CONTROL THEORY APPLIED TO THE DESIGN OF AGC CIRCUITS

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ABSTRACT: This paper presents some applications of Control Theory in the design of Automatic Gain Control (AGC) circuits. First a general model for AGC circuits is presented and an equivalent linear system is proposed. Its behaviour is compared with the dynamical response of two implemented AGC circuits. The results of classic and state variable correctors based on the model are presented. These results show the utility degree of this linear model for the design of the AGC dynamic response. By using a linear and t-variant system the dynamical behaviour is improved. This new point of view is used to design Hiperstability and Lyapunov-based correctors.
The results have been tested experimentally and by computer simulation.

1.- Introduction.

The purpose of AGC circuits is to maintain an almost constant output level independently of their input signal level. These circuits have been used since the beginning of radio communication, and its design has been habitually based on empirical concepts. Although their design and performances have evolved and today their behaviour is good enough in most cases the rise of new and more demanding systems [4], as large-capacity light wave digital transmission systems [5], show the need of a more analytical design of AGC dynamics.

In next chapter, an AGC circuit linear model is presented. The simulation results obtained from the model has been compared with the dynamical response of different implemented AGC circuits, one based on a FET and the other on a BJT.

This model has been used to design different control strategies.

2.- AGC Modeling.

Although the basic principle of gain control is simple, the exact analysis of these systems is very difficult in most cases [1] [8], because the nonlinear equations involved. So different equivalent linear systems have been proposed [7], [10]. The classic paper by Victor and Brockman obtains a linear AGC system using logarithmic (dB) functions.

Figure 1 shows a general model for AGC circuits. De spite of the very different technologies employed to implement the circuits, this model can be applied to most circuits, and it's similar to the models used by [2], [7] and other authors.

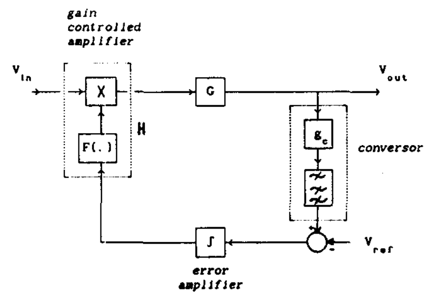


FIG.1.- General model for AGC circuits

The basic element in the circuit is the gain controlled amplifier, modeled in two blocks: the function F(.) being specific of the technology employed, and the multiplier. The amplifiers H and G (fig. 1) are normally modeled without any dynamics, because their frequency response in usually wider than the AGC loop one. The converter (also called detector) is also modeled in two parts. One is the conversion gain and other gains associated. The other part models the low pass filter usually present at the converter output. This linear model of the converter is usually used, and a non-linear one is restricted to overloads [7].

The reference voltage (Vref) and error amplifier are not always present in the AGC circuits, but their use is general in modern circuits. So recent papers include these elements. The error amplifier is modeled as a single low-pass filter or as an integrator. In the following an integrator will be used, because in most cases their bandwidth and gain fits closely the ideal integrator ones. Another reason is that the use of an integrator as error amplifier removes the steady state error, so the AGC performance is improved.

By using a similar model, the classic paper on AGC of Victor and Brockman [10] takes logarithms of the variables, so the gain controlled amplifier function and divider can be remodeled as linear elements. Even with this change a small variation in the signal must be considered to obtain a good model.

2.1.- Linear model.

Taking into account the way used by Victor and Brockman (and also by Mercy [7] to obtain their models, a linear model without the transformation of linear magnitudes to logarithmic ones (dB) is proposed to model AGC dynamics. This model has been obtained using both laboratory measurements and circuit analysis [9], from two different AGC circuits. Using the above considerations and previous results of other authors, the linear model proposed has the following diagram:

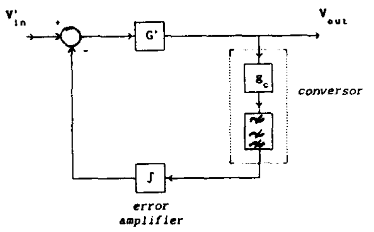


FIG.2.- Proposed linear model.

This model uses normalized values, and it is valid for variations around a working point. In order to test the accuracy of this model, two AGC circuits have been implemented, one based in a FET as a variable resistor and the other based in the change of the polarization current in a BJT differential pair (MC 1445). As both circuits showed in the laboratory similar behaviour, the following results will only present the MC1445 based AGC circuit. Figure 3 shows the response of the circuit and the simulated linear model response. They closely agree that a second order linear system is enough to model an AGC circuit. The correct behaviour of the model is found to be directly related to the amount of signal change.

3.- Lead corrector.

The equivalent linear model allows to design lead, lag or lag-lead correctors for AGC circuits. Their use in the circuit is limited due to linear model don't considers the dc levels present in the circuit. This forces to place the corrector in parallel with the feedback loop in order to prevent disturbances on its dc levels. For the same reason it must be ac coupled. The use of large capacitors to decouple dc modifies the expected system behaviour, so the design must be done in a conservative way. The lead corrector has been designed by canceling the highest AGC pole and adjusting the gain to obtain a closed loop double pole. The corrector was implemented on the test circuit using an operational amplifier to obtain an active lead corrector. Figure 4 presents the response to a Vin step change when a lead corrector is placed in the circuit. Although the response is close to the expected one, some trial was necessary with the decoupling capacitors to fit better the expected response. The tolerances in the other components also slightly change the response.

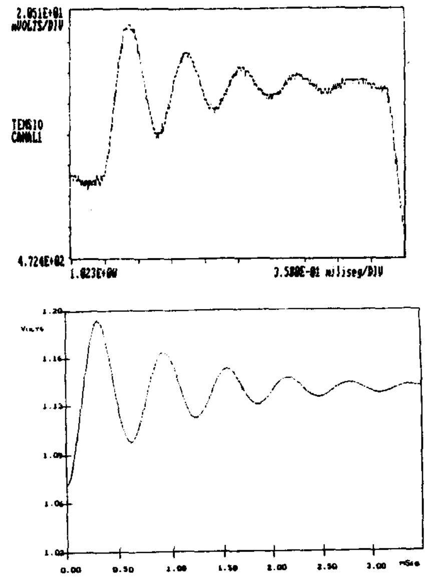


FIG.3.- MC1445 based circuit and linear model responses.

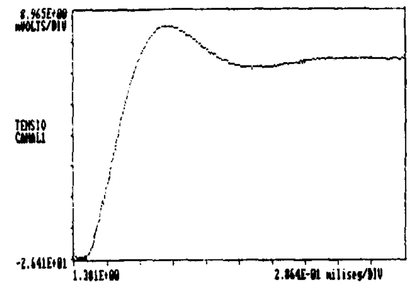


FIG.4.- Response to a step input (lead corrector)

4.- State - variable corrector.

The use of state variable feedback allows a more flexible corrector design. The implementation is also simple, but some difficulties can arise if the chosen state variables are not physical or easily observable in the circuit.

The design criteria has been to place the system poles in a specified point in the Root Locus and by using an optimizing criteria without differences in the results.

Like the previous corrector, the dc decoupling is the main disturbance in implementing the designed corrector.

As in all the correctors used in this paper the feedback can not be done to the circuit signal input and is done to the error amplifier. This is because the feedback is a quasi dc signal while the input signal is an ac one.

A step response of the circuit is presented in figure 5.

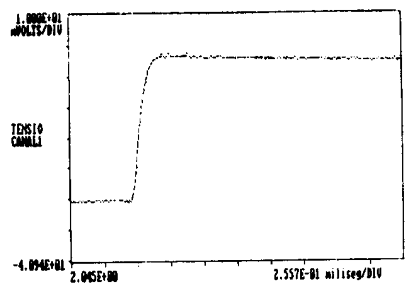


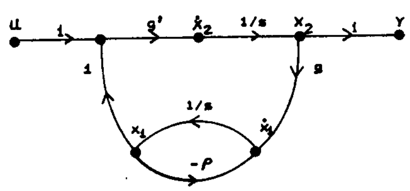
FIG.5.- Step response (state-variable corrector)

As in the lead corrector changes in the working point must be considered in the design. But the state variable method is less sensitive to these changes, mainly because there is a single dominant pole instead the double pole obtained in the lead corrector. So the design can be less conservative.

5.- Lyapunov based corrector.

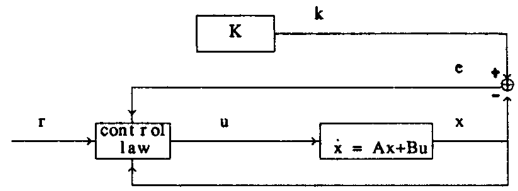
Advanced alternatives to the design methodologies used above are the model reference adaptive systems (MRAS).

In the preceding correctors the AGC model has been approximated with a linear model. An alternative approach to the AGC model is to consider the AGC system as a linear but t-variant system, where the system input is no longer Vin but Vref (fig.1). The former signal input (Vin) and the controlled gain amplifier (H) are modeled now as a Vin controlled t-variable gain (g'). This reflects better the fact that the control is done comparing the converter output and the reference voltage. It reflects also the fact that the feedback signals cannot be feed with the signal input. The flux diagram for that model is:



The main step in the corrector design is to obtain a Lyapunov function for the system, which will ensure the system stability [6].

The control structure is:



The system states $\mathbf{x} = (x_1,x_2)$ are compared with constant states $\mathbf{k} = (k_1,k_2)$. The detected error $\mathbf{e} = (e_1,e_2)$ must be processed by a control law that ensures the system stability. A tentative Lyapunov function is:

$$V(e) = e^T \mathbf{P}\, e$$

where **P** is a symmetric and positive definite matrix.

Using as **P** matrix, $\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} \\ p_{12} & p_{22} \end{bmatrix}$

The obtained control law is:

$$u \sim k_1 + \frac{gk_2 - pk_1}{g'} \, \frac{e_1 p_{11} + e_2 p_{12}}{e_1 p_{12} + e_2 p_{22}}$$

where ~ can be ≥ or ≤ depending on the sign of the term $e_1 p_{12} + e_2 p_{22}$. A simplified control law is:

$$u \sim k_1 + \frac{gk_2 - pk_1}{g'} \, \frac{e_1 p_{11}}{e_2 p_{22}} \quad .$$

It is interesting to note that although in the design it was not used a explicit reference voltage in the obtained corrector, the constant k_1 can be identified as the reference voltage. To full fill the inequalities the error sign must be detected and the gain must by changed accordingly. This can be interpreted as a way of adaptive control where the feedback depends on the error sign.

The simulated system response is presented in figure 6.

The gain changes can be observed as clear dynamic changes in the response of the figure. Although the response is similar to the previous correctors further test showed that there is a significant steady state error when the corrector parameters or the working point change. Because there have been strong simplifications (linearization of g' and assumption that ρ is negligible) it is possible that another implementation will eliminate this effect. Even choosing another Lyapunov candidate function will solve the problem.

But the design gives a clue of how the adaptive correctors can get over the circuit t-variance whit the price of increased complexity (the designed corrector needs a divider to be implemented). Heuristic design based in the obtained results can improve the results.

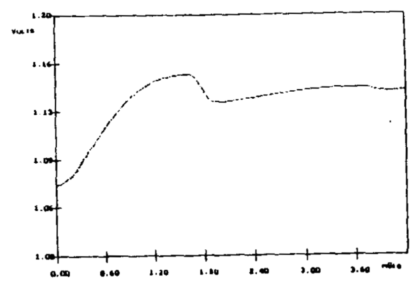


FIG.6.- System response (Lyapunov)

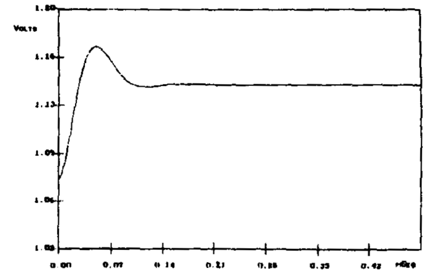


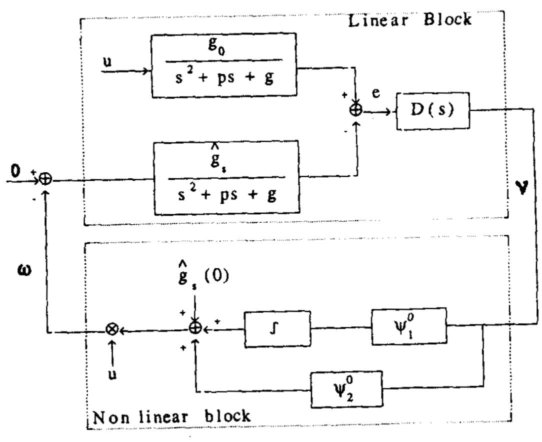
FIG.7.- Response with an hiperstable adaptive corrector

6.- Hiperstability based corrector.

The Hiperstability based corrector also follows the reference model approach. The Hiperstability Theory states that a system that has a Lur'e form is asymptotically stable if the non linear part is passive, that is

$$\eta(0,t) = \int_0^{t_1} v\cdot\omega \; dt \geq -\alpha_0^2 \quad , \quad t_1 > 0 .$$

where v and ω are the input and the output of the non linear block. The linear block must be strictly positive. Landau [6] proposes the following structure, which can be designed to fulfill these conditions:



The non linear part is designed to fill the passivity condition. The D(s) block is included to ensure that the linear system is strictly positive.

The corrector obtained with this approach is also complex to implement. The main difficulty is to implement the multipliers. Also a pure deriver can be needed to ensure a strictly positive linear block. As a result only computer simulation was done for that corrector.

The response of that corrector to an input step change is shown in the figure 7.

It is clear from the figure that the system speed has been improved compared to the above correctors. On the other hand the corrector complexity has increased as previously noted. Compared to the Lyapunov based corrector the main difference is the better linearity in the response obtained by the hiperstable corrector. This can be partly explained by the absence of any abrupt gain change. This linearity is also improved related to the working point changes. It must be noted that the response shape cannot be totally know a priori, but it can be modified by changing the corrector parameters.

7.- Conclusion.

Results show that AGC circuits can be well modeled with second order linear models even using linear units for small signal changes. These models can be used to design Linear Control Theory based correctors. Also a new *t*-variant model can be used with more recent design techniques. This model reflects more accurately the fact that AGC circuits dynamic is basically related to the working point but almost linear for small changes. For wide input changes non linear effects are important and are not accurately represented by the models. This is also true when overloads occurs. For wide changes and overloading adaptive correctors are able to improve the circuit performance.

Provided that the system is not in these situations the results obtained show that linear theory can be applied as useful design tool. The design must be lightly conservative taking into account model approximations and implementation limitations. Non linear correctors show that improved techniques can overcome these limits.

References:

[1] Banta, E. D. "Analysis of an automatic gain control," *IEEE Trans. Automatic Control*, vol. AC-9, pp. 181-182, April 1964.

[2] Green, D. N. "Global Stability Analysis of Automatic Gain Control Circuits," *IEEE Trans. Circuits and Systems*, vol. CAS-30, no.2, pp. 78-83, February 1983.

[3] Green, D. N. "Lock-in , Tracking, and Acquisition of AGC-aided PLL," *IEEE Trans. Circuits and Systems*, vol. CAS-32, no. 6, pp. 559-568, June 1985.

[4] Hughes,R.S. *Analog Automatic Control Loops in Radar and EW*. Artech-House, 1988.

[5] Kinoshita, T.; Yamashita, K.; Maeda, M. y Sekine, Y. "Wideband variable peaking AGC amplifier for high-speed lightwave digital transmission," *Electronics Letters*, vol. 23, no. 1, January 1987.

[6] Landau, Y,D. *Adaptive Control*. Marcel Dekker, 1979.

[7] Mercy, D. V., "A review of automatic gain control theory," *The Radio and Electronic Engineer*, vol. 51, no. 11-12, pp. 579-590, November-December 1981.

[8] Ohlson, J. E. "Exact dynamics of AGC," *IEEE Trans. Communications*, January 1974.

[9] Palacín, J.M. "On the use of Control Theories in the dynamical design of AGC circuits" (in spanish). E.T.S.E. Telecomunicació. U.P.C. 1990.

[10] Victor, W. K. y Brockman, M. H. "The Application of Linear Servo Theory to the Design of AGC Loops," *Proc. IRE*, vol. 48, pp. 234-238, February 1960.