An Automatic Voltage Regulator (AVR) System Control using a P-I-DD Controller

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Abstract — In this paper a simple procedure is given to design a P-I-DD controller for an Automatic Voltage Regulator (AVR) system. The controller is designed such that it produces a dead-beat type output response of the AVR system. The design method is then applied to some typical numerical examples and time response simulation of the P-I-DD controlled system is done. A comparison of time domain specifications like peak overshoot, settling time, steady state value etc. for responses of AVR system with and without P-I-DD controller is made for the examples considered clearly indicate the superiority of the proposed procedure.

Keywords — voltage control; AVR system; P-I-D control; P-I-DD controller; dead-beat response

I. INTRODUCTION

In electric power systems, automatic voltage regulator (AVR) is utilized to maintain the terminal voltage of a synchronous generator at a specified level. AVR basically controls the output voltage by controlling the exciter voltage of the synchronous generator. Variations in load and inductance of field windings of the generator may have an undesirable effect on the regulator response. To ensure stable, fast and efficient response to transient disturbances in terminal voltages, additional control mechanism may sometimes be necessary. PID is the most widely used control structure owing to its simplicity and wide range of operations. The P-I-D control mechanism involves the strategy of proper selection of proportional, integral and derivative gains. This process is often termed as ‘tuning’ in the literature. Recently, many methods have been proposed which rely on some or the other intelligent optimization techniques. Such methods include particle swarm optimization (PSO) [5], artificial bee colony (ABC) algorithm [2], pattern search (PS) algorithm [8], chaotic optimization (CO) algorithm [4]. The application of FOPID controller [10] was also recently employed to control AVR system response. The main contribution of this paper is to propose an algorithm to tune the four term structure P-I-D plus second order derivative (P-I-DD) controller [1] for AVR system. The four gains of the controller are obtained using a simple procedure which produces dead-beat type response. The remainder of the paper is as follows: Section II deals with the block diagram model of an AVR system, dead-beat response and design with pre-filter is given in Section III, the proposed procedure is explained in section IV, Section V deals with the time response simulations of some typical numerical examples along with comparison of time-domain specifications.

II. AVR SYSTEM MODELING

The role of an AVR is to hold the terminal voltage magnitude of a synchronous generator at a specified level. A simple AVR system comprises four main components, namely amplifier, exciter, generator, and sensor. An AVR system with their components is shown in Fig. 1. For mathematical modeling and transfer function of the four components, these components must be linearized, which takes into account the major time constant and ignores the saturation or other nonlinearities. The reasonable transfer function of these components may be represented, respectively, as follows.

![Fig.1. Block diagram of a typical AVR system](image)

Amplifier model:
The excitation system amplifier may be a magnetic amplifier, rotating amplifier, or modern electronic amplifier. The amplifier is represented by a gain $K_a$ and a time constant $T_a$ and the transfer function is...
Exciter model:
There is a variety of different excitation types. However, modern excitation systems use ac power source through solid-state rectifiers such as SCR. The output voltage of exciter is a nonlinear function of the field voltage because of the saturation effects in the magnetic circuit. Thus, there is no simple relationship between the terminal voltage and the field voltage of the exciter. A reasonable model of a modern exciter is a linearized model, which takes into account the major time constant and ignores the saturation or other nonlinearities. In the simplest form, the transfer function of a modern exciter may be represented by a single time constant $T_e$ and a gain $K_e$, i.e.,

$$\frac{V_r(s)}{V_e(s)} = \frac{K_e}{1 + T_e s}$$

Generator model:
The synchronous machine generated emf is a function of the machine magnetization curve, and its terminal voltage is dependent on the generator load. In the linearized model, the transfer function relating the generator terminal voltage to its field voltage can be represented by a gain $K_g$ and a time constant $T_g$, and the transfer function is

$$\frac{V_t(s)}{V_f(s)} = \frac{K_g}{1 + T_g s}$$

Sensor model:
The voltage is sensed through a potential transformer and, in one form, it is rectified through a bridge rectifier. The sensor is modeled by a simple first order transfer function, given by a gain $K_s$ and a time constant $T_s$ will be

$$\frac{V_s(s)}{V_t(s)} = \frac{K_s}{1 + T_s s}$$

The typical typical parameter limits are given in Table 1.

<table>
<thead>
<tr>
<th>Transfer function</th>
<th>Parameter limits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amplifier</strong></td>
<td></td>
</tr>
<tr>
<td>$TF_{amplifier} = \frac{K_a}{1 + T_a s}$</td>
<td>$10 \leq K_a \leq 40$; $0.02 \leq T_a \leq 0.1$</td>
</tr>
<tr>
<td><strong>Exciter</strong></td>
<td></td>
</tr>
<tr>
<td>$TF_{exciter} = \frac{K_e}{1 + T_e s}$</td>
<td>$1 \leq K_e \leq 10$; $0.4 \leq T_e \leq 1$</td>
</tr>
<tr>
<td><strong>Generator</strong></td>
<td></td>
</tr>
<tr>
<td>$TF_{generator} = \frac{K_g}{1 + T_g s}$</td>
<td>$0.7 \leq K_g \leq 1$; $1 \leq T_g \leq 2$</td>
</tr>
<tr>
<td><strong>Sensor</strong></td>
<td></td>
</tr>
<tr>
<td>$TF_{sensor} = \frac{K_s}{1 + T_s s}$</td>
<td>$K_s = 1$; $0.001 \leq T_s \leq 0.06$</td>
</tr>
</tbody>
</table>

III. DEAD-BEAT CONTROL AND PRE-FILTER DESIGN

The characteristics of a dead-beat response [12] is as follows:
- steady state error is zero
- fast response with minimum rise time and settling time
- percent peak overshoot in the range of 0.1% ≤ $M_p$ ≤ 2% percent under shoot ≤ 2%

A controller for any unity feedback closed loop system (no zeros) (Fig.2) can be designed such that the overall closed loop system is expected to give a dead-beat response. Consider the transfer function of the closed loop system as $T(s)$. The coefficients of $T(s)$ that yield dead beat response can be chosen from the table 2. for some considered $\omega_n$ value. An example of 4th order closed loop system transfer function be

$$T(s) = \frac{\omega_n^4}{s^4 + \alpha \omega_n s^3 + \beta \omega_n^2 s^2 + \gamma \omega_n^3 + \omega_n^4}$$

A value of $\omega_n$ is first chosen from the required settling time $T_s$ as . $\alpha, \beta, \gamma$ values are chosen from the Table2.
Table 2. Coefficients and response measurement of a deadbeat response system

<table>
<thead>
<tr>
<th>Sys. order</th>
<th>α</th>
<th>β</th>
<th>γ</th>
<th>δ</th>
<th>ε</th>
<th>% peak over overshoot</th>
<th>% under shoot</th>
<th>Rise time (90%)</th>
<th>Rise time (100%)</th>
<th>Settling time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>1.82</td>
<td>0.1</td>
<td>0.0</td>
<td>3.47</td>
<td>6.58</td>
<td>4.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>1.9</td>
<td>2.2</td>
<td>1.65</td>
<td>3.48</td>
<td>4.32</td>
<td>4.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td>2.2</td>
<td>3.5</td>
<td>2.8</td>
<td>0.89</td>
<td>0.95</td>
<td>4.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5th</td>
<td>2.7</td>
<td>4.9</td>
<td>5.4</td>
<td>1.29</td>
<td>0.37</td>
<td>4.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6th</td>
<td>3.15</td>
<td>6.5</td>
<td>8.7</td>
<td>4.05</td>
<td>1.63</td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sometimes the dynamics of the closed loop controlled system due to unwanted zeros and poles may affect the performance of the system forcing the control engineer to somehow get rid of their effect. It is done by pole-zero cancellation using what is called as a pre-filter. The closed loop system with a controller (compensator) along with a pre-filter is shown in the Fig.3.

The new closed loop transfer function with pre-filter now becomes

\[ G_{cl}(s) = \frac{G_c G_{pref}}{1 + G_c G_{pref}} \]

The pre-filter can be modeled such that it eliminates the unwanted poles and zeros of \( G_{cl} \) and improve the response.

IV. PROPOSED P-I-DD CONTROL PROCEDURE

The P-I-DD (double derivative PID controller) is proposed here for the control of an AVR system such that the output of the controlled system (Fig.4) exhibits dead-beat response. In general, P-I-DD controller alone makes the response faster with shorter rise and settling times but may produce unwanted high peak over/undershoots in the transient part. The reason is due to the dynamics of zeros present in the closed loop system. If this effect of the zeros arises in the output response, then it can be nullified or cancelled by using a pre-filter as shown in Fig.5.
The step-wise procedure for the proposed design method of P-I-DD controller is given below:

Step 1: Consider a P-I-DD controller with transfer function

\[ G_{PIDD} = \left( K_p + \frac{K_i}{s} + K_d s + K_d s^2 \right) \]

in the forward path of the AVR system as shown in Fig.4.1

Step 2: The closed loop Transfer function \( G_{AVR PIDD} = \frac{\Delta(s)}{\Omega(s)} \) in unknown parameters of the PIDD controller is obtained.

Step 3: The denominator polynomial of \( G_{AVR PIDD} \), \( \Delta(s) \) is made a monic polynomial \( \Delta(s) \) by dividing the entire polynomial \( \Delta(s) \) with highest power of s co-efficient.

Step 4: This polynomial \( \Delta(s) = s^5 + \beta \omega_n s^4 + \gamma \omega_n^2 s^3 + \delta \omega_n^3 s^2 + \omega_n^4 s + \omega_n^5 \), \( \alpha = 2.7, \beta = 4.9, \gamma = 5.4, \delta = 3.4 \).

Step 5: Obtain the undamped natural frequency \( \omega_n \) as \( \omega_n = \frac{a}{\alpha} \).

Step 6: The unknown P-I-DD parameters \( A, B, C, D \) and hence \( k_p, k_i, k_d1, k_d2 \) can be obtained by solving the following set of equations

\[ b = 4.9\omega_n^2; c = 5.4\omega_n^3; d = 3.4\omega_n^4; e = \omega_n^5 \]

Step 7: The P-I-DD controller thus obtained is considered in the closed loop.

Step 8: Obtain the unit step response of closed loop system \( G_{AVR PIDD} \).

Step 9: If the time response is not satisfactory, design a pre-filter \( G_{PREF} \) such that the zeros of the closed loop system are cancelled with the poles of the pre-filter without changing the steady state value.

Step 10: Obtain a closed loop system \( G_{AVRPIDD1} \) with both controller and pre-filter considered as shown in Fig.4.2.

Step 11: Obtain the unit step response of closed loop system \( G_{AVRPIDD1} \).

V. EXAMPLE AND RESULTS

EXAMPLE 1[4]: Consider the parameters of an AVR system with the following gain and time constants and reference input 1.0 (p.u.)

Amplifier:
Amplifier gain \( (K_a) \) = 10
Amplifier time constant \( (T_a) \) = 0.1
Exciter:
Exciter gain \( (K_e) \) = 1
Exciter time constant \( (T_e) \) = 0.4
Generator:
Generator gain \( (K_g) \) = 0.7
Generator time constant \( (T_g) \) = 1
Sensor:
Sensor gain \( (K_s) \) = 1
Sensor time constant \( (T_s) \) = 0.01

The PIDD parameters are \( k_{d2} = 0.4155, k_{d1} = 22.7063, k_7 = 7501.1, k_p = 606.55 \)
The PIDD controller Transfer function is
\[ G_{PIDD} = \frac{s^3 + 22.7063s^2 + 606.55s + 7501.1}{s} \]
Transfer function of pre-filter is
\[ G_{PREF} = \frac{52510}{0.02909s^4 + 4.498s^3 + 201.4s^2 + 4771s + 52510} \]

The unit step response for PIDD+pre-filter controlled AVR system for example 1 is shown in Fig. 6.

![Unit Step Response](image)

**Fig. 6** Step response of AVR system with PIDD controller with pre-filter

The comparison of time response characteristics of AVR system for uncontrolled and controlled cases is shown in Table 3.

<table>
<thead>
<tr>
<th>System</th>
<th>% Peak overshoot</th>
<th>Rise time (s)</th>
<th>Settling time (s)</th>
<th>Steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVR Closed loop</td>
<td>50.2</td>
<td>0.322</td>
<td>4.89</td>
<td>0.875</td>
</tr>
<tr>
<td>PIDD</td>
<td>95.5</td>
<td>0.0099</td>
<td>0.282</td>
<td>1</td>
</tr>
<tr>
<td>PIDD + pre-filter</td>
<td>1.27</td>
<td>0.066</td>
<td>0.129</td>
<td>1</td>
</tr>
</tbody>
</table>

**EXAMPLE 2[7]:**
Consider an AVR system with the following parameters with 1.0 (p.u.) reference input.

Amplifier:
- Amplifier gain \( K_a \) = 400
- Amplifier time constant \( T_a \) = 0.01

Exciter:
- Exciter gain \( K_e \) = 0.2
- Exciter time constant \( T_e \) = 4

Generator:
- Generator gain \( K_g \) = 1
- Generator time constant \( T_g \) = 1

Sensor:
- Sensor gain \( K_s \) = 1
- Sensor time constant \( T_s \) = 0.001

The PIDD parameters are
\[ k_{d2} = 0.3569, k_{d1} = 183.1394, k_i = 5.6439 \times 10^6, k_p = 47048 \]

The PIDD controller Transfer function is
The unit step response for PIDD+pre-filter controlled AVR system for example 2 is shown in Fig.7.

![Unit Step Response](image)

**Fig.7 Step response of AVR system with PIDD controller with pre-filter**

The comparison of time response characteristics of AVR system for uncontrolled and controlled cases is shown in Table4.

<table>
<thead>
<tr>
<th>System</th>
<th>%Peak overshoot</th>
<th>Rise time(s)</th>
<th>Settling time(s)</th>
<th>Steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVR Closed loop</td>
<td>69.4</td>
<td>0.255</td>
<td>7.21</td>
<td>0.988</td>
</tr>
<tr>
<td>PIDD</td>
<td>97.2</td>
<td>0.007</td>
<td>0.029</td>
<td>1</td>
</tr>
<tr>
<td>PIDD + pre-filter</td>
<td>1.27</td>
<td>0.0068</td>
<td>0.013</td>
<td>1</td>
</tr>
</tbody>
</table>

**EXAMPLE 3:** Consider an AVR system with the following gain and time constants

Amplifier:
- Amplifier gain \( K_a \) = 40
- Amplifier time constant \( T_a \) = 0.05

Exciter:
- Exciter gain \( K_e \) = 1
- Exciter time constant \( T_e \) = 0.5

Generator:
- Generator gain \( K_g \) = 0.8
- Generator time constant \( T_g \) = 1

Sensor:
- Sensor gain \( K_s \) = 1
- Sensor time constant \( T_s \) = 0.001

The PIDD parameters are 
- \( k_{d2} = 0.5315 \), \( k_{d1} = 229.4181 \), \( k_i = 6.1 \times 10^6 \), \( k_p = 54741 \)

The PIDD controller Transfer function is

\[
G_{PIDD} = \frac{0.5315s^3 + 229.4181s^2 + 6.1 \times 10^6s + 54741}{s}
\]
The unit step response for PIDD+pre-filter controlled AVR system for example 3 is shown in Fig.8.

![Unit Step Response](image)

**Fig. 8. Step response of AVR system with PIDD controller with pre-filter**

The comparison of time response characteristics of AVR system for uncontrolled and controlled cases is shown in Table5.

<table>
<thead>
<tr>
<th>System</th>
<th>%Peak overshoot</th>
<th>Rise time(s)</th>
<th>Settling time(s)</th>
<th>Steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVR Closed loop</td>
<td>92.3</td>
<td>0.148</td>
<td>58.8</td>
<td>0.97</td>
</tr>
<tr>
<td>PIDD</td>
<td>99.7</td>
<td>0.0001</td>
<td>0.0356</td>
<td>1</td>
</tr>
<tr>
<td>PIDD + pre-filter</td>
<td>1.27</td>
<td>0.00732</td>
<td>0.0143</td>
<td>1</td>
</tr>
</tbody>
</table>

**IV. CONCLUSIONS**

A P-I-DD controller design method is proposed for an AVR system which is based on deadbeat response. The method is applied for some typical AVR problems and verified successfully. The transient response specifications are compared for systems with and without P-I-DD controller. It can be concluded that the designed P-I-DD controller gives a better transient as well as steady state response.

**REFERENCES**


