A Study on the Voltage Control Loop of a Self-excited Synchronous Generator in a Micro-Hydroelectric Power Plant

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***Abstract* —This work presents the behaviour of the voltage control loop in a self-excited synchronous generator running in the dynamic regime. The voltage control loop plays an important role in choosing and adjusting the controlling closed-loop. The output regulator of this loop is a specific three-phased rectifier: in the synchronous generator's self-exciting phase the rectifier functions are an uncontrolled rectifier; after the phase nominal voltage is reached, the rectifier functions as a semi-controlled rectifier. The switch between the two functioning regimes is done without a pause. This work underlines the control loop performances in the dynamic regime for type P or PI rectifiers. The stability analysis was done following the simplified Nyquist criterion and hodographs. The analysis method can be used for other applications with minor modifications of the program.**

Keywords—synchronous generator, control loop, voltage, stability, hodograph.

I. Introduction

An essential need of the electrical consumers that are connected to a power supply network is that the voltage levels are constant. The European standard EN 50160 prescribes that the power supply voltage must fall into the ±10% limits [1, 2]. This requirement is imposed also on autonomous synchronous generators equipping micro hydro power plants. Thus, every autonomous synchronous generator must contain a voltage regulation loop which minimizes or eliminates the seized voltage differences, in the shortest possible time.

II. The Transition Role of The Voltage Control Loop

To determine the transition function of the voltage control loop we draw up the control block diagram (Fig. 1).

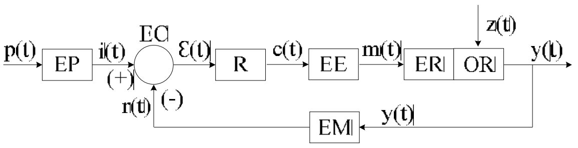

Fig. 1. Block diagram for a voltage control loop.

In this diagram the following components are used:

- EP – the imposed voltage element block;
- EC – the comparison block;
- R – the P (proportional) type or PI (proportional-integrating) rectifier block;
- EE – the execution element (output regulator) block;
- ER – the rectifier element block;
- OR – the regulated object block (synchronous generator);
- EM – the output measurement block.

The quantities used in the voltage control loop are:

- p(t) – the imposed input;
- i(t) – input into the comparison;
- Ɛ(t) – error or deviation;
- c(t) – command;
- m(t) – execution;
- r(t) – reaction;
- z(t) – perturbation given by the consumers' load current powered by the generator.

The imposed voltage block, the comparison block, the regulation and the measurement blocks are of the proportional type with the following transition functions:

$$H_{EP}(s) = k_{EP} \tag{1}$$

$$H_{EC}(s) = k_{EC} \tag{2}$$

$$H_{R}(s) = k_{R} \tag{3}$$

$$H_{EM}(s) = k_{EM} \tag{4}$$

Where K_{EP}, K_{EC}, K_{R}, and K_{EM} in relations (1), (2), (3), (4) are the blocks' proportionality constants.

The execution element block contains the grid driving gear, DCG, and the three-phased rectifier. It is a PT1 type element with the following transition function:

$$H_{EE}(s) = \frac{k_{EE}}{1 + s \cdot T_{EE}} \tag{5}$$

The control element block is made of the synchronous generator's exciter and is a PT1 type element with the following transition function:

$$H_{ER}(s) = \frac{k_{ER}}{1 + s \cdot T_{ER}} \tag{6}$$

where K_{ER} is the transition constant of the control element given by:

$$k_{ER} = \frac{1}{R_{Ex}} \quad (7)$$

and T_{ER} is the idle time of the control element, defined by:

$$T_{ER} = \frac{L_{Ex}}{R_{Ex}} \quad (8)$$

L_{Ex} şi R_{Ex} in equations (7) and (8) are the exciting winding's inductivity and resistance.

The OR block consists of the synchronous generator. The block is of type PT1 and has the following transfer function [3]:

$$H_{OR}(s) = \frac{k_{OR}}{1 + s \cdot T_{OR}} \quad (9)$$

where k_{OR} is the OR transfer constant, and T_{OR} is the time constant, defined by the following equations:

$$k_{OR} = \frac{1}{R_{Ex}} \left[\frac{\partial U_{eE}}{\partial I_{Ex}} \right]_0 \quad (10)$$

$$T_{OR} = N_{Ex} \cdot \frac{L_{Ex}}{R_{Ex}} \quad (11)$$

The transition function for the open look is, then:

$$H_D(s) = \frac{k_{EP} \cdot k_{EC} \cdot k_R \cdot k_{EE} \cdot k_{ER} \cdot k_{OR}}{(1 + s \cdot T_{EE})(1 + s \cdot T_{ER})(1 + s \cdot T_{OR})} \quad (12)$$

We denote with k_D the control open loop constant and we define it as:

$$k_D = k_{EP} \cdot k_{EC} \cdot k_R \cdot k_{EE} \cdot k_{ER} \cdot k_{OR} \quad (13)$$

The voltage control closed-loop transition function for a type P rectifier, is given by:

$$H_1(s) = \frac{k_D}{k_D \cdot k_{EM} + (1 + s \cdot T_{EE})(1 + s \cdot T_{ER})(1 + s \cdot T_{OR})} \quad (14)$$

The transition function for a type PI rectifier is, then:

$$H_R(s) = \frac{k_R}{s \cdot T_R} \quad (15)$$

and the control loop transfer function is:

$$H_2(s) = \frac{k_D}{k_D \cdot k_{EM} + s \cdot T_R (1 + s \cdot T_{EE})(1 + s \cdot T_{ER})(1 + s \cdot T_{OR})} \quad (16)$$

III. The Stability Analysis for the Voltage Control Look

To analyse the stability of the voltage control loop the Nyquist criterion was used in a simplified form [4]. According to this criterion the control loop for the power supply voltage is stable only if the hodograph corresponding to the second term in the equation (14) denominator does not clock-wise circle the (-1;+0·j) critical point in the complex place, when the complex s varies between zero and infinity.

In this stability analysis we considered the time and proportionality constants of the rectifier block, ER. Hence, the type P rectifier whose hodograph we want to examine has the following function:

$$F_1 = \frac{k_{EP} \cdot k_{EC} \cdot k_R \cdot k_{EE} \cdot k_{OR} \cdot k_{EM}}{(1 + s \cdot T_{EE})(1 + s \cdot T_{OR})} \quad (17)$$

The transition and time constants computed values are shown in Table I. To determine the constant values in this table we considered the values for the resistors, c.c. voltage supplied by the three-phased one-way rectifier, with the 257 V nominal voltage, the value of the DCG's charging voltage (2 V), the relationship between the excitation flow and the off-load voltage Us = 39.214·Φ, the resistance value of the excitation winding, R_E = 59.3 Ω [5, 6]. The proportionality constant, k_{OR}, and time constant, T_{OR}, have been determined by analysing the functioning characteristics of the synchronous generator.

TABLE I.
CONTROL LOOP CONSTANT VALUES

Id	Constant	Measure unit	Value
1	k_{EP}	-	1
2	k_{EC}	-	1
3	k_R	-	1÷10
4	k_{EE}	-	128.5
5	k_{OR}	-	0.9463÷1.656
6	k_{EM}	-	0.92
7	T_{EE}	s	0.001÷0.009
8	T_{OR}	s	0.112÷0.0196
9*	T_R	s	0.0005÷0.2

Fixing the proportionality constant to 5 and fixing the minimal values for the time constants (with another method not mentioned here) we constructed the hodograph corresponding to F_1. The behaviour of F_1 for value sets of the complex variable close to zero and for values sets close to infinity cannot be presented on the same hodograph in this paper's context.

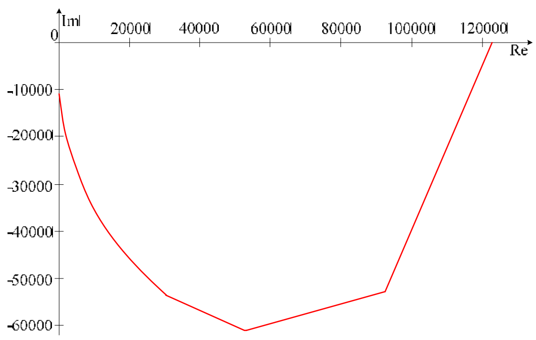

Fig. 1. F_1 hodograph for complex variable values between 0 and 100·j.

Fig. 1 shows the F_1 hodograph for values of the complex variable between zero and 100·j which point out the hodograph's behaviour close to the 0 value of the complex variable.

Fig. 1 does not show how the hodograph varies close to the (-1; +0·j) complex critical point. Repeating the hodograph's representation for other values of the complex variables we arrived to the situation shown by Fig. 2 where s varies within (13500·j ÷ 100000·j) interval and the hodograph's values are close to the axis intersection.

Analysing the hodograph shown in Fig. 2 we conclude that the voltage control loop is stable from the dynamic point of view.

In the following we look at the voltage control loop stability for various values of the proportionality constants product (ranging between their minimum and maximum possible values), for minimal time constant values, and for integer values in the [1÷10] interval for K_R. Fig. 3 shows the hodographs for these computations. It is clear that the voltage control loop remains stable for all these 10 computations.

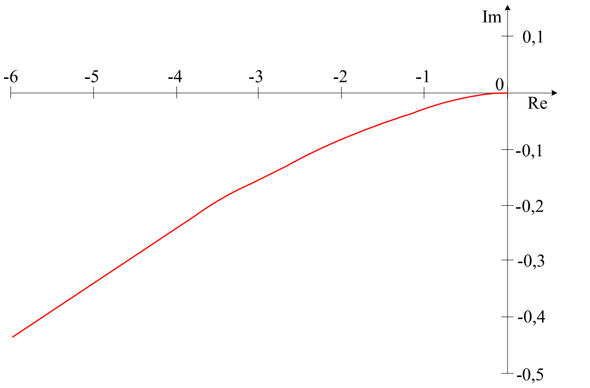

Fig. 2. F_1 hodograph for complex variables values within (13500·j ÷ 100000·j) interval.

It is, actually, true that the voltage control loop stays stable for any product of the constants between the two given limits.

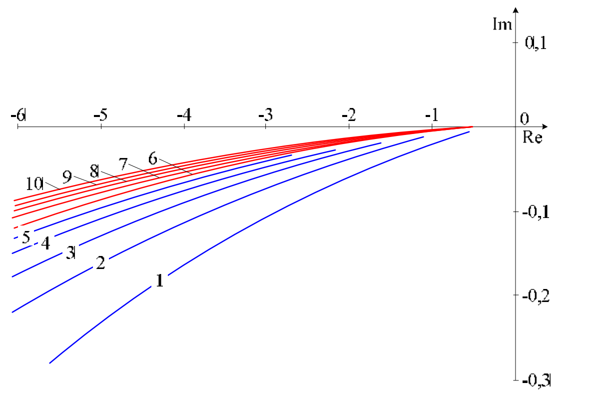

Fig. 3. F_1 hodographs for complex variable values within (13500·j ÷ 100000·j), for the proportionality constants products between 112 and 1958 and minimal time constant values.

The transition function's expression contains the time constants and, therefore, the hodographs for the maximum time values and various values of the proportionality constants products (between their minimum and maximum values) were also constructed. These hodographs are shown in Fig. 4.

Looking closer at the hodographs in Fig. 4 it is clear that none of them circles the critical point. Hence the voltage control loop with a type P rectifier stays stable for any combinations of constant values (proportionality or time) shown in Table I.

In situations where there is a type PI rectifier and the transition function of the controlling element (of the synchronous generator excitation) is not considered, the voltage control loop's transition has the following expression:

$$F_2 = \frac{k_{EP} \cdot k_{EC} \cdot k_R \cdot k_{EE} \cdot k_{OR} \cdot k_{EM}}{s \cdot T_R \left(1 + s \cdot T_{EE}\right)\left(1 + s \cdot T_{OR}\right)} \tag{18}$$

The computed values for the transition and time constants is shown in Table I.

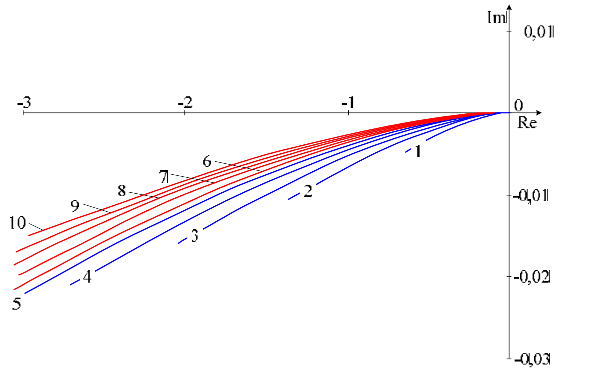

Fig. 4. F_1 hodographs for complex variable values between (13500·j ÷ 100000·j), and for proportionality constants products between 112 and 1958, and maximum time constant values.

To determine the behaviour of the F_2 hodograph we used the theoretical complex variable values between zero and infinity, and the proportionality and time constant values shown in Table I.

Compared to the previous case, the quantity that influences the hodograph's type is the rectifier's T_R constant. The analysis is followed, then, for this time constant values starting from the lowest (T_R=5·10^{-4} s) in steps of 10th powers (T_R=5·10^{-3} s, T_R=5·10^{-2} s, T_R=0.5 s). For the rectifier's proportionality constant value we chose the average value over its variation interval. The resulting hodographs are presented in Fig. 5.

For situations where the rectifier's time constant value is 5·10^{-4} s (curve 1, Fig. 5) or 5·10^{-3} s (curve 2, Fig. 5) the voltage control loop is dynamically instable. This is because the hodographs circle the critical point.

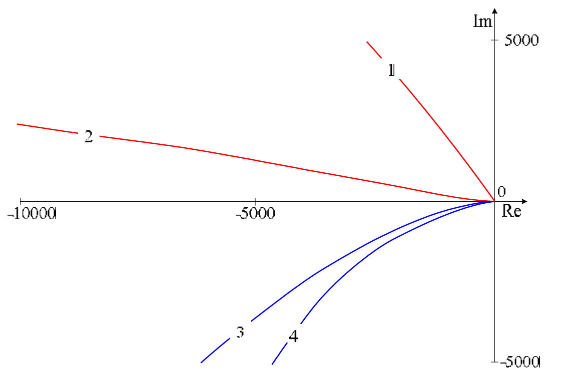

Fig. 5. F_2 hodographs for complex variable values between 0·j and 1000·j, and T_R ϵ (5·10^{-4} s ÷ 0.5 s).

If the rectifier's time constant is 5·10^{-2} s (curve 3, Fig. 5) or 0.5 s (curve 4, Fig. 5) the voltage control loop is dynamically stable.

To determine the exact value of the PI type rectifier's time constant where the hodographs stay in the 3rd quadrant or pass into the 2nd quadrant without circling the critical point, we modify the complex variable's variation interval to (35·j ÷ 200·j). The resulting hodographs are shown in Fig. 6.

Fig. 6 shows that the first two hodographs circle, clock-wise the critical point, while the third passes through the critical point. In these three situations the voltage control loop is not dynamically stable. This analysis was done by changing the rectifier's proportionality constant to take values between 1 and 10.

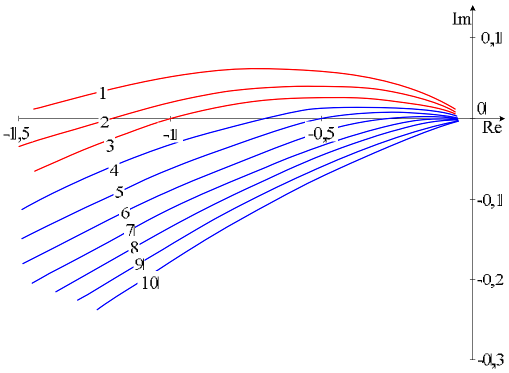

Fig. 6. F_2 hodographs for complex variable values between 35·j and 200·j, and $T_R \in (5 \cdot 10^{-4}$ s ÷ 0.5 s).

The minimum value for the rectifier's time constant is 0.007 s. From this value on the voltage control loop remains stable for any proportionality constants products.

IV. Experimental Results

The voltage control loop properties were tested for a 12 kVA, self-excited, autonomous synchronous generator. For this various loads were connected to the generator. This section presents the experimental results where the load was an asynchronous motor with a power of 1.5 kW (inductive proof).

Fig. 7 shows that immediately after the connection was realised the one-phase voltage, U_{Rvv}, measured at the generator's terminal drops, causing a command increase U_{cd} at the impulse generator. This, in turn, causes the voltage and field current.

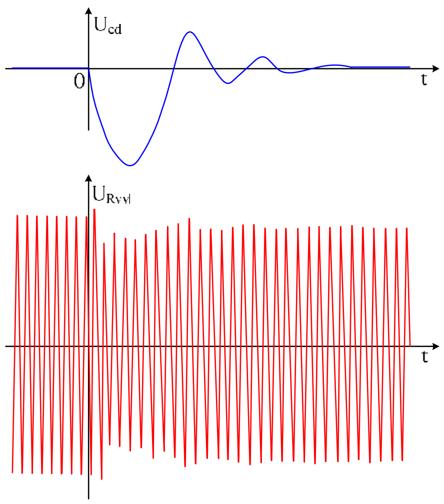

Fig. 7. Rectifier source voltage and generator terminal voltage variations.

After about 10 time periods, the voltage measured at the generator's terminals stabilises. The transitory process dampens out after about 15 oscillations (that is 0.28 s). Measurements done at the generator's terminals show:

- The phase actual value, before the connection time point, is 219.5;
- The maximum phase actual value, after the connection is 222 V for 20 ms (one period);
- The minimum phase value, after the connection is 203 V for 140 ms (7 periods);
- The actual value after the oscillations dampen is 218.2 V.

From these tests follows that the voltage control loop behaves quite well, especially when considering that the generator is self-excited. The filament lamps that were connected to the generator during the tests did not show observable variations in their light intensity.

V. Conclusion

The method presented in this paper to analyse the voltage control loop for the output voltage of a synchronous generator allows the following:

- Determining that, when a type P rectifier is involved, for any pre-determined proportionality constants values the voltage control loop is stable;
- Quick determination of the PI type rectifier's time constant minimal value for which the voltage control loop stays stable independent of the proportionality constants product values;
- The use of equations and hodographs in other applications of this type, with minimal modifications when the number of terms that contain time constants stays the same.

The use of this method allowed to a rapid determination of the proportionality and time constants for a 10 kVA micro hydro power plant.

The author's contributions consist of:

- Designing the analysis method presented here and the result interpretation regarding the voltage control loop behaviour;
- The use of the theoretical results in tuning the PI type rectifier in the implemented model;
- Determining the minimal values for the rectifier's time constant for which the voltage control loop stays stable.

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