The Modulus Optimum (MO) Method Applied to Voltage Regulation Systems: Modeling, Tuning and Implementation

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Abstract - **The modulus optimum (MO) method for optimization of regulators can be applied in a wide variety of cases in the control field. Very often, this method is applied to controlled electrical drives, and in this work a simple systematic approach is developed to extend it to the design of regulators for voltage control. This application has not yet been presented in the literature we know, and for this reason a significant contribution is offered by applying this simple and effective method in voltage regulation of three-phase synchronous machines. The approach for obtaining the controller parameters will be presented, together with appropriate practical applications supported by experimental results.**

Keywords: Static excitation systems. Voltage regulation.

I. INTRODUCTION

The voltage regulator is the intelligent part of an excitation control system. Its main function is to keep the terminal voltage of an electrical generator at a constant reference value, independently on loads being connected on or off the generator.

The static excitation system is made up by a three-phase six-pulse rectifying thyristor bridge, which supplies the synchronous machine field circuit. Therefore, a change on the bridge firing angle α will imply a change in the controlled rectifier voltage, thus causing a change in the field current.

II. EXPERIMENTAL SETUP

Fig. 1 shows the block diagram of the laboratory setup.

The rated values of the machines used in the experiments are:

- Prime Mover: dc motor with independent excitation, 0.25 (CV), 220 (V)
- Synchronous machine: three-phase synchronous generator, 0.25 (kVA), 220 (V.)

In the implemented system there was no speed regulation, only voltage regulation on the synchronous machine. It is intended in the future to implement a speed regulation loop for the synchronous machine, as it happens in water turbines of hydroelectric power plants.

Therefore, as load is connected or disconnected to and from the generator, there will be a change in the system frequency, but the rms value of the synchronous machine will remain the same, due to the automatic control of the field current.

III. MODELING OF THE VOLTAGE REGULATION SYSTEM

Fig. 2 shows the voltage regulation system, and the LEM Hall voltage sensor, model LV 25-P, is shown in Fig. 3.

Three sensors were used, one for each phase, as shown in Fig. 2. The outputs of the sensors are input into a diode bridge with Graetz a configuration, and the transduced signal *(v_u)* is obtained at the 10 (kΩ) resistor.

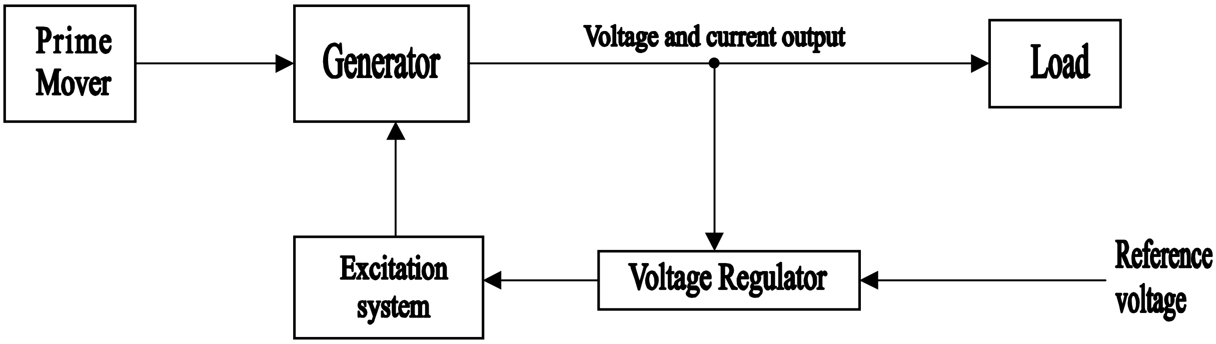

Fig. 1. Implemented laboratory structure.

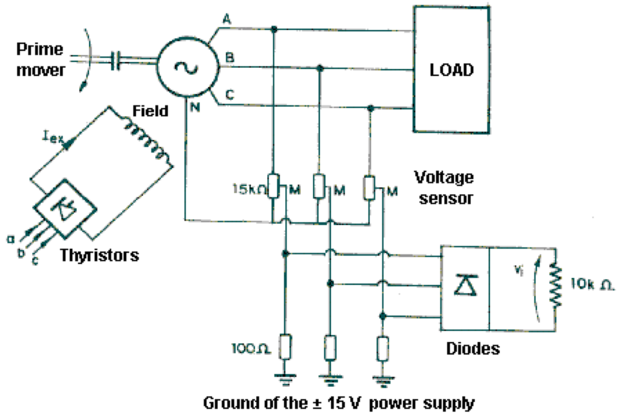

Fig. 2. Voltage regulation system.

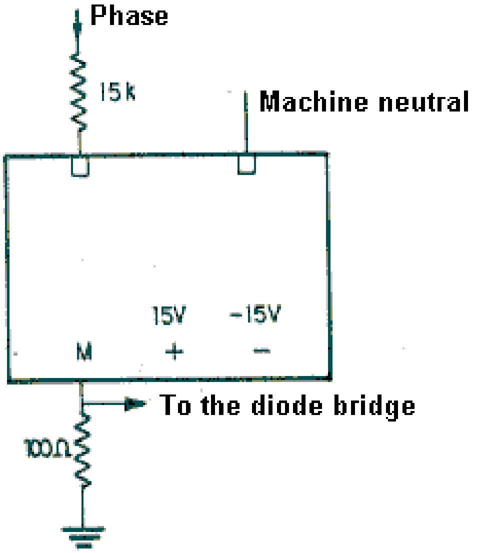

Fig. 3. Hall voltage transducer.

The thyristor bridge (Fig. 2), also having a Graetz configuration, is used to supply the synchronous machine. A symmetrical voltage source (±15 V) is used to supply the three Hall LV 25-P (LEM) sensors used in the voltage regulator.

Fig. 4 shows the field electric circuit of the synchronous machine, where

I_{ex} – field current;
R_c – resistance of the field circuit;
L_c – inductance of the field circuit;
E – voltage applied to the field (three-phase thyristor bridge output)

The development of the circuit equations for Fig. 4 now follows:

$$E = R_c \, I_{ex} + L_c \frac{dI_{ex}}{d_t} \qquad (1)$$

The Laplace transform of this equation is

$$E(s) = R_c I_{ex}(s) + sL_c I_{ex}(s) \qquad (2)$$

hence

$$I_{ex}(s) = \frac{E(s)}{R_c + sL_c} \qquad (3)$$

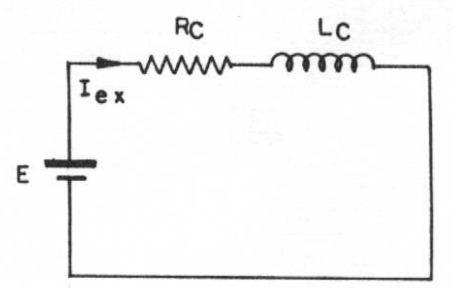

Fig. 4. Field circuit of a synchronous machine

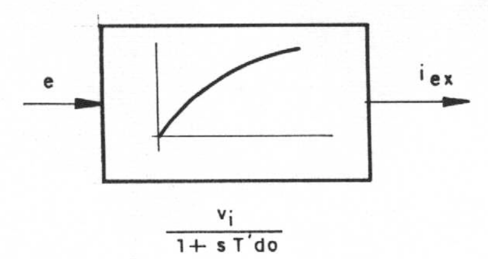

Fig. 5. Block diagram of the synchronous machine field circuit, for “pu” values

Let

$$\tau'_{do} = \frac{L_c}{R_c} \qquad (4)$$

Then (3) becomes

$$I_{ex}(s) = \frac{E(s)}{1+s\tau'_{do}} \times \frac{1}{R_c} \qquad (5)$$

In order to use pu quantities, (5) is modified as follows:

$$\frac{I_{ex}(s)}{I_{exN}(s)} \times I_{exN}(s) = \frac{E(s)}{R_c} \times \frac{E_N(s)}{E_N(s)} \times \frac{1}{1+s\tau'_{do}} \qquad (6)$$

where

$I_{exN}(s)$ – Rated field current;
$E_N(s)$ – Rated field circuit input voltage.

The normalized (pu) values are then defined

$$i_{ex} = \frac{I_{ex}}{I_{exN}} \qquad (7)$$

$$e = \frac{E}{E_N} \qquad (8)$$

$$v_i = \frac{E_N}{R_c I_{exN}} \qquad (9)$$

By using pu values, (6) becomes

$$e \times \left(\frac{v_i}{1+s\tau'_{do}} \right) = i_{ex} \qquad (10)$$

Fig. 5 shows the block that represents this equation.

Fig. 6 shows the block diagram of the complete voltage regulation system. All values are given in pu, and the system parameters are:

T_{gs1} – Time constant of the reference channel filter (to be determined);

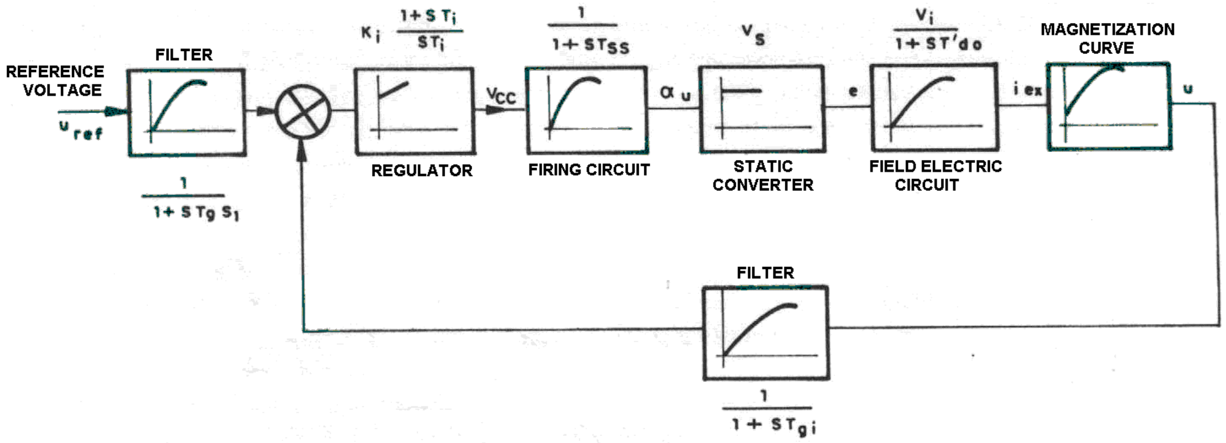

Fig. 6. Block diagram of the complete voltage regulation system.

K_i , T_i – Parameters of the PI voltage regulator (to be determined);

T_{ss} – Firing circuit lag time constant;

T_{gi} – Time constant of the voltage transducer filter - feedback path.

The firing circuit is of the ramp type, and it was implemented with the Siemens-Icotron TCA 780 integrated circuit. Its operation is illustrated in Fig. 7.

The intersection of voltage V_{cc} at pin 11 with the ramp (pin 10) produces pulses P1 and P4 for thyristors 1 and 4 of the rectifying bridge.

Two other TCA 780 integrated circuits are used for the thyristor pairs (3,6) and (5,2). A synchronizing transformer with a Δ/Y (30^o) connection is used to supply the synchronism pins of the TCA's 780 (pins 5).

Every time the synchronizing voltage (pin 5) goes through zero, a ramp is generated at pin 10 of the TCA 780. Three TCA 's 780 are then needed to generate the pulses for the bridge, and pins 5 of each one of them are supplied by phases a, b and c of the 220/10 (V) synchronizing transformer

The V_{cc} voltage at pin 11 varies within the 0 to 10 V range, and the corresponding firing angles will vary between 0^o and 180^o, respectively. The relationship between the firing angle α and the voltage regulator output voltage V_{cc} stays linear. Therefore, for $V_{cc} = 5.0$ (V), the firing angle (α) will obviously be 90^o.

Fig. 8 shows the Graetz configuration of the field rectifying bridge thyristors.

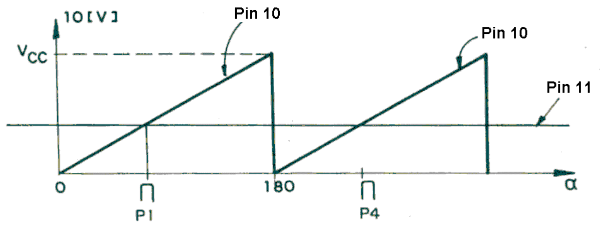

Fig. 7. Illustration of the implemented firing circuit of the ramp type.

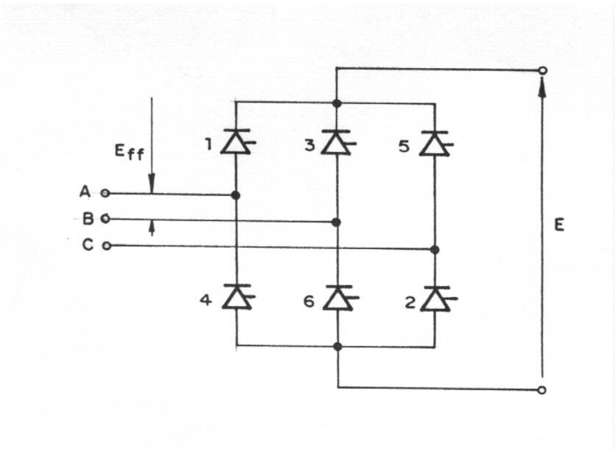

Fig. 8. Graetz configuration of the field rectifying bridge.

IV. REGULATOR AND FILTER DESIGN

The following time constant was obtained:

$$\tau'_{do} = \frac{L_c}{r_c} = \frac{220\times10^{-3}}{67} = 3.28 \text{ (ms)} \qquad (11)$$

The bridge firing circuit does not react instantly to a command for change, and that reaction happens according to a first order lag, which was considered to have the time constant

$$T_{ss} = 1.5 \text{ (ms)} \qquad (12)$$

A filter for the voltage transducer was also needed, as the output voltage of the diode bridge (Fig. 2) has some ripple. It was considered that

$$T_{gi} = 1.5 \text{ (ms)} \qquad (13)$$

The rectifying bridge output voltage is

$$E = 1.35 \times E_{ff} \times \cos\alpha \qquad (14)$$

where E_{ff} is the phase-to-phase voltage supplied to the bridge (Fig. 8).

$$\frac{E}{E_N} = 1.35 \times \frac{E_{ff}}{E_N} \times \cos\left[\left(\frac{\alpha}{\pi}\right)\pi\right] \qquad (15)$$

$$\frac{d(E/E_N)}{d(\alpha/\pi)} = -1.35 \times \pi \times \frac{E_{ff}}{E_N} \times \sin\left[\left(\frac{\alpha}{\pi}\right)\pi\right] \qquad (16)$$

Let $e = E/E_n$ and $\alpha_u = \alpha/\pi$, where α_u is the firing angle α in “pu”. Then

$$\frac{de}{d\alpha_u} = -1.35 \times \pi \times \frac{E_{ff}}{E_N} \sin(\alpha) \qquad (17)$$

For the considered circuit:

$$\left| \frac{d\,e}{d\alpha_u} \right| = V_s \qquad (18)$$

where V_s is the static converter gain. This gain will be given by

$$V_s = \left| \frac{d\,e}{d\alpha_u} \right| = 1.35 \times \frac{220}{216} \times \pi \times \sin\alpha \qquad (19)$$

$$V_s = 4.32 \times \sin\alpha \qquad (20)$$

For $\alpha = 90^o$, this gain will be $V_{s1} = 4.32$ (maximum gain); $\alpha = 43^o$ yields the gain $V_{s2} = 2.94$ (minimum gain). The average value will be the adopted gain in the linear model, as follows

$$V_s = 3.63 \qquad (21)$$

Let

$$v_i = \frac{E_N}{R_c I_N} = \frac{216}{67 \times 3.2} = 1.00 \qquad (22)$$

where $I_N = 3.2$ (A) is the rated field current. The gain of the voltage regulating circuit will be

$$V_{sia} = v_i \times V_s = 3.63 \qquad (23)$$

A PI controller will be used to eliminate the steady-state error. The largest time constant of the regulating circuit is $\tau'_{do} = 3.28$ (ms). The sum of the small time constants is

$$\sigma = T_{ss} + T_{gi} = 3.00 \text{ (ms)} \qquad (24)$$

Fig. 9 shows the filters and regulators that have been used. The filters in the reference channel and in the voltage feedback path have the “T” configuration.

In order to make a decision on the controller to be used, the following ratio is computed:

$$\frac{\tau'_{do}}{4\sigma} = \frac{3.28}{12} = 0.27 \quad \text{(less than 1)}$$

For being less than 1, a PI regulator is indicated. In such cases, the regulator parameters can be tuned by optimization, and the recommended method is the Modulus Optimum (MO) Method [1]. The calculation of the regulator parameters is now described. An analog regulator with a proportional channel (gain) and an integral channel (time constant) will be used, and these parameters are set at the appropriate potentiometers in each channel (R_{q1} and RM_2 in Fig. 9).

The filters in the reference channel and in the voltage feedback path are also included in the regulator structure ("T" filters).

According to the MO method [1], the regulator gain is calculated as follows:

$$K_i = \frac{\tau'_{do}}{2 V_{sia}\,\sigma} = \frac{3.28}{2 \times 3.63 \times 3} = 0.15$$

The regulator time constant is

$$T_i = \tau'_{do} = 3.28 \text{ (ms)}.$$

A data summary of the voltage regulator now follows:

Type: PI
Gain: $K_i = 0.15$
Time constant: $T_i = 3.28$ (ms)
Reference channel filter: $T_{gs1} = T_i = 3.28$ (ms)
Feedback channel filter: $T_{gi} = 1.5$ (ms)

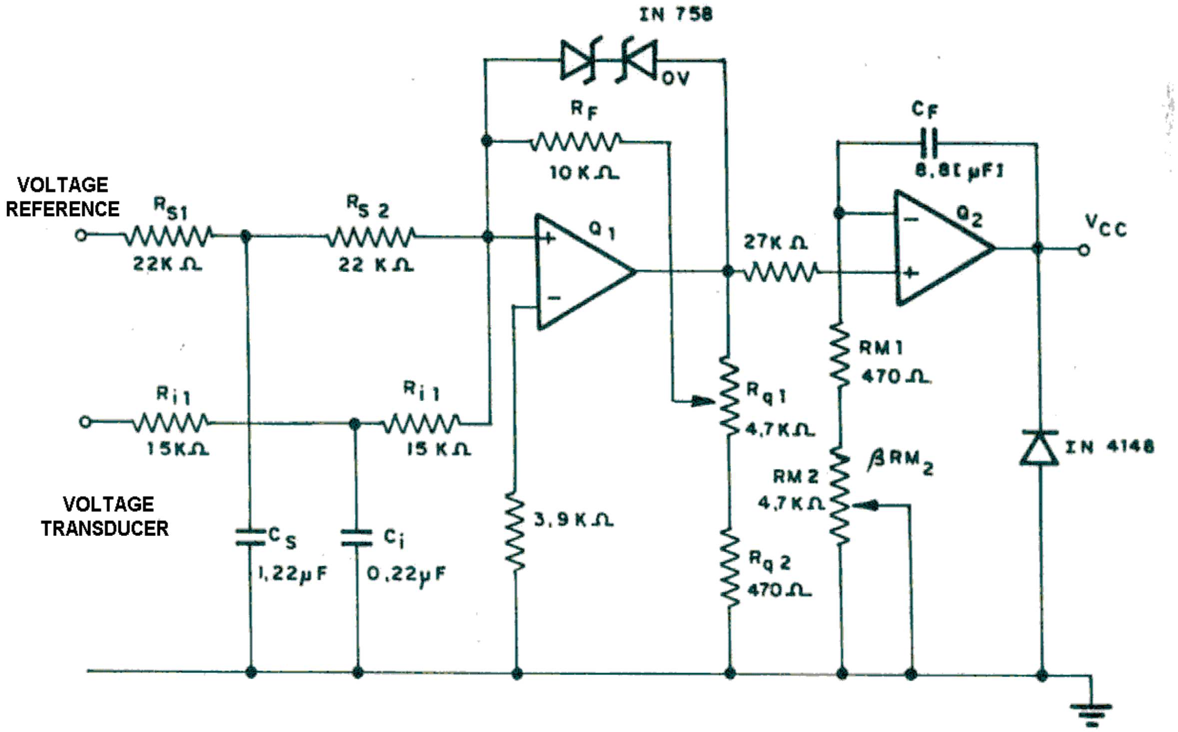

Fig. 9. Circuit with filters and regulators.

V. EXPERIMENTAL RESULTS

For a sudden 100 (W) load increase and load reduction, Fig. 10 was obtained, where a voltage sag can be seen, when the machine operates without regulation. The voltage fell from 220 (V) to 200 (V) for the load increase.

Fig. 11 shows the machine output voltage when the regulator is active, where it can be observed that there is no voltage drop at the machine terminals.

The voltage regulator action is shown in Fig. 12, where the graph of the control voltage V_{cc} for a sudden load increase followed by load reduction is shown.

VI. CONCLUSIONS

The tuning method proposed in this work proved itself to be simple and effective.

The tuned system had a stable response with good regulation dynamics, with an actuating time for a sudden load increase of approximately 0.5 (s).

It is suggested, as a follow-up work, the inclusion of speed regulation of the prime mover.

The tuning method based on the Modulus Optimum optimization criterion, used for tuning up regulators, proved itself to be quite effective for application in automatic voltage control systems. This method, simple and effective, can also be used in various segments of the automatic control field. This work is to be continued with implementation of digital regulators.

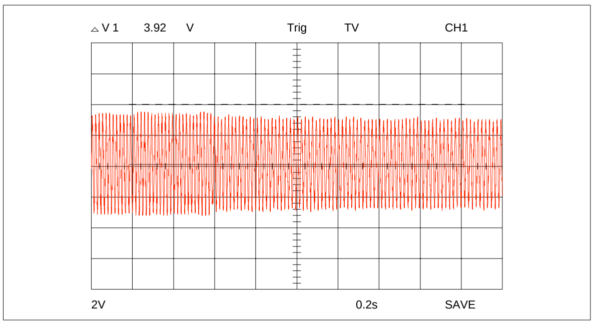

Fig. 10. Voltage sag at the machine for a 100 (w) load increase.

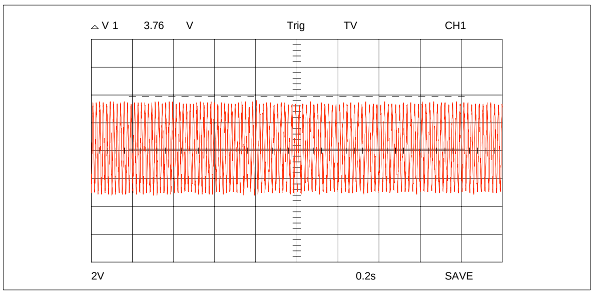

Fig. 11. Machine output voltage for a load increase - regulated system

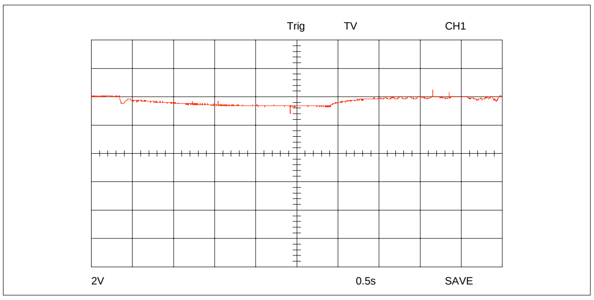

Fig. 12. Control voltage V_{cc} at the voltage regulator output

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