CHAPTER 4: FEED-BACK CONTROLLER DESIGN, FABRICATION AND TESTING FOR MHD DUCT POWER CONTROL

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CHAPTER 4

FEEDBACK CONTROLLER DESIGN, FABRICATION AND TESTING FOR MHD DUCT POWER CONTROL++

4.1 Introduction

An attempt has been made in this chapter to practically demonstrate the steady state and transient response of the simulated system described in Chapter 2, with a feedback controller. The experimental setup described in section 3.2 has been used to design the controller for the control of MHD duct power. The phase shifting transformer has been replaced in the experimental setup by the feedback controller.

In order to predict the behaviour of the chosen system the digital simulation of the feedback controller is done using 1st order controller in closed loop system. Because a closed loop system has the advantage of greater accuracy, improved dynamic response and reduced effects of disturbances.

A proportional plus integral type of controller has been designed to achieve good dynamic and steady state responses and compensation is also provided to improve stability. First order estimates are made for stable operation of the controller. The time constants involved with the feedback loop are assumed

++ A major portion of publication number 2 is based on the theme of the material presented in this chapter.
small compared to that of controller. The mathematical model of the controller is obtained and then simulated on the digital computer. The approximate parameters of the controller are determined using step by step calculations as described in chapter 2. An analogue simulation has been done to evaluate exact parameters. With the exact parameters, the feedback controller is designed, fabricated and tested for the steady state and dynamic response of the system. The control logic has been designed with CMOS integrated circuits for low power consumption and high noise immunity.

4.2 Description of the system

The experimental setup chosen for automatic feedback control of MHD power to a.c. system is same as described in section 3.2. The block diagram of the control arrangement is shown in figure 4.1. The detailed diagram of the system is shown in figure B-1 of the appendix B. Model HM-3000 Hall-Pack multipliers are used as power transducer. The detailed specifications, circuit connections and characteristics are attached in table C-1 and figure C-2 in appendix C. The transfer function of this transducer is approximated as pure gain. Tests conducted have shown that this transducer has excellent performance under steady state but unreliable under transient conditions. Therefore a digital integrating type transducer [65] has been used for transient response. The transfer function of this transducer is approximated as
FIG. 4.1 BLOCK DIAGRAM OF MHD GENERATOR INVERTER LINK WITH FEEDBACK CONTROLLER
\[ G_p(s) = \frac{K_1}{(1 + T_1 s)} \]  

where
\( K_1 \) = Gain of transducer and realised as \( 10^{-3} \)
\( T_1 \) = Time constant of transducer and realised as 0.1 sec.

The controller compares the power flow to a.c. bus with set reference power and gives a voltage proportional to the difference power that controls the firing angle \( \alpha \). The transfer function of the PI controller is as under [66].

\[ G_p(s) = \frac{\text{d}P}{\text{d}\alpha} = \frac{K_2}{T_c}(1 + T_c s)/T_c s \]  

where
\( \text{d}P \) = change in power
\( \text{d}\alpha \) = a proportional change in phase shift
\( K_2 \) = gain of PI controller
\( T_c \) = Time constant of PI controller

The output of PI controller is given to firing circuit of the inverter whose transfer function is given as

\[ G_p(s) = \frac{K_3}{1 + T_3 s} \]  

where
\( K_3 \) = gain of the firing circuit of SCR
\( T_3 \) = time constant of the firing circuit
The value of $K_3$ is realised as 0.131. Average gain of inverter firing circuit is calculated as 7.7 degrees/volt from the swing of PI controller as shown in figure C-5 in appendix C. The time constant $T_3$ is taken as 3.3 ms using transportation time delay model [67]. The inverter control system analysis has been subject of many studies [68, 69, 70] but at present none of the thyristor models are considered for theoretical analysis of the system because the exact parameters of the simulated system may be quite different from that of actual system. Therefore an analogue simulation has been carried out for the determination of steady state and transient response of the system.

4.3 Digital simulation of the controller

The usual procedure for simulating the controller on the digital computer is to obtain mathematical model of the controller and then to write the program for simulating this model. For such simulation program, the behaviour of the control system under normal and abnormal operating conditions must be known in advance to enable writing mathematical equations. The assumptions and approximations necessary to translate the actual system characteristics into the mathematical form always introduce inaccuracy. Since the approximate parameters of the controllers are determined with digital simulation, therefore, the unforeseen conditions like harmonics
in the supply voltage, unbalance in the system etc. are left in mathematical formulation.

The proportional controller gives appreciable steady state error and an integral controller gives zero steady state error but adds a phase shift to the system and this decreases the stability. To overcome the above problems a PI controller is used which adjusts gain and phase both. For the present study the PI controller and analogue firing circuit is used. The mathematical model of the transfer function is written from equation 4.2 as

\[ d\delta = (K_2 + 1/T_c) \, dP \]  \hspace{1cm} (4.4)

where the terms used are already defined earlier. In practice the control circuit is provided with compensation such that the transfer function has an extra term as

\[ (1 + T_a s)/(1 - T_b s) \]

However, since the function of compensation circuit is to improve the stability limit of the control loop and the aim of the present analysis is to mapout the onset of instabilities for the worst possible case, the compensation term is ignored for the present analysis.
4.3.1 Computational procedure

Computation is carried out on the digital computer with the approximate analysis of the control system under consideration using an iterative solution [71]. The operating point is same as discussed in section 2.2. For the transient analysis, the step change in duct voltage and resistance is made from operating point. A computer programme has been developed for the calculation of dynamic response of the controller as described by equation 4.4. This programme neglects the resistances in the system and time constants involved in the firing circuit and power transducer. Generally the controller time constant is appreciably larger than the dead time involved in cascade loop. Therefore the effect of transducer and firing circuit dynamics is neglected for the initial design of feedback controller. Figure 4.2 shows the flow chart for the calculation of transient response of the system.

4.3.2 Transient response of the simulated system

The approximate value of the proportional and integral gain is determined following the iterative procedure [71]. First operating point is defined and reference power is chosen. Time step for calculations and controller gain are selected. A step change in operating voltage is made by switching the charged batteries. The power variation with time due to step
INPUT
AK, EB, A, XL, V0, R0

SELECT
REFERENCE POWER, TIME STEP AND CONTROLLER GAINS

INITIALIZE PROGRAM VARIABLES

COMPUTE REAL AND REACTIVE POWER, APPLY PHASE SHIFT CONTROL USING STEP BY STEP ITERATION METHOD

OUTPUT
TIME, REAL AND REACTIVE POWER

INCREASE TRANSIENT TIME (T) \( \rightarrow T + \Delta t \)
PHASE SHIFT ANGLE (A) \( \rightarrow A + \Delta A \)

STOP

YES

IS TRANSIENT PERIOD FINISHED

NO

FIG. 4.2. FLOW CHART OF TRANSIENT RESPONSE OF CONTROLLER
increase and decrease in operating voltage is shown in figure 4.3(a). The transients are oscillatory and continue for longer time for selected gains. Now the proportional gain is kept constant and the integral gain is varied as shown in figure 4.4(a). The overshoot and settling time both reduce and settling time is approximately calculated as 0.5 second.

Similarly the transient response due to setp change in resistance is calculated and the power variation for step decrease in resistance is plotted in figure 4.3(b). The proportional and integral gains were varied and the best response was calculated and potted as shown in figure 4.4(b). The transients due to voltage variation is more pronounced compared to resistance variation. This is obvious and can be realised from equation (2.29) of section 2.3.3.

4.4 Analogue simulation of PI controller

An important application of analogue computer is the simulation of control systems by employing computing modules, namely integrators, summers and potentiometers. The greatest asset of an analogue computer is that when setup, it resembles closely the system studied, a one to one correspondence between the variables of the physical problem and the analogue computer setup may be ensured with fast operation. The analogue computer works in real time and accepts continuous waveforms as
(a) Step Change in Voltage

(b) Step Change in Resistance

FIG. 4.3 TRANSIENT RESPONSE OF SIMULATED FEED BACK CONTROLLER.
FIG. 4.4 TRANSIENT RESPONSE OF SIMULATED FEEDBACK CONTROLLER.
inputs. Thus use of analogue computers as compensators or controllers in feedback system is easily implemented. Therefore the PI controller is simulated on analogue computer type YEW 3316-11 and 3316-21 and YEW 3318-11 and 3318-21 series. Figure 4.5 shows the analogue computer simulation of PI controller. The power transducer described earlier gives a proportional voltage for the power flow to infinite bus from MHD duct. This is compared to a reference power available from preset potentiometer after necessary amplification. The error signal is fed to controller and gains are adjusted to get stable operation of the system for step change in duct resistance and voltage. The symbolic representation and use of above analogue computer components are shown in figures C-3 and C-4 in appendix C.

4.4.1 Transient response of the system with PI controller

The approximate values of the controller gains are already calculated from the digital simulation described in section 4.3. The power variation with time due to step increase and decrease in voltage is recorded on X-Y recorder for open loop system. The potentiometers are varied till best response is obtained. Figure 4.6(b) shows the open loop response to a step change in duct voltage. The best results are obtained for proportional gain ($K_p$) = 10 and integral gain ($K_i$) = 10. Figure 4.6(a) shows similar response for step
FIG. 4.5 ANALOGUE COMPUTER SIMULATION OF THE PI CONTROLLER.
FIG. 4.6 TRANSIENT RESPONSE OF ANALOGUE SIMULATION OF PI CONTROLLER.
change in resistance for different settings of $K_p$ and $K_I$.

A closed loop system generally has the advantage of greater accuracy, improved transient response and reduced effects of disturbances. Therefore closed loop operation is preferred. Figure 4.7 is a plot for power versus time variation due to step change in resistance and voltage of the MHD duct in closed loop system. The best response is recorded for $K_p = 7.5$ and $K_I = 8.9$ in closed loop operation.

4.5 Analogue simulation of PID controller

The performance of a control system is measured by its stability, accuracy and speed of response. In general these items are specified when a system is being designed to satisfy a specific task. Quite often the simultaneous satisfaction of all these requirements cannot be achieved by using the basic elements in the control system. The desired transient response as well as steady state behaviour of a system may be obtained by introducing the compensatory elements into the control system. These compensatory elements are designed so that they help achieve system performance i.e. bandwidth, phase margin, peak overshoot, steady state error etc. without modifying the entire system in a major way. Therefore a compensation is provided to the analogue simulation of figure 4.5. Figure 4.8 shows analogue simulation with compensation. The gains $K_p$, $K_I$ and $K_d$ are changed to get the best performance.
(a) Step Change in Ro (Closed loop)

K_p = 7.5, K_I = 8.9

FIG. 4.7 TRANSIENT RESPONSE OF ANALOGUE SIMULATION OF PI CONTROLLER.
FIG. 4-8 ANALOGUE COMPUTER SIMULATION OF THE PID CONTROLLER
of the controller for step change in duct voltage and resistance.

4.5.1 Transient response of the system with PID controller

The controller gains determined in section 4.4.1 are set on potentiometer and a derivative gain is also added. The power variation with time due to step change in resistance and voltage is recorded. Figure 4.9 shows the power variation due to step change in voltage with and without compensation. It can be seen from above figure that with compensation the system response improves and time taken for the transients to die down is approximately half than that in the uncompensated case.

4.6 Design and fabrication of feedback controller

The analogue simulation of the controller in last section determines the gains for the best performance of the controller and possible swing of the controller. These two parameters are used to design the controller. For chosen operating point as discussed earlier, the reference power gives a proportional voltage of 6 volts after amplification. This voltage is taken as reference power. The swing of the PI controller is determined from this reference for 25 percent change in voltage and resistance of the duct as shown in figure C-5 in appendix C. The fixed time delay is adjusted
FIG. 4.9 TRANSIENT RESPONSE OF ANALOGUE SIMULATION OF PID CONTROLLER
from the timing components of the dual monostable and variable time delay is adjusted so that the zero feedback gives a fixed time delay as 3 ms. The pulse to the input of the dual monostable is obtained from phase A, B and C with a $240/9.5$ v volts transformer through a squaring and waveshaping circuit. The control logic uses dual pack type 747 C operational amplifier, dual pack MM 74C221 monostable and CD4013B type dual D' type flip-flop. The detailed specification of these devices are given in figures C-6 to C-11 in appendix C. The designed feedback controller is fabricated as shown in Figure 4.10.

4.6.1 Transient response of the system with fabricated feedback controller

The analogue controller is replaced by the above fabricated controller. The step changes in resistance and voltage are made as already discussed in section 4.4.1. The response is stored on a multichannel oscilloscope and photographed for the best performance of the controller with and without compensation. Figure 4.11 shows the oscillograms for transient, response of the controller with step change in $R_o$. Following cases are considered for stable operation of the controller.
Figure 4.11(a) Without compensation

(i) \( K_p = 1.2 \) and \( K_I = 10 \)

(ii) \( K_p = 2.4 \) and \( K_I = 10 \)

(iii) \( K_p = 4.0 \) and \( K_I = 10 \)

Figure 4.11(b) With compensation

(i) \( K_p = 10, K_I = 8.3 \) and \( K_d = 5.7 \)

(ii) \( K_p = 10, K_I = 8.0 \) and \( K_d = 5.7 \)

(iii) \( K_p = 10, K_I = 6.0 \) and \( K_d = 2.7 \)

Figure 4.12 shows the oscillograms for transient response of the controller with step change in \( V_o \). Following cases are considered for stable operation of the controller.

Figure 4.12(a) Without compensation

(i) \( K_p = 1.0 \) and \( K_I = 9.5 \)

(ii) \( K_p = 5.0 \) and \( K_I = 9.5 \)

(iii) \( K_p = 6.0 \) and \( K_I = 9.5 \)

Figure 4.12(b) With compensation

(i) \( K_p = 1.0, K_I = 9.5 \) and \( K_d = 2.8 \)

(ii) \( K_p = 5.0, K_I = 9.5 \) and \( K_d = 2.8 \)

(iii) \( K_p = 6.0, K_I = 9.5 \) and \( K_d = 5.7 \)

Using these results, the control system performance was examined
FIG. 4.11. TRANSIENT RESPONSE OF CONTROLLER WITH STEP CHANGE IN Ro.
FIG. 4.12. TRANSIENT RESPONSE OF CONTROLLER WITH STEP CHANGE IN Vo.

(a) WITHOUT COMPENSATION

(b) WITH COMPENSATION

Scale:
X-Axis: ~ 0.2 Sec/cm.
Y-Axis: ~ 10 mV/cm.

Scale:
X-Axis: ~ 0.1 Sec/cm.
Y-Axis: ~ 10 mV/cm.
for various combinations of $K_p$, $K_I$ and $K_d$. The best performance was obtained with

$$K_p = 1.0, \quad K_I = 9.5 \quad \text{and} \quad K_d = 2.8$$

The feedback controller was finally designed and fabricated as photographed in figure 4.15.

4.7 **MHD duct power control**

The quasistatic changes in fluid-dynamic conditions ($M \neq N \neq 1$) has been discussed in section 2.2.2. In this section, the changes in resistance and voltage of the simulated duct are made for the automatic power control. The variation in resistance is made as discussed in section 3.3.3 for duct voltage of 2 PU. The variation in voltage is made as discussed in section 3.3.4 for 30 degrees phase shift for the safe inverter operation.

4.7.1 **Power control for changes in internal resistance**

The variation of resistance is considered from operating point as shown in figure 4.13. The negative sign signifies the reduction in resistance from operating point. The variation of power is shown in the above figure with and without phase shift control. Reference power is maintained for reduction in resistance but the system becomes unstable beyond an increase of 25 percent in resistance. The reactive
FIG. 4.13 VARIATION OF REAL POWER WITH \( R_0 \)

- With Phase Shift Control
- Without Phase Shift Control

\[ V_0 = 2.0 \text{ P.u.} \]

 Powers in P.U.: 1.4, 1.2, 0.8, 0.4

% Change in \( R_0 \):

- Pref.
- Unstable

135
power remains within the limit so that the desired power factor is maintained. The changes in resistance are made in steps as described in section 3.3.5.

4.7.2 Power control for changes in duct voltage

Variation in duct voltage is considered in this section for rated value of internal resistance. The negative sign signifies reduction in duct voltage. Figure 4.14 shows the variation of real power with and without phase shift control. The graph shows that the system becomes unstable for reduction in voltage beyond approximately 25 percent. The variation in voltage is made as described in section 3.5.2. The reactive power does not vary much and remains within the desired limit as discussed in section 2.6.6.

4.8 Discussion and comparison of the results

The feedback controller described in section 4.2 is used for automatic control of power for the simulated MHD duct. The controller for 2 MW (thermal) MHD test facility may be designed from the experience gained in this chapter. The digital simulation of the controller gives approximate parameters because of simplified analysis. However, higher order mathematical modelling can be made to account for the other time constants involved with the control loop. In this chapter the analogue simulation has been used to determine the
FIG. 4.14 VARIATION OF REAL POWER WITH Vo.
behaviour of the simulated system instead of going to mathematical modelling. The transient response of the analogue simulation and fabricated feedback controller are found to be in reasonable agreement with each other.

### 4.9 Summary and Conclusion

This chapter is devoted to demonstrate the steady state and transient response of the MHD-inverter link with feedback controller. The manual control described in last chapter has been replaced by the feedback controller. The design of the controller is carried out first with digital simulation then with analogue simulation. The controller is designed, fabricated and tested on the MHD-inverter link in open loop and closed loop system. Transient response has been recorded on the X-Y recorder and oscillograms are also obtained. Theoretical results of the transient response are compared with those of fabricated controller. The controller designed in this chapter may be utilised for power control of the 2 MW (thermal) MHD generator test facility.