On Automatic Voltage Regulator Design for Synchronous Generators

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Abstract: An investigation for a new generation of practical adaptive automatic voltage regulators for synchronous generators is reported. Root locus methods are used to convincingly demonstrate the nature of the AVR problem. The multivariable structure of an existing additional feedback solution is explored. The design requirements for a polynomial LQG controller are reported as a preliminary framework for an ongoing self-tuning controller development.

Keywords: *AVR design, AVR implementation, Power Systems, LQG controller.*

1. Introduction

In a power station there is usually more than one generator connected to the same busbar and each has an individual automatic voltage regulator (AVR). The design objective for an AVR is to control the voltage at the terminals of the generator, namely achieve primary voltage control. Over recent years, ENEL has had a research programme investigating various aspects of the AVR and related control problems. Among the achievements of this programme was the construction of a real-time digital simulator of the power station-network system called STAR. The simulator can be used to test and fine-tune generator voltage regulators and excitation systems. It reduces the times for factory testing and installation at the power plant (*Arcidiacono et al*, 1989). ENEL have a history of technical innovation and its interest in the AVR problem and power system stabilizers is long standing (*Arcidiacono et al*, 1980). For new power plant and for power plant refurbishment ENEL has developed and is applying a new generation of excitation control systems using microprocessor technology. The numerical potential of this advanced technology allows the economic implementation of sophisticated control algorithms.

1.1 *AVR research literature review*

The literature also show similar trends and there has been a sequence of recent publications showing interest in applying *adaptive* control techniques to the AVR problem. *Ibrahim et al* (1989) reported the theoretical development and laboratory testing of several adaptive control algorithms based on minimum variance and pole-placement concepts. The need for thoroughly tested jacketing software was highlighted in their study. *Mao et al* (1990) also pursued an adaptive approach but used a discrete optimal linear quadratic control law solving a (3x3) algebraic Riccati equation. *Farsi et al* (1991) proposed an adaptive Generalised Predictive Control (GPC) solution to the design of an AVR. A microprocessor implementation using a laboratory scale model turbogenerator simulator showed that the computational burden of the GPC algorithm was feasible in real-time. *Unbehauen and Keuchel* (1992) developed a direct robust model reference adaptive control (MRAC) strategy for use with a broad class of electrical machines. The basic MRAC was modified to accommodate a non-minimum phase system, and this scheme was shown to work well even in the presence of model-plant mismatch.

The ENEL approach has also been to accommodate system variations using an adaptive method. However, the control algorithm has been closely linked to the idea of improving the electromechanical damping using the additional feedback of electric power and angular speed (*Arcidiacono et al*, 1980; *Brasca et al*, 1993). This particular development used on-line recursive least squares with a forgetting factor to up-date the model and an optimization procedure to determine the additional feedback gains. The study included tests using the real-time STAR simulator and experimental field trials at Monfalcone Power Station in Italy. The results reported by *Brasca et al* (1993) were considered quite promising. Subsequent to the field trials and the evidence supporting an adaptive scheme, some fundamental studies were performed to create the framework for a second generation prototype design. This paper reports these findings and anticipates some of the research directions to be pursued in projected future work.

1.2 *Outline of the paper*

In Section 2, the AVR system characteristics and the pole-zero properties of the system are investigated. In Section 3, the conventional additional feedback solution is shown to be a multivariable controller of constrained structure. Section 4 describes the motivation for a multivariable polynomial LQG design framework for AVR design. Some preliminary design results are presented in Section 5. Conclusions brings the paper to a close.

2. Features of the AVR Problem

Although the AVR literature describes the need to increase the damping of the electromechanical modes these

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papers do not explicitly display the real crux of the AVR design problem. In this section, advantage is taken of a nonlinear model (*Brasca,* 1993) to demonstrate the design difficulty using a root-locus investigation.

2.1 *AVR's for synchronous generators : Open loop model*

The AVR is designed to regulate the excitation voltage for a single synchronous generator connected to an infinite bus, as in Fig. 1. A full nonlinear state-space model has been developed for the interactive electromechanical and electromagnetic loops of the generator-alternator-network. It is this model, when linearised, which forms the basis for the results given here. The linear state space model has five states, one manipulatable input, the voltage reference and three measurable outputs, namely the terminal voltage, v, electrical power, P_e, and angular velocity of the rotor, ω.

The automatic voltage regulator is designed to control the terminal voltage to a reference value, v_r. However, the AVR degrades the stability of the electromechanical modes and the conventional Power System Stabilizer (PSS) uses additional feedbacks to compensate for this effect. Whilst the use of additional feedbacks may improve the damping of the electromechanical modes, the interaction between the loops causes a deterioration in the dynamic performance of voltage tracking. This interactive nature of the system behaviour cannot be readily seen in the linearised model block diagrams. A return to fundamentals reveals a simple single input, multi output system as shown in Fig. 2, where the transfer functions were obtained from the linear state-space form. Three operating points were selected. The system was fifth order and exhibited the following open loop features.

	Operating Point			Characteristics of Open Loop System	
	P_o	Q_o	V_o	Poles (Least Stable)	Zeros of $G_{11}(s)$
1	0.9	-0.33	0.95	Unstable (p=+0.0051)	Damping 0.02
2	0.9	0.0	1.0	Stable (p=-0.12)	Damping 0.155
3	0.9	0.4	1.05	Stable (p=-0.3116)	Damping 0.258

Table 1 : ***Open Loop System Features*** where external reactance $X_e = x_t + x_l = 0.2$ pu, P_o = active power, Q_o = reactive power and V_o = machine voltage.

The complex conjugate pair of zeros were only found in the transfer function $G_{11}(s)$.

2.2 *AVR design as a SISO control problem*

Classical control of the external voltage uses PI control of the excitation voltage as a SISO design around $G_{11}(s)$. The design method involves selecting an operating point, and designing a PI controller. The characteristics of the open loop plant shown in Table 1 will obviously create difficulties for this design solution since the selected controller may not be able to stabilize some operating points. A root locus exercise demonstrates this feature succinctly. Fig. 3 shows the SISO closed loop PI compensated system. Fig. 4 shows the root locus for the least stable operating condition, No. 1, and Fig 5 shows the locus for the more stable operating condition, No. 3. A look at the associated step responses shows highly oscillatory components and it is clear that SISO design will not solve the problems of AVR design. Indeed, although the use of additional feedbacks is long standing (*Arcidiacono et al,* 1980), the multivariable control aspects of this technique do not appear to have been clarified and this is described next.

3. Additional Feedbacks as Multivariable Control

To improve the stability and the associated time responses of a SISO AVR design additional feedbacks are used. A practical AVR based on ENEL's design developed by *Brasca et al* (1993) is shown in Fig 6. As can be seen the additional feedbacks are taken from the active electrical power variable, P_e and the angular speed ω. These are filtered by a high pass filter to remove the low frequency components.

3.1 The multivariable system context of AVR design

Multivariable system theory intimates that:

(i) Transmission zeros will attract closed loop poles as the controller gain is increased. Thus, a lightly damped pair or right half-plane transmission zeros will create constraints on the achievable closed loop pole positions and the related time domain performance obtainable.

(ii) Transmission zeros are associated with square systems and generically non square systems almost always have no transmission zeros (Davison and Wang, 1974).

As Fig 6 shows, the AVR and additional feedbacks control is a multivariable (3x1) linear system. The results of Table 1 show that $G_{11}(s)$ has a complex conjugate pair of transmission zeros whose position (damping) depend on the prevailing operating condition. The transfer functions $G_{21}(s)$ and $G_{22}(s)$ do not contain this complex conjugate zero pair. Clearly in the SISO design exercises of Section 2.2 it is the presence of the changing complex conjugate transmission zeros which restricts achievable performance. In the multivariable case, $G_{11}(s)$, $G_{21}(s)$ and $G_{31}(s)$ have no common zero and overall, this non-square system transfer function has no transmission zeros. Consequently there is no inherent restriction to achievable performance.

3.2 *Implications for multivariable AVR design*

The recognition that the additional feedback structure is a multivariable controller leads to some straightforward analysis. Use Fig. 6 to obtain:

$$U(s) = K_p I(s)[V_r(s)$$
$$-[-H(s)(K_\omega \Delta\omega(s) - K_{pe}\Delta P_e(s)) + \Delta V(s)]]$$

Introduce a reference vector $\mathbf{R}(s) = [V_r(s), 0, 0]^T$ and output vector $\mathbf{Y}(s)=[\Delta V(s), \Delta P_e(s), \Delta\omega(s)]^T$ and seek a controller of the form $\mathbf{U}(s) = \mathbf{K}(s)[\mathbf{R}(s) - \mathbf{Y}(s)]$. It is not difficult to show $\mathbf{K}(s)=[K_p I(s)][1, H(s)K_p, -H(s)K_\omega]$ and the multivariable control structure is shown in Fig 7. In this form it is easy to see how the practical problem requirements have constrained the available freedom in the multivariable controller. There is the same PI controller in all three loops, the same high pass filtering in two loops and the controller constants K_p, K_{pe}, K_ω and T_I are the only tuning variables. These fundamental considerations lead to two conclusions:

(i) The variation of system characteristics for different operating conditions requires an adaptive control mechanism.
(ii) The full multivariable control structure of the additional feedbacks method should be investigated and exploited (*Brasca*, 1993).

4. A Multiloop LQG Polynomial Approach

A general framework was sought for the multivariable AVR design which has the potential to accommodate the requirement for adaptation. For this a polynomial multivariable LQG setting was adopted. The requirement for microprocessor implementation and online recursive identification indicates that a discrete formulation would eventually be required for use. However, the preliminary study reported here concentrated on a s-domain version of the LQG multivariable polynomial controller. The reasons for this choice included:

(i) The stochastic nature of the AVR problem suits a LQG formulation.
(ii) The relationships between the discrete and s-domain polynomial LQG solution equations are very close with useful conceptual and computational connections.
(iii) The LQG multivariable polynomial formulation is extremely general and readily leads to a range of structures SISO, SIMO and MIMO and incorporates useful design facilities like the use of dynamic weightings (*Grimble*, 1986 ; *Grimble and Johnson*, 1988).
(iv) The structure inherent in the multivariable formulation can be exploited in the development programme to enable the engineer to learn about the design method through evolutionary steps as is reported in the sequel.

4.1 *The multi-input, multi-output framework for LQG polynomial system design*

The full MIMO structure is shown in Fig. 8. Introduce system dimensions as, r = number of outputs, m - number of inputs and the usual notation for transfer function matrices $\Re^{axb}(s)$ and polynomial matrices $\Re^{axb}[s]$ of dimension, *(axb)*. The following definitions are useful:

Plant:

$$W_p(s) = A_p^{-1}(s)\tilde{B}_p(s) \in \Re^{rxm}(s)$$

Input Disturbance:

$$W_d(s) = A_d^{-1}(s)\tilde{C}_p(s) \in \Re^{rxm_1}(s)$$

Output Disturbance:

$$W_n(s) = A_n^{-1}(s)\tilde{C}_n(s) \in \Re^{rxm_2}(s)$$

Reference System:

$$W_r(s) = A_r^{-1}(s)\tilde{E}(s) \in \Re^{rxr}(s)$$

The plant and its subsystems are assumed to be free of hidden unstable modes. A common denominator framework is used so that:

$$[A_p^{-1}\tilde{B}_p, A_d^{-1}C_d, A_n^{-1}C_n, A_r^{-1}\tilde{E}] = A^{-1}[B_p, C_d, C_n, E]$$

The cost function to be minimised is:

$$J = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} trace\{Q_c\Phi_{ee}\} + trace\{R_c\Phi_{uu}\}ds$$

with dynamic weights given by:

$$Q_c = A_q^{-*}B_q^{*}B_q A_q \in \Re^{rxr}(s) \quad and$$

$$R_c = A_r^{-*}B_r^{*}B_r A_r \in \Re^{mxm}(s)$$

The solution procedure is analogous to the proof for the discrete case given by *Grimble* (1986). Further useful material can be found in *Grimble and Johnson* (1988).
The solution yields the following set of equations:

Re-defined Outputs/Inputs (to incorporate the cost weightings):

(i) $A_q^{-1}A^{-1}B = B_1A_1^{-1} \in \Re^{rxm}(s)$

(ii) $A_r^{-1}A_1 = A_{1o}A_{ro}^{-1} \in \Re^{mxm}(s)$

(iii) $A_c = A_rA_{1o} = A_1A_{ro} \in \Re^{mxm}[s]$

Control Spectral Factor;

$$D_c^{*}D_c = A_{ro}^{*}B_1^{*}B_q^{*}B_qB_1A_{ro} + A_{10}^{*}B_r^{*}B_rA_{10}$$

Filter Spectral Factor:

$$D_f^{*}D_f = EE^{*} + C_dC_d^{*} + C_nC_n^{*}$$

Right Coprime Decompositions:

(i) $D_f^{-1}AA_q = A_2D_2^{-1}$

(ii) $D_f^{-1}BA_r = B_2D_3^{-1}$

Coupled Diophantine Equations : Minimum degree solution (H_o, G_o, F_o) with respect to $F \in \Re^{mxm}[s]$ sought.

$$\overset{*}{D}_c G + FA_2 = L_1$$

$$\overset{*}{D}_c G - FB_3 = L_2$$

where $L_1 = \overset{*}{A}_{ro} \overset{*}{B}_1 \overset{*}{B}_q B_q D_2$ *and* $L_2 = \overset{*}{A}_{1o} \overset{*}{B}_r B_r D_3$

Third Diophantine Equation : Min. deg. solution (L_o, P_o) w.r.t. P where

$$\overset{*}{D}_{fq} \overset{*}{D}_c L + PA_{qf} = L_3$$

and $\overset{-*}{D}_{fq} L_3 A_{qf}^{-1} = \overset{*}{A}_{ro} \overset{*}{B}_1 \overset{*}{B}_q B_q A_q^{-1} A^{-1} C_n \overset{*}{C}_n \overset{-*}{D}_f$ with L_3 polynomial, A_{qf} and D_{fq} both polynomial and strictly Hurwitz.

Controller

$$C_o = (H_o D_3^{-1} A_r^{-1} + L_o A_{qf}^{-1} D_f^{-1} B)^{-1} x$$
$$(G_o D_3^{-1} A_q^{-1} - L_o A_{qf}^{-1} D_f^{-1} A)$$

Implied Equation:

$$G_o D_2^{-1} B_1 A_{ro} + H_o D_3^{-1} A_{1o} = D_c$$

Closed Loop Characteristic Equation:

$$\rho_{c\ell}(s) = \det(D_f D_c)$$

This multivariable polynomial LQG system configuration provides a framework for an evolutionary approach to AVR design because the SISO, and SIMO systems can be extracted by the following simple specializations:

(i) *SISO solution* : Set r = m = 1
(ii) *SIMO solution* : Set r = 3 and m = 1

It is not intended in this paper to develop the algebraic development and simplifications for these two solutions. Details can be found in *Brasca* (1993) in so far as they apply to the AVR design problem. Of more interest is to briefly address the preliminary design results arising from the research so far.

5. Preliminary Design Studies

The results to be presented were obtained from a preliminary design study. The tests and experiments were designed to comprehend the LQG polynomial philosophy and its applicability to AVR problem.

5.1 Single input, single output AVR design

In this case only the voltage loop was considered, and hence by setting $r=m=1$, the general formulation collapsed to a SISO problem. Clearly, from a computational viewpoint, the important fact is that all the polynomial matrix equations of Section 4.1 become scalar polynomial equations.

The three operating conditions shown in Table 1 were used for the tests since these permit a complete view of open loop pole-zero changes with operating point. The stochastic disturbances of the system are represented by the various noise models $W_d(s)$ and $W_n(s)$. The parameters to be changed to obtain satisfactory control performance are the cost function weightings $Q_c(s)$ and $R_c(s)$. As can be seen, dynamic weights are permitted. A series of experiments were performed to achieve the following control objectives:

(i) No steady state offset in the voltage signal to a step change in voltage reference.
(ii) A rise time in the voltage signal from 200 millisecs. up to 2 secs. These values cover most of the typical operation condition requirements.
(iii) A 5 % settle-time from 1.5 secs. up to 10 secs. is sought in the voltage signal. Again this should cover the demands of most operating conditions.
(iv) An overshoot of less than 30% in the voltage signal when experiencing a step change in voltage reference.
(v) In the electric power signal, the 5% settle time should be less than 10 secs. for a step change in voltage reference.
(vi) The disturbance to the electric power signal should not exceed a 2 unit peak disturbance.

It should be emphasized that these objectives are for the SISO AVR design (that is, without additional feedbacks). However, it is interesting to note that they are time-domain specifications and have features which are related to the multivariable nature of the AVR problem. It would seem far more natural to adopt a multivariable view of the AVR design and anticipate significant benefits for such an approach. Future research will pursue this direction. However, in this paper the SISO polynomial design is pursued.

5.1.1 *Omission of the reference model, $W_r(s)$*

Aim: To see the effect of omitting the reference model from the formulation. Constant weights assumed.
Results: Integral action is not present in the controller and a steady-state voltage offset persists. Figs. 9a and 9b show this offset. The offset decreases and the system's speed of response increases when the error costing Q_c is increased, however, P_e is quite unacceptably disturbed.

5.1.2 *Constant weights with reference model installed*

Aim: To establish the effect of incorporating a reference model, and to determine if one cost weighting set will provide satisfactory control over several operating conditions.
Results: Fig. 10a shows the time responses for the least stable operating point, No. 1. Fig. 10b shows the results for the same controller applied to operating point No. 3. The

poles of the controller reveal that integral action (or a pole very close to the origin) is now present in the controller. This explains the zero steady state error observed in the step responses. The evidence is that one set of weighting values will provide a controller which stabilizes across operating points. Of course, the high value of $Q_c = 10^4$ selected here implies that the control term is lightly costed and the control signal should be examined for acceptability.

5.1.3 *The use of dynamic weights*

Aim: To examine the effectiveness of introducing integral action using the weights of the cost function.

Results: A fairly extensive investigation was performed involving a comparison of different numerical solution procedures. The most interesting results came from the weight selection process. After a few trials, weights were selected with a simple structure:

$$Q_c(s) = B_q^* B_q \,/\, (A_q^* A_q) \text{ and } R_c(s) = B_r^* B_r \,/\, (A_r^* A_r)$$

$$\text{with } B_q = q_o^{1/2} s + q_i^{1/2} \text{ and } B_r = r_o^{1/2}$$

$$A_q = d_o^{1/2} s + d_i^{1/2} \text{ and } A_r = 1$$

Useful values giving satisfactory results were:

Set (i)	$q_o = 1$	$q_i = 100$	$d_o = 1$	$d_i = 0$	$r_o = 1$
Set (ii)	$q_o = 1$	$q_i = 900$	$d_o = 1$	$d_i = 0$	$r_o = 1$
Set (iii)	$q_o = 1$	$q_i = 2500$	$d_o = 1$	$d_i = 0$	$r_o = 1$

The time responses for Set (iii) are given in Fig. 11a and 11b. The conclusions from these exercises was that one set of weights can be used for good global responses. Some investigations of the numerical routines seems necessary to ensure numerically robust calculations.

5.2 ***Single-Input, Multi-Output LQG AVR Design***

The use of an advanced control technique does not in its self guarantee improved performance. Performance is dependent on the system's characteristics. In earlier section of the paper, the control system features of the AVR problem were clarified. The LQG polynomial framework is a natural setting for an additional feedbacks solution which has been demonstrated to be a SIMO control system design problem.

5.2.1 *LQG Additional Feedbacks with Constant Weights*

Aim: A first formulation of the SIMO LQG polynomial approach was constructed and tested.

Results: Constant weights of a diagonal structure were assumed for the first procedure which used $m = 1$ and $r = 3$. The algorithm has four scalar spectral factorizations as its most computationally demanding step. Fig. 12 shows the responses obtained after only a few trial runs and that different weights on the different outputs has given the best results.

6. **Conclusions**

A multivariable control perspective of the conventional additional feedbacks solution to AVR design has been presented. The advantage achieved is a clear appreciation of the problems inherent to AVR design from a control systems viewpoint.

A multivariable LQG polynomial systems framework was proposed for AVR design. The conceptual benefits of this proposal was described. The need to tailor the general framework of Grimble (1986) to the different SISO and SIMO AVR problems was detailed.

Finally, some simple design experiments were performed to investigate the hierarchy of design freedoms available. This initial work showed significant promise and indicated some future research directions to be pursued.

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8. **References**

1. Arcidiacono V., C. Brasca and S. Corsi, 1989, *STAR : simulatore in tempo reale del sistema alternatore rete*, Riunione Annuale AEI.
2. Arcidiacono V., E. Ferrari, R. Marconato, J. Dos Chali and D. Grandez, 1980, *Evaluation and improvement of electromechanical oscillation damping by means of eigenvalue-eigenvector analysis : Practical results in the Central Peru Power Station*, IEEE Trans PAS, March/April.
3. Brasca C.L., 1993, MPhil Thesis, Industrial Control Centre, University of Strathclyde, Glasgow, U.K.
4. Brasca C., V. Arcidiacono and S. Corsi, 1993, *An adaptive excitation controller for synchronous generators : Studies and experimental results at a power station*, 2nd IEEE Conference on Control Application, Vancouver, Canada.
5. Davison E.J. and S.H. Wang, 1974, *Properties and calculation of transmission zeros of linear multivariable systems*, Automatica, Vol 10, 643-658.
6. Farsi M., K.J. Zachariah, J.W. Finch, and P.A.L. Ham, 1991, A *self-tuning voltage regulator for turbogenerators*, Paper WP15 14:30, 1026-1031, American Control Conference, Boston, U.S.A.
7. Grimble M.J. 1986, *Multivariable controllers for LQG self-tuning applications with coloured measurement noise and dynamic cost weighting*, Int. J. Sys. Sci., Vol 17, No.6, (543-557).
8. Grimble M.J. and M.A. Johnson, 1988, *Optimal control and stochastic estimation : Theory and applications*, Volume 2, John Wiley and Sons Ltd, Chichester, U.K.
9. Ibrahim A.S., B.W. Hogg and M.M. Sharaf, 1989, *Self-tuning automatic voltage regulators for a synchronous generator*, IEE Proc., Vol. 136, Part D, No.5, 252-260, September.

10. Mao C., O.P. Malik, G.S. Hope and J. Fan, 1990, *An adaptive generator excitation controller based on linear optimal control*, IEEE/PS Summer Meeting, Paper 90 SM 425-9 EC, Minneapolis, Minnesota, July 15-19.
11. Unbehauen H. and U. Keuchal, 1992, *Model reference adaptive control applied to electrical machines*, Int. J. of Adaptive Control and Signal Processing Vol 6, No 2, 95-109.

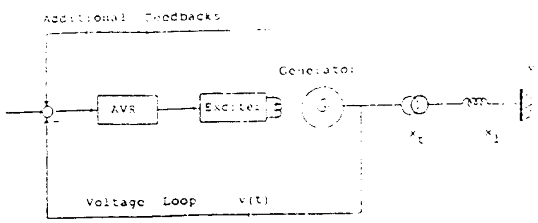


Fig. 1 : Single Synchronous Generator Connected to an Infinite Bus

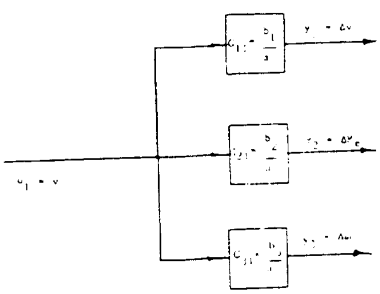


Fig. 2 : Single -input, Multi-output AVR System Structure

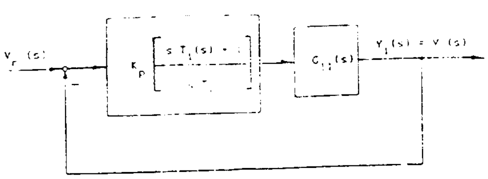


Fig. 3: SISO P plus I AVR Design

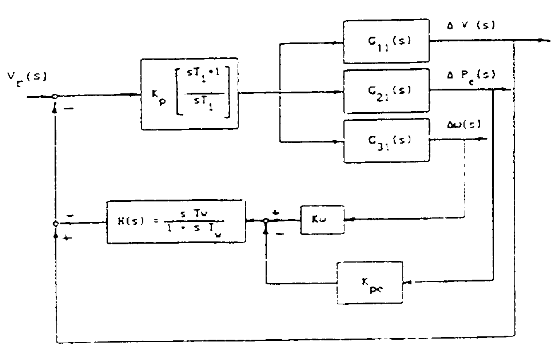


Fig. 6 : Practical AVR Circuit with additional feedbacks

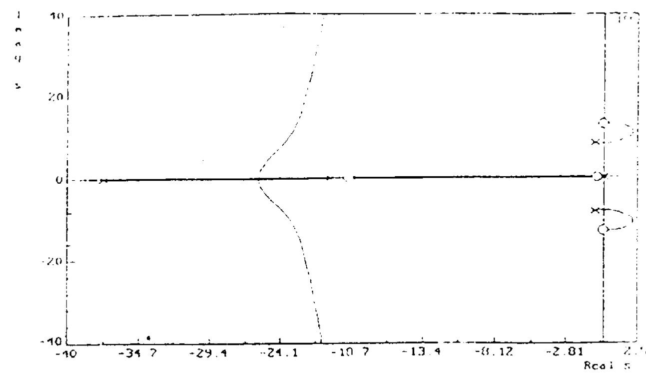


Fig. 4 : Root Locus for Operating Point No.1.

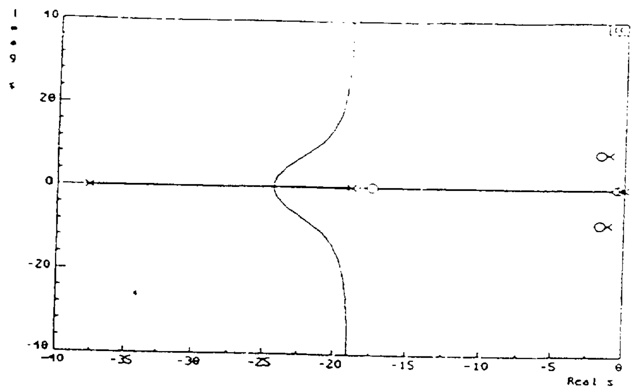


Fig. 5: Root Locus for Operating Point No.3.

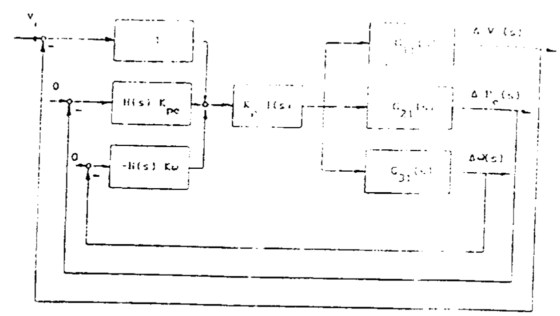


Fig. 7 : AVR as a Multivariable Control Structure

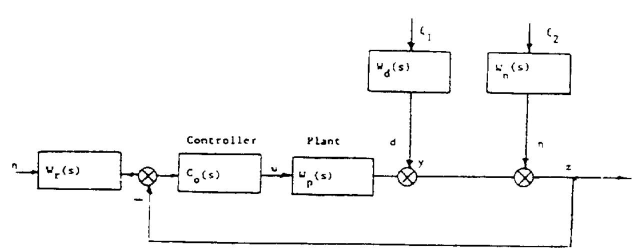


Fig. 8 : MIMO LQG Polynomial System Structure

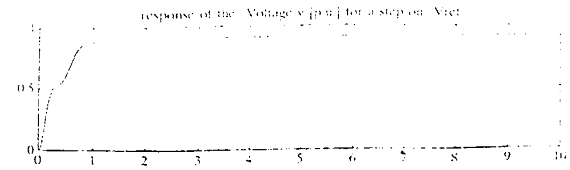
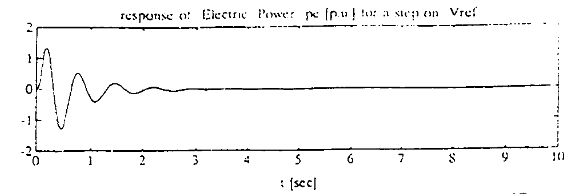


Fig. 9a : $Q_c = 10^4$



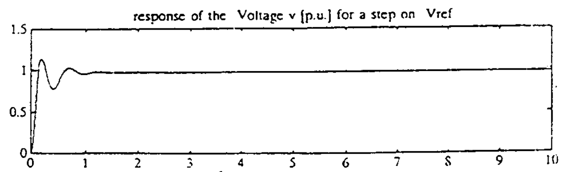


Fig. 9b : $Q_c = 10^6$

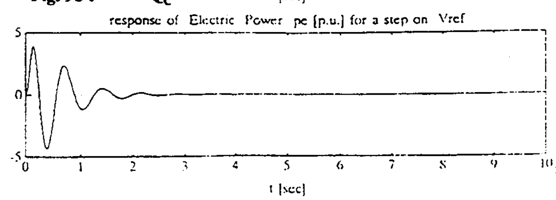


Fig. 9: **Step responses of voltage and electric power for operating point No. 3. Reference model omitted**

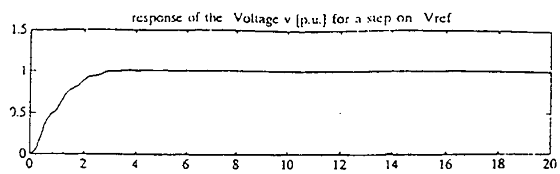
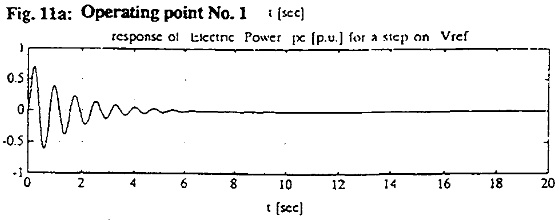


Fig. 11a: Operating point No. 1



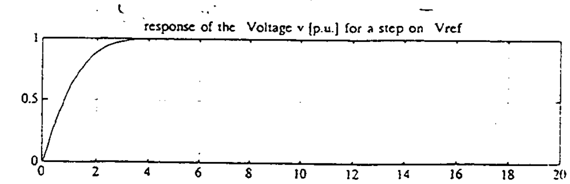


Fig. 11b: Operating point No. 3

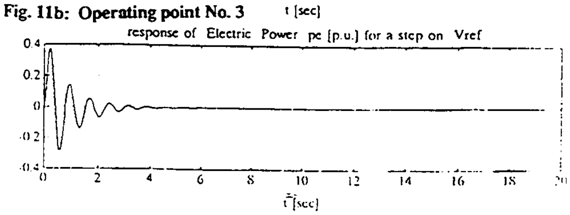
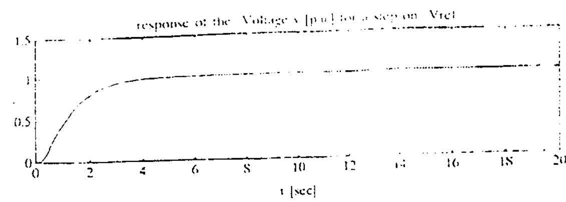


Fig. 11: **Step responses of voltage and electric power. Dynamic Weights : $B_r/A_r = 1$, $B_q/A_q = (s+50)/s$**



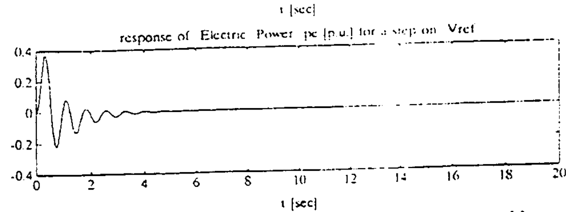
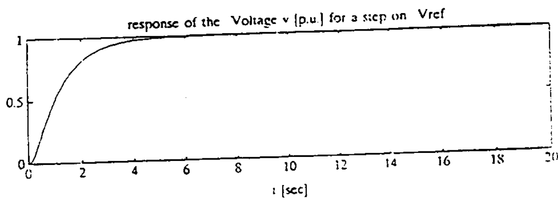


Fig. 10a : **Step response of voltage and electric power with reference subsystem. Operating point No. 1 with $R_f = 1$ and $Q_c = 10^4$.**



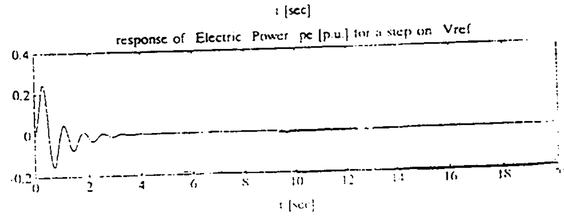


Fig. 10b: **Step response of voltage and electric power with reference subsystem. Operating point No. 3 with $R_f = 1$ and $Q_c = 10^4$.**

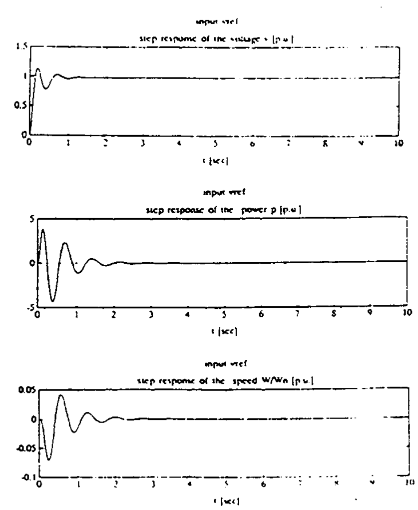


Fig. 12: **Responses of the three outputs of the controlled system Operating point No. 3. $Q_{11} = 10^6$, $Q_{22} = Q_{33} = 1$**