INTERNAL REPORTS IN

SIMULATION, OPTIMIZATION AND CONTROL

No. SOC-251

POSTPRODUCTION PARAMETER IDENTIFICATION AND TUNING OF ANALOG CIRCUITS

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June 1980

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1980 European Conference on Circuit Theory and Design, Warsaw, Poland, September 1980

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Invited Paper

ABSTRACT

This paper discusses some topics related to postproduction tuning and repairing of analog electrical circuits. Suitable design techniques are reviewed and a general formulation of the tuning problem is given. Appropriate testing conditions are discussed. Recent developments in the field of postproduction tuning and fault analysis are reviewed.

1. INTRODUCTION

Postproduction tuning has been known and used for many years as an effective way of improving the performance or at least to meet the required specifications of electrical, especially electronic, devices. If, for example, the number of components is small enough tuning can usually be carried out experimentally. It is simply done by changing very few tunable parameters, trying to achieve desired input - output characteristics, which are simultaneously observed. This process, which can be said to be a man-performed on line optimization, has the advantage that the device performance is directly optimized without accounting for the actual state of the components. Also, the optimizer can take advantage of his understanding of the particular circuit behaviour, so he can easily decide whether the circuit is tunable or not. Moreover, based on his knowledge and experience he is able to identify faulty components and then replace them. This approach, however, can hardly be used when many parameters are to be tuned and becomes almost impossible with increasing complexity of electronic devices.

In this paper we discuss different formulations, approaches and some methods of design and fault analysis in the context of the aforementioned postproduction tuning and repairing problems. In Section 2 a short review of suitable design formulations such as design centering, optimal tolerance assignment, manufacturing yield and tuning is given. Then, in Section 3, we discuss objectives of testing as well as particular testing conditions relevant to electronic circuits. Also, recent developments in fault analysis are briefly discussed. Finally, Section 4 presents a general formulation of the postproduction tuning problem and some efficient algorithms.

2. DESIGN - A SHORT REVIEW

The advent of computers has brought powerful new tools for designers and manufacturers. Fast computer analyses enabled designers to simulate the circuit model, while the design itself and the design adjustment was still performed in a more or less traditional way according to the designer's experience. Simultaneously, programs for circuit syntheses became available. Later, approaches based on optimization techniques have been developed (e.g., [1-3]). The goal of optimization is to find the nominal vector

$$\underset{\sim}{\phi}^0 \triangleq [\phi_1^0 \; \phi_2^0 \; \cdots \; \phi_p^0]^T \tag{1}$$

of the circuit parameters $\phi_1, \phi_2, \ldots, \phi_p$, so that the response best meets the specifications. The network topology as well as types of components are usually assumed. Thus, the design adjustment within a fixed network topology can be done automatically. Next, more realistic approaches taking manufacturing tolerances into account have been developed. <u>Tolerance assignment</u> and more general <u>design centering</u> together with <u>optimal tolerance assignment</u> have been established and worked out [4 - 13]. Both deterministic and statistical approaches are used. Tolerance assignment should provide the tolerance vector

$$\underset{\sim}{\varepsilon} \triangleq [\varepsilon_1 \; \varepsilon_2 \; \cdots \; \varepsilon_p]^T \tag{2}$$

such that any outcome of the manufacturing process with actual parameter values

$$\underset{\sim}{\phi} = \underset{\sim}{\phi}^0 + \underset{\sim}{E}\,\underset{\sim}{\mu}, \tag{3}$$

where $\underset{\sim}{E} \triangleq \text{diag}\,(\underset{\sim}{\varepsilon})$ and $\underset{\sim}{\mu} \triangleq [\mu_1 \; \mu_2 \; \cdots \; \mu_p]^T$ represents the random effect of the process, $\underset{\sim}{\mu} \in R_\mu$, satisfies the required specification. For the sake of simplicity as well as the implication of statistically independent design parameters, R_μ is usually considered as

$$R_\mu = \{\underset{\sim}{\mu} \mid -1 \leq \mu_i \leq 1, \; i = 1, 2, \ldots, p\}. \tag{4}$$

Various interpretations of the tolerance assignment problem are associated with either worst-case, i.e., with 100% yield, or less than 100% yield designs. The manufacturing yield is simply defined by

$$Y \triangleq N/M, \tag{5}$$

where M is the total number of outcomes and N is the number of outcomes which satisfy the specification. Obviously, tolerances should be assigned to be as large as possible.

Design centering with optimal tolerance assignment optimizes the nominal design $\underset{\sim}{\phi}^0$ in order not only to meet the specifications but also to obtain the largest tolerances. The objective function to be minimized represents the manufacturing cost which, in general, is higher for tight tolerances and smaller for larger ones or the cost-yield relation where the larger tolerances, smaller yield, higher cost model is used. However, most of these approaches are based on a throw-away model of the manufacturing cost.

The use of computers and recent developments in technology have enabled manufacturers to produce devices of very high complexity. Mass production of integrated circuits reduced the manufacturing cost substantially, so the throw-away approach became economically proper even in the case of low yield. Because of this the role of tuning should not be overestimated. However, for certain devices, e.g., active filters, with narrow performance specifications, tuning is still either necessary or highly desirable. Moreover, for the production where this process is not used presently it may substantially reduce the manufacturing cost in the future. Of course, it depends on the cost of tuning itself and its availability.

The problem of design centering with optimal tolerance assignment taking postproduction tuning availability into account was initiated by Bandler et al. [14]. An outcome of the manufacturing process after tuning can be described by

$$\underset{\sim}{\phi} = \underset{\sim}{\phi}^0 + \underset{\sim}{E}\,\underset{\sim}{\mu} + \underset{\sim}{T}\,\underset{\sim}{\rho}, \tag{6}$$

where $\underset{\sim}{T} \triangleq \mathrm{diag}(t_1\ t_2\ \dots\ t_p)$ assigns tuning ranges and $\underset{\sim}{\rho} \triangleq [\rho_1\ \rho_2\ \cdots\ \rho_p]^T$ is a scaling vector representing the actual amount of tuning. Tuning ranges (absolute or relative) may be specified or may be optimized. Usually some of them are optimized while the other ones are specified (at least those which correspond to untunable parameters) and the tuning matrix can be expressed as

$$\underset{\sim}{T} = \mathrm{diag}(t_1\ t_2\ \dots\ t_k\ 0\ \dots\ 0). \tag{7}$$

For any fixed $\underset{\sim}{\mu}$ the tuning region is defined by [14]

$$R_t(\underset{\sim}{\mu}) \triangleq \{\underset{\sim}{\phi} \mid \underset{\sim}{\phi} = \underset{\sim}{\phi}^0 + \underset{\sim}{E}\,\underset{\sim}{\mu} + \underset{\sim}{T}\underset{\sim}{\rho},\ \underset{\sim}{\rho} \in R_\rho\}. \tag{8}$$

R_ρ may be defined, in general, as

$$R_\rho \triangleq \{\underset{\sim}{\rho} \mid a_i \leq \rho_i \leq b_i,\ -1 \leq a_i \leq 0,\ 0 \leq b_i \leq 1\}, \tag{9}$$

where a_i=0 or b_i=0 corresponds to one-way tuning. A suitable term representing the cost of tuning which, in general, is higher for larger tuning ranges and when more parameters are tunable is added to the objective function.

Design specifications are mathematically expressed as constraint functions $g_i(\underset{\sim}{\phi})$, i = 1, 2, ..., m_c such that the feasible (constraint) region is given by

$$R_c \triangleq \{\underset{\sim}{\phi} \mid \underset{\sim}{g}(\underset{\sim}{\phi}) \geq \underset{\sim}{0}\}. \tag{10}$$

The worst-case solution of the design centering, tolerancing and tuning problem must satisfy the expression

$$\forall\ \underset{\sim}{\mu} \in R_\mu\ \exists\ \underset{\sim}{\rho} \in R_\rho \text{ such that } \underset{\sim}{\phi} = \underset{\sim}{\phi}^0 + \underset{\sim}{E}\,\underset{\sim}{\mu} + \underset{\sim}{T}\,\underset{\sim}{\rho} \in R_c, \tag{11}$$

which means that for all $\underset{\sim}{\mu} \in R_\mu$ the intersection of $R_t(\underset{\sim}{\mu})$ and R_c is nonempty. In the case of cost-yield optimization the notion of the <u>potential yield</u> can be defined by [15]

$$Y_p \triangleq N_p/M, \tag{12}$$

where N_p is the number of outcomes which meet the specifications, after tuning if necessary.

Because of (10) where $\underset{\sim}{\phi}$ is given by (3) the nonlinear programming formulation of the optimal design centering and tolerancing problem involves an infinite number of constraints. However, selecting or assuming [12,13] worst-case candidates over the tolerance region (under the assumption of one-dimensional convexity of R_c the vertices of the tolerance region can be considered [6]) the number of constraints can be made finite. In contrast, the optimal design centering, tolerancing and tuning problem has the constraints described by (11), whose form is not suitable for algorithmic computation. Bandler and Abdel-Malek [15] and also Polak and Sangiovanni-Vincentelli [16] proposed essentially the same approach to convert the design centering, tolerancing and tuning problem to an equivalent tolerance problem. Here,

$$R_c' = \{\underset{\sim}{\phi} \mid \max_{\underset{\sim}{\rho} \in R_\rho} \min_i g_i(\underset{\sim}{\phi} + \underset{\sim}{T}\,\underset{\sim}{\rho}) \geq 0\} \tag{13}$$

with $\underset{\sim}{\phi}$ given by (3) is the tunable constraint region replacing the constraint region (10) for the ordinary design centering and tolerancing problem. The functional form of the constraints (13), however, is not as easy in implemention. Polak [17] showed that the problem can be solved by solving a sequence of ordinary differentiable constrained optimization problems and proposed what he considered to be an implementable algorithm for the general nonconvex case.

3. TESTING

After a circuit is manufactured one can examine whether the performance specifications are satisfied or not. If they are not then the choice of tuning, replacing of some components, if possible, or throwing away arises. This has to be done based on measurement tests appropriately chosen for the particular circuit [18-42]. Testing itself is most commonly referred to as fault analysis or fault diagnosis. The problems which fall into the field of fault diagnosis can be, in general, classified as either fault location or parameter identification. The first group corresponds to the situation where we want to locate an element or a number of elements which are faulty. By a fault we mean, in general, any large change in the value of an element w.r.t. its nominal which can cause the failure of the whole circuit. Two kinds of faults can be distinguished:

(a) soft faults, when the element is working properly but its value is far enough from assigned tolerances, and

(b) catastrophic faults, when the element fails its function, typically creating an open circuit or short circuit.

Parameter identification is the process of finding the actual values of circuit parameters, usually its components. Dependent on a particular problem we may be interested in identification of selected parameters assuming all the other parameters as known or in identification of all parameters where only circuit topology and model description are known. The first situation appears, for instance, when the circuit under test is measured through a known environment. Another example is fault evaluation when, after locating the faulty elements, we want to know their actual values.

It is seen that fault location and parameter identification cannot be completely separated from each other. For example, one of the possible approaches to fault location makes use of the identification of all component values [18-28]. Then we can easily decide which elements are faulty. Also, the fault evaluation is done simultaneously. This approach could be suitable for soft fault location, however, it has some disadvantages which will be stated later.

The solvability of the parameter identification problem was first considered by Berkowitz [18]. He introduced the concept of accessible (and partly accessible) terminals where voltages and/or currents (or only voltages) can be applied and/or measured. In fact, testing conditions differ from one circuit to another and strongly depend on technology. From the theoretical as well as practical point of view there is almost no difference as to which kind of excitation is applied. Morever, the use of nonideal sources does not pose any difficulty because the source resistance can easily be treated as an additional element of the circuit. Therefore, the only serious limitation in exciting the circuit is nonaccessibility to some of its terminals. On the other hand, the kind of measurements which can be taken is usually more limited. If the circuit is not assembled and terminals of all elements are accessible then, in general, both kinds of measurements are available, and so the parameter identification can easily be done. However, if the circuit is assembled and no existing connection can be broken then current measurements are difficult to take. Although there exist quite sophisticated measurement techniques of so-called element - isolation which enable us to measure component values, one by one, without breaking the existing paths (in fact, this is a kind of current measurement) this is a very time-consuming process since, for every component, an adjustment of the applied excitation is required. Moreover, terminals of all measured components have to be accessible. Therefore, the use of current measurements is limited. It can be assumed that only excitation currents and currents in external short-circuits (shorts between two accessible terminals) are available to the measurement process. The use of voltage measurements is limited only by accessibility of terminals.

The test conditions include also the shape of excitation signals used and the state of the circuit under test. The easiest and most practical approach makes use of sinusoidal steady state measurements for dynamic circuits and d.c. measurements for memoryless circuits. This is also satisfactory from the theoretical point of view. The single-frequency testing can provide the values of passive admittances and control coefficients of control sources. Repeating the identification at different frequencies enables one to identify the component values provided that there is a unique dependence of them on the frequency response (as for canonical structures). In fact, the number of frequency points required is not greater than the number of dynamic elements. On the other hand, the transient behaviour of a linear, time-invariant circuit is uniquely determined by its frequency response, so the single-frequency testing, repeated at different frequencies if necessary, supplies full information about the circuit. Therefore, unlike digital testing, the approach based on synthesizing an appropriate stimulus and measuring the response seems to be not only more but also unnecessarily complicated.

An excellent and exhaustive review of fault diagnosis methods for analog circuits was given by Duhamel and Rault [23]. Thus, in this paper we shall concentrate on problems related to postproduction tuning and more recent developments in fault analysis.

A brute-force approach to the parameter identification problem could make use of an optimization algorithm in a manner similar to design optimization. This would incorporate external parameters measured, e.g., frequency response, as specifications to be met exactly. However, the results of such an optimization are meaningless unless the solution is unique at least for a set of "reasonable" parameter values, e.g., positive passive element values, most components having values close to nominals, etc.

The question of uniqueness can be formulated as <u>diagnosability</u> of a system described by the equation

$$\underset{\sim}{y} = F(\underset{\sim}{u}, \underset{\sim}{\phi}), \tag{14}$$

where $\underset{\sim}{y}$ is the vector of parameters measured when the excitation vector $\underset{\sim}{u}$ is applied. The system is diagnosable if the equation (14) can uniquely be solved for $\underset{\sim}{\phi}$. Although the problem of diagnosability is still open for the general case of nonlinear dynamic circuits, however, valuable results for linear circuits [18-28] and for nonlinear resistive circuits [27] have been obtained. The notion of diagnosability in a generic sense (or local diagnosability) [23,27] has been found to be useful in order to relax the strict uniqueness required for global diagnosability.

In the case of linear circuits a description which does not depend on a particular input is available, i.e.,

$$\underset{\sim}{m} = f(\underset{\sim}{\phi}), \tag{15}$$

where $\underset{\sim}{m}$ may be a vector of trans-admittances, trans-impedances, etc., in particular, at a single frequency. Dependent on a particular choice of measured parameters $\underset{\sim}{m}$ and parameters $\underset{\sim}{\phi}$ to be identified, the same circuit may be or may not be diagnosable. It has been shown [18,22-26] that if all component values are to be identified and all nodes of a linear circuit are accessible then the circuit is diagnosable. For the case when some terminals are not accessible, Navid and Willson [23] formulated sufficient conditions for the solution of the equations (15) to uniquely exist. Trans-admittances corresponding to all accessible and partly accessible terminals, expressed in symbolic form, are used to form the nonlinear algebraic equations (15). When all terminals are accessible the solution can be found by means of linear equations [22, 24-26], which is much simpler. Also, not all the available transfer functions have to be used, and so the number of tests required can be smaller [28].

Unfortunately, for the identification of all component values most terminals have to be accessible. In practice, test points which are available to the measurement process often form only a small set of all terminals. Such circuits can be diagnosable if only some component values are to be identified whereas the other ones are known or assumed. This, in turn, leads to the problem of selected parameter identification.

As was mentioned, fault location can be performed by means of any method which identifies all component values and then comparing the actual and nominal values. This approach, however, requires an extraordinary number of measurements and can hardly be used in the case of catastrophic faults. Usually, one looks for a few faults assuming that all other elements are within the prescribed tolerances.

Catastrophic faults are often located by comparing actual responses with a fault dictionary [23,29-31] which is constructed by simulating typical faults on a computer. This approach, however, is almost impossible in the case of soft faults. Recently, there has been a number of contributions [32-42] dealing with the soft fault location under limited measurements. It has been shown [40-42] that in order to locate k simultaneous faults k+1 measurement ports have to be accessible. These methods are based on checking consistency of certain equations. However, the consistency can be achieved only if all nonfaulty elements have exactly nominal values, which is somehow unrealistic.

4. TUNING

There are two conceptually different approaches to postproduction tuning. The first one follows the traditional on-line optimization process where the output charcteristics are measured directly. The performance specifications are checked and, if necessary, the circuit is tuned. An example of this approach is tuning of active filters, where separate elements (usually resistors) are mostly responsible for different performance parameters like center frequency, Q-factor, gain, etc. Which elements to use for the adjustment of each parameter and their best sequence are known from the design. Because the circuit under tuning has to be assembled and in operation this process is called functional tuning. One of the advantages of this approach is that the influence of parasitic effects on performance parameters are automatically taken into account and tuned out [43]. Also, component values need not be identified. Natural generalization of this approach could incorporate an optimization algorithm with the circuit itself substituting for the function evaluation in every iteration. According to the results obtained from every iteration the tuning elements could be adjusted and again the performance parameters measured. This approach, however, could suffer from the lack of sensitivity information. Furthermore, the method is a slow process involving a great number of iterations and becomes almost impossible to use in the case of irreversible tuning, e.g., laser-beam trimming, because of the nature of any optimization process. That is why so-called deterministic tuning is preferred over functional tuning.

In deterministic tuning, the circuit is not in operation and may not be assembled yet. Based on measurements the component values are determined and then the required tuning amounts are computed in a process of tuning assignment. In principle, once tuning amounts are computed the tuning procedure is carried out in one step. Tuning assignment can be performed as an off-line optimization where an appropriate model of the circuit has to be used. Obviously, parasitic effects should be taken into account since the tuned circuit is expected to function as accurately as the functionally tuned circuit [43].

In general, the tuning assignment problem can be formulated as follows [49]. Based on any method of parameter identification the actual circuit parameter values ϕ_1^a, ϕ_2^a, ..., ϕ_p^a are found. The tunable elements

$$\underset{\sim}{\phi}_t \triangleq [\phi_1 \; \phi_2 \; \cdots \; \phi_k]^T \tag{16}$$

are the only variables in the problem, so the remaining parameters

$$\underset{\sim}{\phi}_r \triangleq [\phi_{k+1} \; \phi_{k+2} \; \cdots \; \phi_p]^T \tag{17}$$

have to be kept at their actual values, i.e., $\underset{\sim}{\phi}_r = \underset{\sim}{\phi}_r^a$, which, obviously, can be different from the nominals. Thus, the constraint (or error) functions representing required specifications can now be expressed as

$$\underset{\sim}{g}_a(\underset{\sim}{\phi}_t) \triangleq \underset{\sim}{g}(\underset{\sim}{\phi})\Big|_{\underset{\sim}{\phi}_r = \underset{\sim}{\phi}_r^a}, \quad (18)$$

and the constraint region for the problem is defined by

$$R_{ct} \triangleq R_c(\underset{\sim}{\phi}_r) \triangleq \{\underset{\sim}{\phi}_t \mid \underset{\sim}{g}_a(\underset{\sim}{\phi}_t) \geq \underset{\sim}{0}\}. \quad (19)$$

The objective of the tuning assignment problem is to find an appropriate k-vector $\underset{\sim}{\rho}_t$ such that

$$\underset{\sim}{\phi}_t^a + \underset{\sim}{T}_t \underset{\sim}{\rho}_t \in R_{ct}, \quad (20)$$

where $\underset{\sim}{T}_t$ is k x k submatrix of $\underset{\sim}{T}$. The optimization can be performed in a least squares, least pth or minimax sense. For instance, the <u>minimax tuning assignment</u> problem can be formulated as

$$\underset{\underset{\sim}{\rho}_t}{\text{minimize}} \ \max_i \ (-\underset{\sim}{g}_a^i(\underset{\sim}{\phi}_t^a + \underset{\sim}{T}_t\underset{\sim}{\rho}_t)) \quad (21)$$

subject to

$$\underset{\sim}{a} \leq \underset{\sim}{\rho}_t \leq \underset{\sim}{b}, \quad (22)$$

where the linear constraints (22) represent limits on tuning. If, after optimization, the resulting function value (21) is greater than zero it means that the circuit is not tunable. If the value is less than zero then the resulting vector $\underset{\sim}{\rho}_t$ gives the tuning amounts to be carried out. In fact, the tuning assignment problem is quite similar to the design problem with only the tunable elements taken into account. Therefore, it may be simpler because of lower dimensionality.

The above approach assumes accurate parameter identification and exact tuning. However, that both are practically unrealistic should be reflected in tuning assignment. Inaccurate tuning can be formulated as a <u>tuning tolerance problem</u>. Starting from the point $\underset{\sim}{\phi}_t^a$ appropriate nominal settings $\underset{\sim}{\rho}_t^0$ have to be found such that the whole tuning tolerance region is placed within the constraint region (19). Usually, the tolerances on tuning, absolute or relative, are prescribed since the accuracy of tuning devices is often known. Therefore, if the candidates for worst-case tuning can be selected, e.g., vertices of the tuning tolerance region, then the above minimax formulation extended over all worst-case candidates can be used. This approach has the disadvantage that the most likely of all the tunable elements will be assigned to be tuned, although a satisfactory or even better solution can often be obtained when only a subset of them is used. Thus, unnecessary tuning should be penalized.

For better centering of the tuning assignment as well as to maximize tolerances on tuning, design centering approaches [49] can be incorporated. This would be unnecessary if the accuracy of the tuning devices were known, however, this could allow us to relax the accuracy of the component value identification. Inaccurate identification shows up in two ways corresponding to both tunable and untunable parts of the parameter vector $\underset{\sim}{\phi}$, namely $\underset{\sim}{\phi}_t$ and $\underset{\sim}{\phi}_r$. Because of inaccurate measurements the actual value $\underset{\sim}{\phi}^a$ can be any point of a certain region R^a. Let

$$R_t^a \triangleq \{\underset{\sim}{\phi}_t \mid \underset{\sim}{\phi} \in R^a\}, \tag{23}$$

$$R_r^a \triangleq \{\underset{\sim}{\phi}_r \mid \underset{\sim}{\phi} \in R^a\}. \tag{24}$$

The tuning assignment problem consists of finding the appropriate vector $\underset{\sim}{\rho}_t^0$ such that the whole region R_t^a would be placed within the constraint region. However, the constraint region itself will be, in general, narrower than that of (19). In general, taking the worst-case situation into account, it can now be defined as

$$R_{ct} = \bigcap_{\underset{\sim}{\phi}_r \in R_r^a} R_c(\underset{\sim}{\phi}_r), \tag{25}$$

where $R_c(\underset{\sim}{\phi}_r)$ is given by (19). In practice, finding the constraint region (25) may be extremely difficult, and so some approximation methods might be useful.

Less general yet more efficient methods of deterministic tuning have been proposed [43-52]. Traditionally, the tuning assignment problem was formulated as a solution of nonlinear equations representing zero deviation of transfer function coefficients. More precisely, the coefficients z_1, z_2, ..., z_n are expressed in the symbolic form as functions of the parameters $\underset{\sim}{\phi}$, i.e., $\underset{\sim}{z} = \underset{\sim}{f}(\underset{\sim}{\phi})$ and then the equations

$$\Delta \underset{\sim}{z} \triangleq \underset{\sim}{f}\,(\underset{\sim}{\phi}_t^a + \Delta\underset{\sim}{\phi}_t, \underset{\sim}{\phi}_r^a) - \underset{\sim}{f}(\underset{\sim}{\phi}_t^0, \underset{\sim}{\phi}_r^0) = \underset{\sim}{0} \tag{26}$$

are solved for $\Delta\underset{\sim}{\phi}_t$. However, the problem may have no solution. A good extension of this approach was proposed by Lopresti [48]. He linearized the equation (26) using semirelative sensitivities $\underset{\sim}{S}_{\phi}^{f}$ and then formulated the problem in terms of quadratic control theory. The state equation considered has the form

$$\underset{\sim}{x}_{\ell+1} = \underset{\sim}{x}_\ell + \underset{\sim}{h}_\ell\, u_\ell, \qquad \ell = 1, 2, \ldots, k \tag{27}$$

$$\underset{\sim}{x}_1 = \underset{\sim}{S}_{\phi_r}^{f}\, \underset{\sim}{\phi}_r, \tag{28}$$

where

$$\underset{\sim}{h}_\ell = (\partial \underset{\sim}{f}/\partial\phi_\ell)\, \phi_\ell, \qquad \ell = 1, 2, \ldots, k \tag{29}$$

and controls $u_\ell \triangleq d\phi_\ell/\phi_\ell$ represent tuning amounts to be assigned. The final deviation $\underset{\sim}{x}_{k+1}$ is minimized in a weighted least squares sense in order to obtain optimal controls u_ℓ. Moreover, excessive amounts of tuning are penalized.

The above method is fairly efficient since there are explicit formulas to calculate optimal controls. Furthermore, since the process is sequential, inaccurate tuning can easily be treated by measuring elements after trimming and then reoptimizing the remaining controls. However, it seems to be a disadvantage of this approach that the optimization deals with the coefficients of the transfer function instead of actual specifications. It might happen that the transfer function would be very sensitive w.r.t. some coefficients. To remedy this appropriate weighting factors may be used, but ill-conditioning can appear.

Another interesting approach to tuning assignment was proposed by Alajajian, Trick and El-Masry [50-52]. Using Tellegen's theorem they formulate equations of the form

$$\sum_{\ell=1}^{k} (V_\ell^i + \Delta V_\ell^i)\, \hat{V}_\ell^i\, \Delta G_\ell - c\, \overline{V}_{out}^i = - V_{out}^i, \tag{30}$$

where $i = 1, 2, \ldots, n$ correspond to different frequency points, V_ℓ and $\hat{V}_\ell$, $\ell = 1, 2, \ldots, k$ are the voltages in the original circuit before tuning and its adjoint, respectively, across the all tunable elements, V_{out} is the actual output voltage, $\overline{V}_{out}$ is the desired output voltage and $V_\ell + \Delta V_\ell$ are the voltages after tuning. The latter can be approximated as

$$V_\ell + \Delta V_\ell \simeq \overline{V}_\ell, \qquad \ell = 1, 2, \ldots, k, \tag{31}$$

where $\overline{V}_\ell$ are desired voltages of the nominal design. Thus, the required amounts of tuning ΔG_ℓ, $\ell = 1, 2, \ldots, k$ can be simply obtained by solving the system of linear equations. The method is very fast and, though there is no proof, it shows excellent convergence.

This algorithm is efficient because it forces not only the output response but also some internal voltages to meet desired values. However, the amounts of tuning are out of control and there is nothing that one can do if they are unreasonably high. In fact, as was mentioned, it may be better to achieve a different response from the original design, especially in the case of limited tuning ranges.

5. CONCLUSIONS

This paper has considered a variety of topics related to postproduction parameter identification and tuning of analog circuits. Advantages and disadvantages of different approaches have been stated, indicating possible extensions and future work. The state of the art is felt not to be particuarly advanced from the point of view of the practical requirement of rapid and unambiguous identification and tuning of large systems.

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SOC-251

POSTPRODUCTION PARAMETER IDENTIFICATION AND TUNING OF ANALOG CIRCUITS

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June 1980,   No. of Pages: 16

Revised:

Key Words: Tuning, parameter identification, fault analysis, testing, computer-aided design

Abstract: This paper discusses some topics related to postproduction tuning and repairing of analog electrical circuits. Suitable design techniques are reviewed and a general formulation of the tuning problem is given. Appropriate testing conditions are discussed. Recent developments in the field of postproduction tuning and fault analysis are reviewed.

Description: Invited paper presented at the 1980 European Conf. on Circuit Theory and Design, (Warsaw, Poland, Sept. 1980).

Related Work: SOC-233, SOC-235, SOC-236, SOC-244.

Price: $ 6.00.