Optimization of an automatic voltage regulator AVR on a synchronous machine using fuzzy control

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Abstract.

The constantly developing society demands more and more electronic devices and microchips that perform vital tasks such as medical services, emergency lighting, communication systems, among others, however these are sensitive to variations and failures of the power supply, such as voltage fluctuations, voltage spikes and interference, for this reason and because of its great importance for its proper functioning must have a continuous power supply. Thus, the work shown in this article proposes to optimize the operation of automatic voltage correction devices AVR used in synchronous power generating machines whose main function is to ensure that the voltage has been constant, for this a solution is proposed based on the use of non-traditional control techniques such as fuzzy logic. For this purpose initially recognizes the relevant elements that make up the AVR system which are amplifier, exciter, generator and sensor then illustrates the mathematical block model that represents the operation of the system which is reduced to transfer function or otherwise as the relationship of the input and output signal of the system., Then a possible classical PID proportional integral derivative proportional control is suggested with the help of the PID tools of the software Matlab®, where the fuzzy logic inference set is programmed in three stages: first stage: input of the set of rules for voltage error correction, second stage: input of the set of rules for the voltage field output in the synchronous machine, and in a third stage: programming of the fuzzy inference sentences. Finally, the response of each control is compared and the methodology in the design of the alternative control in the synchronous machine is exposed, with the use of the software Matlab®, all this as a study of new trends in control for educational purposes, in the context of Technology in Electricity and Electronic Technology.

1. introduction

Electricity is the most widely used type of energy in the world, so it is essential to guarantee the continuity of this resource at every stage of its generation, distribution and transmission. However, the electrical components installed to supply and transfer energy make up a dynamic system subject to disturbances and other phenomena that affect the operation of the entire system [1]. According to the above, the following study proposes to improve the voltage control in synchronous machines, which are affected by the adverse effects of the network, that means the disturbances of the system affect the stability and synchronism of the generators, which produces power losses [2].
Automatic Voltage Regulator (AVR) devices are currently used to correct these effects, these devices are based on classical PID controllers. [3]. However, new control trends propose the use of artificial inference algorithms such as fuzzy logic, which could become faster by stabilizing the voltage control variable and therefore be more efficient. This is developed in the Simulink tool and the Fuzzy Logic toolbox of Matlab®. The following sections present the methodology for the development of the AVR system based on fuzzy logic. In the first section the study of the mathematical model is presented, in the second section the block model that represents an AVR system, in the third section the classical PID auto-tuned control is developed with the toolbox pidtools of Matlab®. Then, in the fourth section, the theory for the implementation of the fuzzy control is developed and finally the two models are compared in terms of the stabilization.

The relevant components for the study of the operation of synchronous machines, as proposed by C. Millan in [4] and other authors [5].

- Exciter: Provides direct current to the field winding of the synchronous machine, and constitutes the power stage of the control system.
- AC regulator: Processes the inputs from the sensors and provides a suitable control signal for the exciter. Signal processing employs classical regulation and stabilization techniques.
- DC regulator: Adjusts the field winding voltage to a certain reference value and allows manual control of the excitation. For special situations such as tests or automatic control failures.
- Excitation: Used to control excitation in special situations such as tests or automatic control failures.
- Field winding tension sensor: This sensor allows closing the loop of the manual tension control.
- Maximum excitation limiter: This protection prevents overheating due to excessive field winding current. Typically, this protection acts as a function of the field winding current.

Along with these elements described in the generator a voltage regulator AVR works correcting voltage fluctuations, these devices largely operate based on proportional integral derivative PID control, however this type of control does not have an inference engine that allows you to re-adjust and adapt quickly to adverse conditions, as the technique of fuzzy logic does, based on reasoning and ideas from fuzzy sets identifying the degree of membership that characterize an ideal signal and uses the set theory to correct the error and remain stable over time [6]. The latter is of great relevance considering that technology students rarely explore control techniques other than those described in traditional control theory. This paper proposes a methodology to implement fuzzy controllers applied to AVR as an alternative to classical PID, making use of all the tools available in Matlab® software.

2. Block model for AVR system

The mathematical model that represents the operation of the elements described are illustrated in figure 1 and are composed of four blocks: amplifier, exciter, generator and sensor according to F. Naeim [7].
Amplifier Model: The transfer function of the amplifier model is:

$$\frac{V_t(s)}{V_r(s)} = \frac{KA(s)}{1 + TA(s)}$$ (1)

Where, the value of $KA$ is a constant in the range of 10 to 400 and the value of $TA$ is in the range of 0.02 to 0.1s, a near value for $KA$ is 5 and $TA$ 0.1 s.

Exciter model: the transfer function of the exciter model is:

$$\frac{V_t(s)}{V_r(s)} = \frac{KE(s)}{1 + TA(s)}$$ (2)

Where, the constant value $KE$ is in the range of 1 to 200 and the constant value of the amplifier time $TE$ in the range of 0.5 to 1s. $KE$ is set to 1 and $TE$ is set to 0.4s for this work.

Generator Model: The transfer function of the generator model is:

$$\frac{V_t(s)}{V_r(s)} = \frac{KG(s)}{1 + TG(s)}$$ (3)

Here the constants depend on the load; the value of the constant $KG$ varies between 0.7 to 1 and the generator time constant $TG$ in the range of 1 to 2s this represents the full load on the machine. Then $KG$ was set to 1 and $TG$ to 1s.

Sensor model: The transfer function of the sensor model is:

$$\frac{V_t(s)}{V_r(s)} = \frac{KR(s)}{1 + TR(s)}$$ (4)

Where, the gain $KR$ is generally kept at 1 and the time constant $TR$ is very small, ranging from 0.01 to 0.06s. $KR$ was set to 1 and $TR$ was set to 0.01s.

3. Transfer function

By reducing the blocks proposed in the previous section, the coefficients describing the amplifier, exciter, generator and sensor are replaced by the coefficients $a$, $b$, $c$, $d$ for ease of subsequent calculations, so the new transfer function is given by transfer function is given by:

$$H(s) = \frac{a_1(s)}{as^4 + bs^3 + cs^2 + ds + 1}$$ (5)
where

\[ a_1 = KA \cdot KE \cdot KG \cdot KR \]

\[ a = TA \cdot TE \cdot TG \cdot TR \]

\[ b = TA \cdot TE(TG + TR + TG) + TG \cdot TR(TA + TE) \]

\[ c = TA \cdot TE + TR + TG + TR \cdot TG(TA + TE) \]

\[ d = TR + TA + TG + TE \]

According to this relationship, the values for each constant representing the behavior of the system are summarized in Table 1.

**Table 1.** Constants for the AVR automatic regulator model [7].

| KA | KR | KE | KG | TA | TR | TE | TG |
|----|----|----|----|----|----|----|----|
| 5  | 1  | 1  | 1  | 0.1| 0.05| 0.4| 1  |

Replacing the values in Table 1 in equation (5) gives the transfer function representing the AVR system:

\[ H(S) = \frac{5}{0.002s^4 + 0.067s^3 + 0.115s^2 + 1.55s + 1} \]  

Next, the initial behavior of the system with respect to time is plotted in the Matlab® software, from which the following initial overshoot values of 2.52 s, settling time 9.61 s and rise time 2.92 s are obtained, see figure 2 [8].

![Step Response](image_url)
4. Classic PID control
Once the initial behavior of the AVR device is recognized, the PID control is auto-tuned by means of the pidtools toolbox of Matlab® thus achieving the stabilization of the system response, as shown in figure 3 [9].

Therefore the control constants after autotuning would be proportional constant $k_p = 0.029$, integral constant $k_i = 0.011$ constant derivative $k_d = 0$.

5. Fuzzy PID Controller
In the first instance, the set of input and error correction rules for the variable to be optimized "voltage" is established using the Matlab® fuzzy logic toolbox, where the system is modeled by means of simple logic rules [10]. Subsequently, these rules are implemented in a fuzzy inference engine (see table 2 and figure 4).

| If the voltage error is     | Then the field voltage is |
|-----------------------------|---------------------------|
| Very Negative               | Very Small                |
| Negative                    | Small                     |
| Normal                      | Medium                    |
| Positive                    | Large                     |
| Very Positive               | Very Large                |
Once the voltage error rules are established, the fuzzy control is programmed in three stages: first stage: input of the set of rules for voltage error correction, second stage: input of the set of rules for the voltage field output in the synchronous machine, and finally the programming of the fuzzy inference statements [11].

First stage: Figure 5 illustrates the ranges for the fuzzy rules where, MN (Very Negative), NE (Negative), no (Normal), PO (Positive), MP very positive [12].
**Second stage:** Figure 6 shows the input ranges for the field voltage of the synchronous machine where MP (very small), PE (small), ME (medium), Gr (large), MG (very large) [13].

![Figure 6. Field voltage output as a function of fuzzy rules.](image)

**Third stage:** Figure 7 illustrates the input of the fuzzy control sentences, where the error voltage variable and field voltage are assigned [14].

![Figure 7. Programming of fuzzy inference rules.](image)

Once the fuzzy control is programmed, the blocks are created in Simulink of Matlab® with the properties of the proposed fuzzy control and in parallel the PID control, in order to graphically compare the responses of each case, as shown in figure 8 [15] [16].
6. Results and discussion

It is validated that the proposed fuzzy control can represent an improvement in both the rise time and over oscillation time (see figure 9), since this response has a stabilization time of 6 seconds before the classical PID, this means that the machine will come out faster from a sub-transient effect, which can represent an improvement in the useful life of the synchronous machine. On the other hand, the steady state error is minimized, which in turn can improve the power quality indexes.

Figure 8. Parallel of Fuzzy Control and Classic Pid Control.

Figure 9. Responses fuzzy PID control in red compared to classical PID control in blue.
The study of the mathematical model of the synchronous machine, through the use of Matlab® Simulink, illustrates a practical way for academic purposes to validate the responses of the designs based on alternative controllers to PID, thus encouraging technology and engineering students to explore alternative techniques to conventional control applied to electrical machines.

As future work, it is proposed to make use of optimal control techniques on the traditional PID controller and optimization techniques on the fuzzy controller proposed (using alternative algorithms such as genetic algorithms), in order to make a comparison of the best possible results for both the PID and the fuzzy PID, using the same tools used in the development of this work.

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