MULTI-LEVEL APPROACH TO THE CONTROL OF INTERCONNECTED POWER SYSTEMS

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ABSTRACT

The design of the control system necessary for the reliable operation of an interconnected power system is based on the multi-level approach for the control of systems. The power system is divided into areas and each area control is structured according to the multi-layer hierarchy described in a previous paper.[1]

Work done to date within the multi-level framework described in Reference 1 has been in the development of an optimizing control model. The optimizing model is seen to be one which may be applied, with minor modifications, to other optimizing problems in electrical operation and system planning.

INTRODUCTION

Automatic control has always been integral to an electric power system since the earliest beginnings of the utility industry. A major part of this automation has been directed to maintaining reliability of electric service by automatic protection of the system against the immediate effects of electrical faults. The evolution of the modern power system has been marked by outstanding developments in automatic protection methods and devices to meet each new set of circumstances and problems as brought about by each major step in the evolutionary process. Although automatic protection has played a primary role in maintaining service reliability through high-speed corrective action, its function has been limited to specific types of faults and to very short time periods ranging from a few cycles to a few seconds, during and immediately after an electrical fault. Many other factors and situations affecting reliability which fall outside the sphere of action of automatic protection have been left to the human operator to resolve by means of manual corrective action. The justification for this has been that many plausible or foreseeable situations are taken care of by power system design (of which automatic protection is a part) so that circumstances which would create serious operating decision problems would have a very small likelihood of occurring.

While indeed, operating emergencies not foreseen or provided for by system design have been relatively infrequent, the consequences of an emergency have over the years become more extensive and damaging. As power systems increase in capacity the burden on the system operator of maintaining service reliability becomes increasingly heavier and more complex. Very-large-capacity generation, extra-high voltage transmission, and an increasing number of interconnections have added complicating factors to an already highly-dimensioned and complex problem. Cases of emergency where the human operator is the only decision-maker left to cope with the problem are now of such a nature that, generally, prompt and correct remedial action can no longer be justifiably expected.

It has become increasingly clear that in modern, interconnected power systems there exists a need for an expanded concept of system protection for improved reliability. New automatic control functions need to be developed to assist the operator in maintaining a reliable system. It is also quite clear that such automatic functions should be developed within the framework of an overall control system design. Although new control devices or control sub-systems may be developed and installed piecemeal, such a procedure may be done only as the functions of these devices are identified beforehand in the structure of the overall plan.

A previous paper[1] by one of the authors, discusses the design considerations for the improvement of the reliability of the generation-transmission system of the Cleveland Electric Illuminating Company in Cleveland, Ohio, U.S.A. The control system is conceived on a multi-level structure[2] which is applicable to any power system or interconnected power systems. The purpose of the present paper is to present some of the significant aspects of the control system especially of the optimizing control level in which development work has been concentrated over the past year.

Superior numbers refer to similarly-numbered references at the end of this paper.

A summary of the multi-level structure is given in Section I. In Section II the optimizing control model is described. The model is seen to be one which may be applied with slight modifications to a number of power system problems. Section III considers the decomposition of the optimizing control problem into subproblems where large power systems or interconnections of power systems are involved.

A MULTI-LEVEL CONTROL SYSTEM FOR A POWER SYSTEM

The first step in the decomposition of the control problem for the generation-transmission system is to consider the electric network and treat it as a whole or else subdivide it into several areas. The need for subdivision into areas will depend on: the complexity and computational difficulty associated with the control model; the influence of geography; the disposition of generating sources, heavy load centers, and interconnections; ownership or political boundaries; overall considerations of reliability.

For each network area the operating problem can be viewed as a series of control actions taken to maintain continuity of electric service at standard electrical frequency and voltage. Electrical operation may then be decomposed, time-wise, into three modes of operation or "operating states", designated as: preventive, emergency, and restorative.

In the preventive operating state, the generation-transmission system is being operated so that the demands of all customers are satisfied at standard frequency and voltage. The control objective is to continue indefinitely the satisfaction of customer demand without interruption and at minimum cost. Continuous operation implies that all system constraints are being complied with.

In the emergency operating state, certain constraints are being violated. The control objective is to take corrective action in such a way as to satisfy all constraints while supplying a maximum amount of customer demand.

In the restorative operating state, service to some customers has been lost. The control objective is the safe transition from partial to complete satisfaction of all customer demands in minimum time.

Thus as power system and environmental conditions change, the performance requirements could be any of the following:

(1) Minimum operating costs at a desired level of reliability.
(2) Maximum satisfied demand without violating constraints.
(3) Minimum duration of customer outage.

The control system (a man-machine combination) would adapt to the changes in performance requirements and effectively influence the electrical system so that departures from continuous operation (i.e., the preventive state) will be as infrequent as possible. That is, the overall control strategy would be to keep the system operating in the preventive state.

A hierarchy of three control levels is proposed for each of the three operating states, as the means for achieving the various control objectives. These correspond to the first three of what I. Lefkowitz[2] refers to as control "layers": direct control; optimizing control; and adaptive control.

Direct Control Functions

The first level, or direct control, performs high-speed decisions using logic or a logical decision process and carries out directly the necessary control action. This level of control will be predominantly located at local points within the system rather than at a control center. As much as possible the logic used at a given location would make use of local information and would be kept fairly simple. Although Level 1 decisions should have a minimum of dependence on central processing, there would be some decisions which would have to be done at the control center. Whether done locally or centrally, the distinguishing features of Level 1 control are its high-speed and the use of logic programming. Direct control is also influenced by instructions from the upper levels.

Table 1 lists the automatic sub-systems at the direct control level for each of the three operating states.

Table 1. Direct Control Functions

Preventive

1. Load-frequency control
2. Turbine governor control
3. Generator voltage regulation
4. Transformer tap changing
5. Capacitor switching
6. Circuit reclosing

Emergency

1. Fault clearing
2. Load shedding
3. Generator shedding
4. Automatic switching
5. System splitting

Restorative

1. Automatic feeder restoration
2. Automatic load transfer

In the preventive state, the direct control sub-systems are all found in present-day power systems. The functions of these existing controls would be extended and improved on a system basis by the addition of instructions from the higher control levels. The power industry already has an example of this in economic dispatch where optimal raise and lower models determined by an optimizing model are applied to the turbine governor control.

The direct emergency control functions, as listed in Table 1, are intended to relieve an emergency immediately in cases where there is not enough time or when there is no means for finding the best solution at the optimizing level. The cases are usually those involving instability, low or rapidly decreasing frequency or critically low voltage levels.

Optimizing Control Functions

The second level, or optimizing control, solves for the "best" control decisions using a mathematical model of the operating state and an appropriate criterion for optimum performance. In contrast to the first level, all second level functions would be done on a central computer because of the mathematical calculations involved in arriving at optimal solutions. A further distinction is that second level decisions take time. The mathematical model should be as simple an approximation as possible consistent with the quality of performance desired. Because the model is only an approximation and because of the time lag between the system conditions input and the decision output, the second level decisions are, strictly speaking, sub-optimal.

Table 2 lists the optimizing control functions planned for each of the three operating states.

Table 2. Optimizing Control Functions

Preventive

1. Unit commitment
2. Economy interchange determination
3. Economic generation dispatch
4. System voltage control

Emergency

1. Maximum load solution

Restorative

1. Dynamic restoration procedure

For the optimization processes in all three operating states, there is a common set of decision variables, i.e., variables which may be manipulated for the best combination of values to meet the objective without breaking any constraints. The set of decision variables consists of:

(1) Units on line
(2) MW output of generators
(3) Interchange schedule
(4) System voltages
(5) System load connected

To put into effect a desired set of values, orders will be sent to the direct control subsystems, to the system itself, or to the system operator. Some orders will be carried out automatically, and some manually. Orders sent out to the system itself will be for breaker operations, generally tripping operations. Thus to effect a desired system load level so as to relieve an emergency, trip signals would be sent to various stations to drop prescribed amounts of load.

In general the problem may be expressed in terms of voltages as the decision variables, as follows:

Find maximum of $F(V)$ (1)

subject to: $g(V) \geq 0$ (2)

$h(V) = 0$ (3)

where V is the vector of complex voltages of all active busses (or nodes) in the area. The inequality and equality constraints derive from a set of requirements for service continuity which all solutions to the optimization problems should satisfy. These are:

Network equations
MW and MVAR demands at substations
MW and MVAR limits of generators
Thermal ratings of equipment
Interconnection limits
Generator voltage limits
Substation voltage limits
Stability loading limits
Service reliability factor

Identification of which constraints are applicable and with what values will be specified by the adaptive control level.

The solution of the optimization problem as expressed in Equations (1), (2), and (3) will be discussed in Section II.

Adaptive Control Functions

The third level, or adaptive control, determines and adjusts the settings, parameters, and logic used in the first and second levels. Whereas both the first two levels are automatic, the decision-making process at the third level is a man-machine combination with the system control operator playing an active part. The third level compensates for disturbances or environmental conditions not considered in the first two levels. Any adjustments done by the operator would as much as possible be aided by off-line computer calculations or by predetermined decision tables or both.

Table 3 lists the adaptive control functions for each of the three operating states.

Table 3. Adaptive Control Functions

Preventive

1. Regulator & relay setting changes
2. Integrated control error
3. Constraint values
4. Lower-level logic
5. Load estimates
6. Tie-line flow model
7. System reliability evaluation
8. Stability analysis
9. Fault location procedure
10. Switching operations
11. Manual intervention

Emergency

1. Constraint values
2. Lower-level logic
3. Tie-line flow model

Restorative

1. Constraint values
2. Lower-level logic
3. Tie-line flow model

Adaptive control has to anticipate, in some fashion, the disturbance inputs to the generation-transmission system. The disturbance set consists of: loads, tie-line flows, and faults. One method of dealing with the disturbance set is to reduce the uncertainty by prediction.

Loads for the day can be predicted with reasonable accuracy. The results of such load forecasts would be used in making direct and optimizing control decisions in the prventive state. Load forecasts would also be one of the factors considered in making adaptive decisions for near-future conditions of the system. Restorative procedures would also require estimates of loads in areas or at substations.

A method of prediction would also be of great value in representing the interconnection. Although it may be possible to develop a good network equivalent to represent the interconnection, the adaptive problem is to keep this equivalent up-to-date under all system conditions. What is required is a fairly accurate estimate of what the flows would be as changes are made in the area generation, load, and network configuration.

One of the functions of adaptive control is to supplement, if necessary, the direct and optimizing controls with manual intervention. Such manual action would be dictated by decisions based on consideration of other information not available to the lower levels. Manual intervention could be exercised on the central control, on the system via communication channels, or by dispatching personnel to substations.

THE OPTIMIZING CONTROL MODEL

In Table 2 of the preceding section, the optimizing control function in the emergency state is listed as "maximum load solution". The maximum load solution is the combination of generation, load, and interconnection interchange such that an emergency condition involving overload or low voltage or both would be corrected while the load being satisfied is at a maximum. The discussion that follows is based on the work that has been done on this particular problem at the Cleveland Electric Illuminating Company. Since, in general, there is a common constraint set, the model will in fact be applicable not only to the emergency state but also to the preventive state and possibly, to the restorative state. Furthermore the basic routines would be applicable to many engineering problems associated with the power system.

Let G = the set of generator busses in the system

T = the set of interconnection busses in the system

L = the set of load busses in the system

P = the set of passive busses in the system

Si = the complex power into bus i

V = the vector of complex voltages at all active busses, i.e., G, T, and L

Vi = the complex voltage at bus i , $(i \in G, T, L, P)$

Ai = MVA limit at bus i , $(i \in G, T)$

Bi = MW limit at bus i , $(i \in G, T)$

Ci = voltage limit at bus i , $(i \in G, T)$

Di = demand at bus i , $(i \in L)$

Ei = voltage limit at bus i , $(i \in L)$

Hij = thermal limit of branch between bus i and bus j

For the maximum load solution we want to find:

$$\underset{V}{\text{Max}}\ F = \sum_{\forall i \in L} |Si(V)|$$

Subject to

$$Ai - |Si(V)| \geq 0 \qquad i \in G, T$$

$$Bi - Re\{Si(V)\} \geq 0 \qquad i \in G, T$$

$$Ci - |Vi| \geq 0 \qquad i \in G, T$$

$$Re\{Di\} - Re\{Si(V)\} \geq 0 \qquad i \in L$$

$$|Vi| - Ei \geq 0 \qquad i \in L$$

$$Re\{Si(V)\} \geq 0 \qquad i \in G$$

$$Im\{Si(V)\} \geq 0 \qquad i \in G$$

$$-Re\{Si(V)\} \geq 0 \qquad i \in L$$

$$Hij - |Vi - Vj| \geq 0$$

$$\mathrm{Im}\{Si(V)\} - \frac{\mathrm{Im}\{Di\}}{\mathrm{Re}\{Di\}} \cdot \mathrm{Re}\{Si(V)\} = 0 \quad i \in L$$

$$\mathrm{Re}\{Si(V)\} - \beta \sum_{\forall i \in T} \mathrm{Re}\{Si(V)\} - \alpha = 0 \quad i \in T$$

The objective function, F, and most of the constraints, are non-linear in V.

For the purposes of the present discussion it will be assumed that the equality constraints may be satisfied to within a certain tolerance. Thus the equality constraints can be expressed as inequalities and the original problem will be of the form:

Find maximum of $F(V)$

subject to $g_k(V) \geq 0 \quad k = 1, 2, \ldots, Y$

where Y is the total number of constraints.

By the use of penalty function techniques the original problem can be reformulated into a minimization problem without constraints. The motivation for this transformation is the existence of rather powerful methods of unconstrained minimization. Of these minimization methods, the Fletcher-Powell technique[3] has been found by various investigators to be highly efficient. The Fletcher-Powell technique is a first-order gradient method which has the power of a second-order gradient method without the need for explicit calculation of second partial derivatives. Conjugate directions are generated through the use of a symmetric, positive definite matrix which is updated at each iteration. This matrix remains positive definite at each iteration, insuring that each direction is one of descent.

The unconstrained minimization formulation that has been applied to the maximum load problem is that due to Fiacco and McCormick,[4] or the so-called "sequential unconstrained minimization technique", (SUMT). By this approach, the new problem is:

Find the minimum of $F'(V,r) = -F(V) + \psi(V,r)$

where $F(V)$ is the original objective function and $\psi(V,r) = r \sum_{k=1}^{Y} \frac{1}{g_k(V)}, \quad r > 0$,

is the "penalty function".

In accordance with the SUMT procedure, we start with an initial value $r_1 > 0$ and a feasible point, V_o, and find the point $V^*(r_1)$ which minimizes $F'(V, r_o)$, using the Fletcher-Powell method. This minimization process is repeated for a sequence of r's, $r_1 > r_2 > r_3 \ldots r_n > 0$. The minimizing point $V^*(r)$ always stays within the constraint space and as r approaches zero the penalty term ψ is weighted less and less. Thus the minimizing point $V^*(r)$ approaches the solution of the original problem. That the solution in fact converges to a local minimum of the original problem is proven by Fiacco and McCormick under certain assumptions of differentiability and boundedness which the original functions and constraints of our power system problem do satisfy.

The maximum load flow solution using the Fiacco-McCormick procedure and Fletcher-Powell minimization has been recently programmed in full Fortran IV for systems up to 30 active busses and up to 75 passive busses.

DECOMPOSITION OF THE OPTIMIZING CONTROL PROBLEM

If the power system is treated as a composite of several areas connected to one another by interconnections, each area would have the multi-level control described in Section I. A higher-level control would be required to coordinate the actions of each area controller. The decomposition of optimization problems has been investigated in several papers.[5,6,7] In this section we will consider the case of the electric power system and how its optimization problems may be approached via decomposition techniques.

Assume we have a large system made up of several interconnected areas as shown in Figure 1. The usual approach is to tear the system into its component areas by cutting across all tie-lines. We will make a slight variation by tearing the system so that we cut across all interconnection points, an interconnection point being a specified node on a tie-line. In the case of interconnections among several companies the interconnection points would correspond to the metering points.

In Figure 1, the interconnection points are the nodes labelled: a, b, c, d, e, f, g. When the system is torn we get Figure 2. The interconnection points have each been split into 1a, 2a, 1b, 2b, 1c, 2c, 3c, etc.

It will be noted in Figure 2 that each tie-line has, in effect, been subdivided into component parts assigned to the areas which share the same interconnection point. Thus all tie-lines are still physically represented in the model by their component parts.

In the general case, assume we have a large system made up of N areas and a set of interconnection points.

Let $M = \{m : m$ is an interconnection point$\}$

$M_s = \{m : m \in M$ and is connected to area $s\}$

C = connection matrix defining interconnection of areas. $C_{ms} = 1$ when interconnection point is connected to area s,

$C_{ms} = 0$, otherwise

V_s = vector of complex voltages of all nodes in area s including all nodes "sm" which are parts of interconnection points $m \in M_s$.

I_{sm} = vector of complex currents entering area s at node sm, $(m \in M_s)$

The optimization problem for the whole system may be expressed as:

Find the minimum of $F = \sum_{s=1}^{N} f_s(V_s)$

Subject to:

$$G_s(V_s) \geq 0 \qquad s = 1, 2, \ldots, N$$

$$U_{sm}(V_s) - I_{sm} = 0 \qquad s = 1, 2, \ldots, N; \; m \in M_s$$

$$\sum_{s=1}^{N} C_{ms} I_{sm} = 0 \qquad m \in M$$

$$H_s(V_s) = 0 \qquad s = 1, 2, \ldots, N$$

G_s is a set of inequality constraints associated with area i. The first two equality constraints are due to the interconnections. H_s is a set of equality constraints associated with area s.

For the optimum, the Kuhn-Tucker conditions which must be satisfied are:

(1) $$\nabla_s f_s(V_s^*) + \sum_{M_s} \lambda_{sm}^* \nabla_s U_{sm}(V_s^*) + \pi_s^* \nabla_s G_s(V_s^*) + \rho_s^* \nabla_s H_s(V_s^*) = 0 \qquad s = 1, 2, \ldots, N$$

(2) $$-\lambda_{sm}^* + \mu_m^* = 0$$

(3) $$\pi_s G_s(V_s^*) = 0$$

(4) $$\pi_s^* \geq 0$$

(5) $$U_{sm}(V_s^*) - I_{sm}^* = 0$$

(6) $$\sum_{s=1}^{N} C_{ms} I_{sm}^* = 0$$

(7) $$G_s(V_s^*) \geq 0$$

(8) $$H_s(V_s^*) = 0$$

(a) The $*$ attached to a variable indicates that the value of the variable is at the optimum.

(b) ∇_s = the gradient with respect to the vector of voltages V_s.

From the Kuhn-Tucker conditions it is evident that the optimization for the whole system may be decomposed into two levels. The first level would consist of independent sub-problems on an area basis where it is imagined that the system has been torn at the interconnection points into several areas. For each area the problem would be to find the minimum of $f_s(V_s)$, subject to:

$$G_s(V_s) \geq 0$$

$$U_{sm}(V_s) - I_{sm}^o = 0$$

$$H_s(V_s) = 0$$

for a fixed value of I_{sm}^o.

The assigned values of interconnection currents, I_{sm}^o, $(s = 1, 2, \ldots N)$, while arbitrary, should satisfy Equation (6). This assignment will be done by the second level. The other function of the second level is to coordinate the first-level solutions according to Equation (2). Equation (2) requires that the values of the λ_{sm}'s should be such that $\lambda_{sm} = \lambda_{tm} = \ldots = \lambda_{wm}$ for all $s, t, \ldots, w$ where $C_{ms} = C_{mt} = C_{mw} = 1$. Hence the coordination algorithm would be:

$$\Delta I_{sm} = k_1\{\mu_m - \lambda_{sm}\}.$$

The optimization problem involves complex quantities. In the Kuhn-Tucker conditions given by Equations (1)-(8), there are really two sets of conditions, one for the real and one for the imaginary part of the complex voltage.

RESULTS AND CONCLUSIONS

A general optimizing programme for power systems optimization problems has been written and successfully tried on a sample system consisting of seven active busses. The emergency optimizing control formulation is now being tried on a large network representing the Cleveland Electric Illuminating Company system and its interconnection points. Numerical results will be presented in the conference.

A unified control system for the reliable operation of a power system is feasible via the multi-level approach.

Work to-date has been in the development of an optimizing control model which, with minor modifications, may be adapted to various operating and planning problems associated with a power system.

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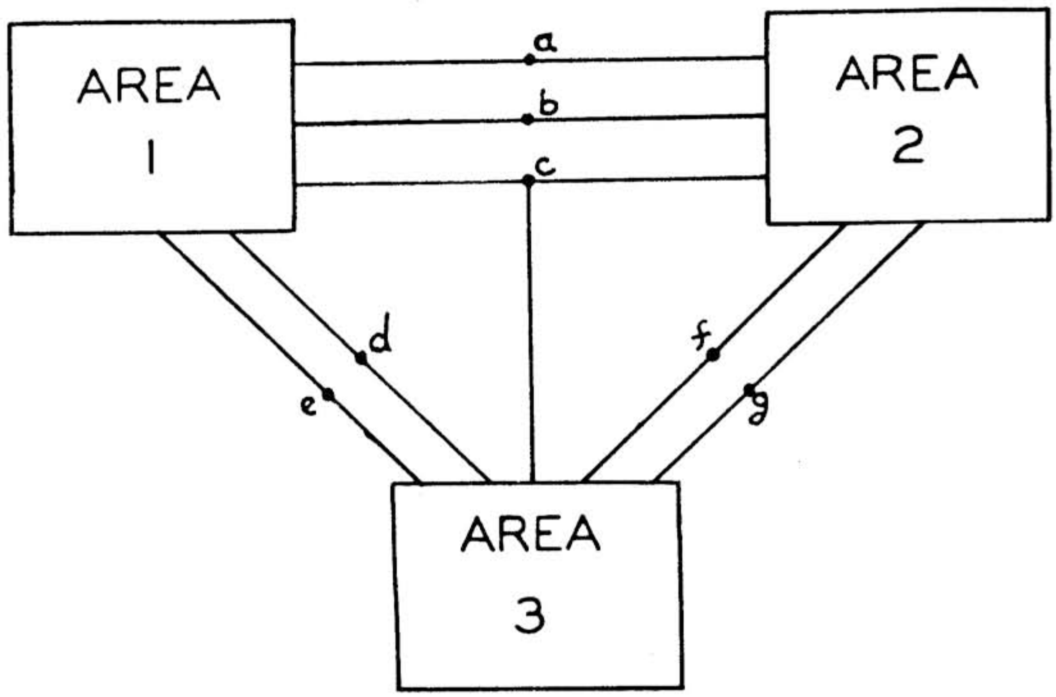

FIGURE 1. INTERCONNECTED SYSTEM

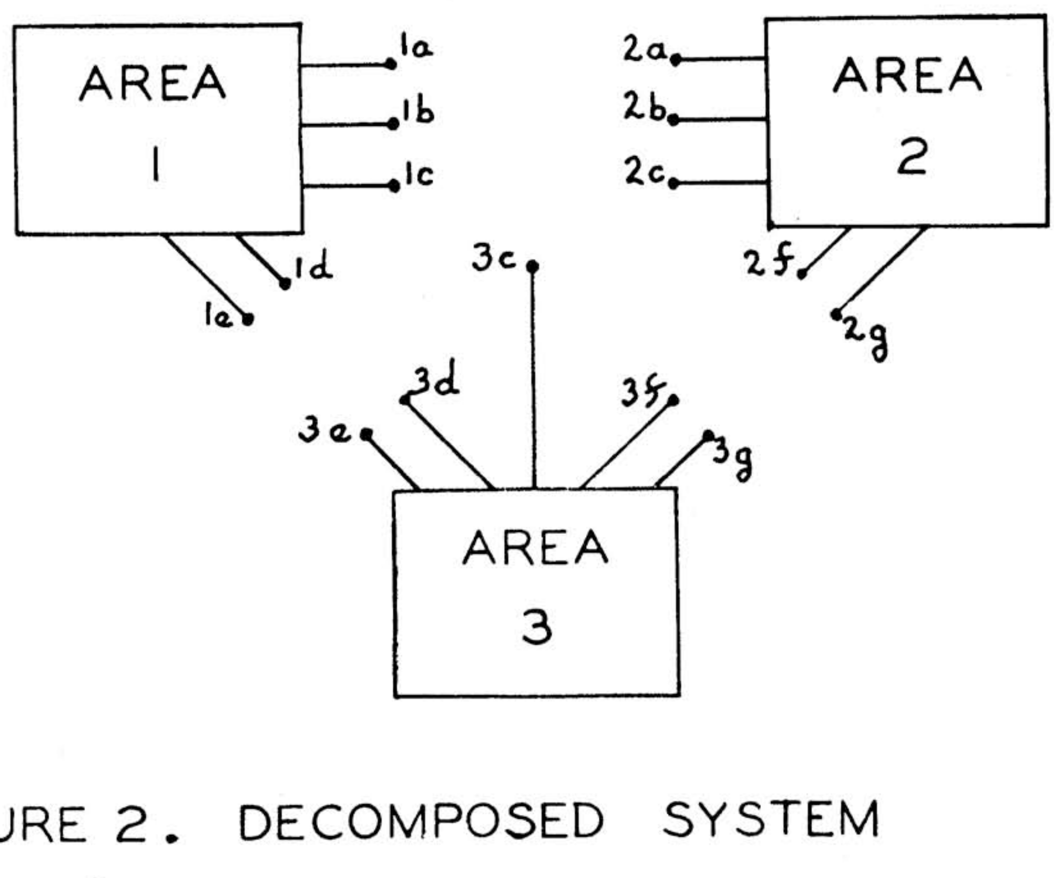

FIGURE 2. DECOMPOSED SYSTEM