Park model, which includes the components of rotation, but no components of transformation. As a consequence, there are only aperiodic components in the excitation current during disturbances, and no oscillation components are present. The models of the grid infrastructure elements are described with the values for compliant components. These models of excitation and voltage regulation systems, and of the EPS, are tested, widely used and they have proven to be useful in the investigation of symmetrical states, including symmetrical faults. The calculations of this type are completed quickly even in the case of large EPSs. However, these models are not useful in the investigation of states with various asymmetrical disturbances. Building a model that enables analyses of asymmetrical states incurs numerous difficulties and significantly increases the time of calculations.

Simulation research environment

The simulation research uses the Matlab-Simulink environment. The developed model is in the class of the so-called rigid systems. On one hand, the time constants of a synchronous generator amount to seconds, while on the other, the processes related to the modelling of an excitation rectifiers require integration counted in tenths of microseconds. In many points of the model, it is necessary to cyclically determine precise times of zero crossing of voltages or to sample signals with defined frequencies. Another complication is that it is necessary to achieve a steady state prior to the introduction of disturbances to the model and repeatedly calculate from the same initial state. All of these problems are solved, while the average calculation time for one second of the simulation process requires approximately two minutes of real time.

Abstract

This paper concerns the analysis of performance of static thyristor excitation and voltage regulation control systems of a high-power synchronous generator in asymmetrical operating states. Presented results were obtained from the model that reflects instantaneous processes both in the grid and in the excitation and voltage control system. The model of the synchronous generator includes the components of transformation. The rectifier model is based on a detailed thyristor model in the circuit of three-phase six-pulse thyristor converter, instead of simplified block model with defined external characteristics, as it is usual. It enables to monitor instantaneous values of rectifier voltages. The input signals for the voltage regulator model are not derived from the generator model the control system model includes digital measurement units of generator signals. The described model enables precise analysis of a synchronous generator with an excitation and voltage control system during disturbances and asymmetric operation in the grid. Such modelling is essential for analysis of novel solutions of excitation systems with digital controllers. This kind of analysis is not feasible using simplified models based on mean signals values and external characteristics of excitation systems.
2. DESCRIPTION OF THE MODEL FOR ASYMMETRICAL STATES

The basic elements of the model of a synchronous generator with a static thyristor excitation and voltage control system for asymmetrical states are presented in Fig. 1.

Fig. 1. The model of the generator with the excitation and voltage control system used in the investigation of asymmetrical states (legend: G – generator, TB – power unit transformer, WT, WS – circuit breakers, LINIA – substitute transmission line, TW – excitation transformer, PR – excitation rectifier, ZP – controlled current source, REG – voltage regulator, UWT – thyristor tripping system, A, B – locations of investigated faults)

2.1. Models of grid infrastructure elements

The basic structure of the model is the high-power generator which cooperates through the power unit transformer and the supplementary transmission line to feed power to a rigid grid. It is a three-phase model with explicit representation of the three phases. The generator model uses the Park model, which accounts for the components of rotation and transformation. The generator works with the isolated neutral point, which is a typical solution [1].

The model of the substitute transmission line is presented in Fig. 2. The model includes the grid impedance parameters for the compliant and zero components.

Fig. 2. The model of the substitute transmission line for asymmetrical states

The parameters of the line are defined by these dependences:

\[ R_s = \frac{2R_1 + R_0}{3} \quad (2.1) \]
\[ L_s = \frac{2L_1 + L_0}{3} \quad (2.2) \]
\[ R_m = \frac{R_0 - R_1}{3} \quad (2.3) \]
\[ L_m = \frac{L_0 - L_1}{3} \quad (2.4) \]
\[ C_p = C_1 \quad (2.5) \]
\[ C_g = \frac{3C_1 C_0}{C_1 - C_0} \quad (2.6) \]

The power unit transformer adopts the Ynd11 group with the earthed star point.
2.2. Excitation system model

In the investigated model, both the rectifier (PR) and the tripping system (UWT) are modelled to represent with a high accuracy the phenomena which actually occur. The rectifier is the model of a six-pulse converter controlled by the pulses from the tripping system. The output voltage of the rectifier, after adaptation of the units, is fed to the input which corresponds to the excitation voltage in the generator model. The converter is loaded by a current source the output current of which corresponds to the excitation current of the generator. The current source is controlled by the excitation current received from the synchronous generator model. The converter is powered from the excitation transformer which has the Yd connection group. The transformer impedance is responsible for the switching processes of the converter. The rectifier supply voltage is used in the basic variant of the model to synchronise the tripping pulses for the thyristors. Another variant is also investigated, in which the pulses are synchronised with the signal from the generator voltage transformers.

2.3. Voltage regulator model

The regulating system model included the primary voltage regulating loop at the generator terminals, the system stabiliser with the signal from the active power and the current compensation stage. The regulation limiters are not modelled.

The measurement stages at the generator stator terminals use the signals of phase voltages and currents from the converters. The signals are sampled at the sampling time of one millisecond and the calculations are performed to determine the signals of voltage, active power, reactive power and frequency.

2.4. Thyristor tripping system model.

The model of the thyristor tripping system is presented in Fig. 3.

Fig. 3. Schematic diagram of the thyristor tripping system (TW – excitation transformer, PR – excitation rectifier, TRsyn – synchronisation transformers, REG – voltage regulator, UWT – thyristor tripping system)

The input signals for the tripping system (UWT) are: the trip angle $\alpha$ from the regulator and the synchronisation voltages from the synchronisation transformers (TR) connected to the supply power of the excitation rectifier. The connection system of the synchronisation transformers and the filter transmittance are selected in the way which allows reception of sinusoidal signals without practically any interferences, and which are required to determine the moment of zero crossing of the converted supply voltages. The filter is selected to ensure a phase shift by -90° for the component with the fundamental frequency. This is accounted for in the selection of the connection group for the synchronisation transformers by shifting the voltage by +90°. The combined effects of the filter and of the transformer connection group enables near complete elimination of disturbance of the voltage used to synchronise the tripping pulses, caused by switching dips.

The output signals of the tripping systems are the control pulses for the tripping of the converter thyristors, sent individually to each of the six thyristors. The pulses are sent in pairs – the activating pulse and the sustain pulse, just as in the case of real systems.
2.5. Model verification

The correctness of the developed model is verified by comparing the simulation results to the model built in one of the professional system dynamics testing tools (DSATools). Analogous symmetrical disturbances are introduced to both models and the time courses are compared. Fig. 4 presents the courses for a three-phase fault at point B (see Fig. 1), while Fig. 5 presents the courses for the incremental change of the preset voltage value. The courses of both models show a good compliance. The models of voltage regulating systems used by the Institute of Power Engineering, Gdańsk Division in the investigations in system dynamics are repeatedly verified by comparing them to the actual courses in the EPS [2, 3].

**Fig. 4.** The courses of the components of the generator voltage and power \((U_g, P_g, Q_g)\), of the excitation voltage and current \((U_f, I_f)\) and of the generator rotational speed deviation \((\Delta \omega)\) for the tested model and for the standard model in the DSATools simulation software during a three-phase fault at point B.

**Fig. 5.** The courses of the components of the generator voltage and power \((U_g, P_g, Q_g)\) and of the excitation voltage \((U_f)\) for the tested model and for the standard model in the DSATools simulation software after the step change of the preset voltage by 5%.
3. THE RESULTS OF SIMULATING THE ASYMMETRICAL STATES

The paper presents the results of the model testing for the following:
• a two-phase earth fault on the generator voltage at point A (see Fig. 1)
• a two-phase earth fault in the 400 kV grid at point B (see Fig. 1)
• the loss of one of the synchronising signals in the thyristor tripping system.

The investigations also included the effect of changing the signal source for thyristor tripping (converter supply voltage or generator voltage transformers).

3.1. The two-phase earth fault on the generator voltage at point A

In the steady state of operation at the rated power, a two-phase earth fault is effected with the duration of 400 ms at point A. The figures present the courses of the symmetrical components of voltages and currents at the generator terminals and at the EHV side of the power unit transformer (Fig. 6), as well as the instantaneous courses of the excitation voltage and of the excitation transformer currents (Fig. 7).

The generator remains stable under the tested conditions. The courses of the excitation voltage and of the excitation transformer currents (see Fig. 7) show that upon the fault only those thyristors work, which are powered from the two voltage phases from the excitation transformer (a and c); the instantaneous excitation voltage value changes almost symmetrically from the maximum value (ca. +1000 V) to the minimum value (ca. -1000 V), which means that the mean value is close to zero.

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![Fig. 6](image)

*Fig. 6. The two-phase earth fault (t\_fault = 400 ms) at point A. The courses of the symmetrical components of voltage and current at the generator terminals (U\_g1, U\_g2, U\_g0, I\_g1, I\_g2, I\_g0) and at the PV of the power unit transformer (U\_s1, U\_s2, U\_s0, I\_s1, I\_s2, I\_s0)*

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![Fig. 7](image)

*Fig. 7. The two-phase earth fault at point A. The courses of the excitation transformer currents (I\_wa, I\_wb, I\_wc) and of the instantaneous excitation voltage (U\_f)*
3.2. The two-phase earth fault in the 400 kV grid at point B

In the steady state of operation at the rated power, a two-phase earth fault is effected with the duration of 400 ms at point B. Fig. 8 presents the courses of the symmetrical components of voltages and currents at the generator terminals and at the EHV side of the power unit transformer. Fig. 9 and 10 present the instantaneous courses of the excitation voltage and of the excitation transformer currents (Fig. 9 – for the synchronisation of the tripping system by the converter supply voltages, Fig. 10 – for the synchronisation by the generator voltage transformers).

As implied by Fig. 8, in the tested conditions the generator becomes unstable. The fault limit duration, after which the system resumes stable operation, is ca. 370 ms.
During the fault, all thyristors conduct electricity, but each of them does it in a different manner. The detailed analysis of the conduction time and of the current values is critical to assess the threats to safe operation of the converter. The courses of the excitation voltage indicate the complex nature of the tripping process under these operating conditions.

By comparing the excitation voltage courses of both synchronisation variants (see Fig. 9 and 10), it is concluded that in the investigated cases the thyristor converter works more smoothly when the thyristor tripping system is synchronised by the signals from the generator voltage transformers.

### 3.3. The loss of one of the synchronising signals

Fig. 11 and 12 show the behaviour of the model upon the loss of one of the generated synchronising signals (signal $S_a$ in Fig. 3). The emergency loss of the synchronising signal $S_a$ results in the loss of the tripping pulses of two thyristors at the converter, and as a consequence, their lock-up (see Fig. 12). The regulator maintains the preset generator voltage value by changing the thyristor tripping angle $\alpha$ from 60° to approx. 30° – the thyristors in operation take over the current from the two locked thyristors. The disturbance of the mean excitation current value lasts for approx. 1 s. The generator voltage drops a maximum of 0.97 pu and returns to the value prior to the disturbance in approx. 10 s.
4. SUMMARY

The developed model of the generator with the excitation and voltage regulation systems allows testing and analysing any asymmetrical states of the generator and of the excitation system. It is a novel design that has not been applied to the research of excitation systems. The authors have applied a discrete model of the regulating system with real-time sampling and complete representation of measurement systems. The developed model of the thyristor tripping system allows representing the actual courses in excitation systems. The model will be applied in the development of excitation and voltage regulation systems, in the analysis of complex asymmetrical states of the system and in training.

REFERENCES