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Survey paper

CONTROL PROBLEMS IN ELECTRIC POWER SYSTEMS

G. Quazza

ERRATA	CORRIGE
page 1 - 9th line from the bottom	
Indeed, units of more than 1000 MVA rating are.....	Indeed, units rated more than 1000 MVA are......
3rd and 2nd line from the bottom	
Why this can happen it is open to question : but is may not look so strange, even in the years of technological maturity, if it is noticed	Why this happens now, although technological maturity has been achieve in this field, it is open to question; but it may not look so surprising, if it is noticed
page 2 - 3rd line	
.....and design methods have halved ma	and design methods have led to halved ma
4th line	
chine......power, or increased.....	chine...... power, and increased.......
last line	
.....propagation, system restoration procedures.	propagation, careful study of system restoration procedures.
page 3 - 13th line	
....improvement of the single-loop response, they were...	improvement of the response of single feedback loops, they were......
25th and 26th line	
....., is very relevant in clarifying the conceptual approach to system problems.	is very relevant in the basic engineering approach to system analysis for design and operation.
27th line	
Including network and.....	Accounting for network and......
28th line	
viewpoint in the electric power system design poses, of course, serious	viewpoint in the design of electric power system poses, of course, heavy and delicate
3rd line from the bottom	
......; and for each level list the auto	.....; and for each level we will list the auto

page 4 - 5th line tion includes load protections, load.....	tion includes governor emergency biasing, load.....
8th line "Optimizing Control" in normal or preventive conditions includes active	To "Optimizing Control" in normal or preventive conditions belong active
11th and 12th line ges; while in emergency and restorative operation includes maximum load determination and dynamic restoration procedure.	ges; while possible optimizing functions for emergency and restorative operation are the determination of maximum acceptable load and the choice of an optimal dynamic restoration procedure.
13th line "Adaptive Control" includes relay setting changes, controller parameter	As "Adaptive Control" functions we list here - besides some of the above quoted direct control emergency actions, which might also be called adaptive - relay setting changes, controller parameter
20th, 21st, 22nd line The relative roles of automatic and manual controls, including information processing and display, in system operation and planning will be illustrated for each of the above functions in the next sections.	The relative roles of automatic and manual controls in system operation and planning, with special reference to information processing and display will be illustrated for each of the above functions in the next sections.
page 7 - 5th and 6th line 2n load-flow equations :	line 5 is to be cancelled. However, the 2n load-flow equations :
7th line or, in more compact form,......	or, in equivalent but more compact form,...
10th line vector E (alternatively, the line transit vector) :	vector E (alternatively, the line transit vector), the system of equations ; $G(E, U) = 0 \qquad (10)$ need not necessarily be solved directly for the optimizing program.

11th line What is needed is, more frequently -	It is enough, more frequently - .....
12th line coordination equations - the derivatives of (10),...	coordination equations - to obtain the derivatives of (10),....
page 8 - 11th line The only item 3).....	Only item 3).....
13th line (8) : actually, since 1)....	(8) : consequently, since 1).....
26th line frequent controlling element adjustments, say.....	frequent adjustments of controlling elements., say.....
page 10 - 17th line from the bottom down....shut down are accounted for,.....	down.....shut down, are accounted for.......
page 14 - 3rd line as already....., and	as already......., and should
17th line ....to be the switching a new line	.....to be the switching of a new line
14th line from the bottom A further step, say by one decade, towards higher frequencies is need -	A further step, towards higher frequencies, say by one decade, is need-
page 15 - 18th line function $G_f = \ f/ \ P$ as a spectral	function $G_f = \Delta f/\Delta P$ as a spectral....
22nd line with.....variations ϕ_{P_c}, P_c :	with....variations ϕ_{P_c}, P_c : .....
25th line two conditions to be comparated are :	two conditions to be compared are :
equation (23) $\frac{\phi_{f_b} - \phi_{ff}}{\phi_{PePc}} = G_f\bar{G}_f + \bar{G}_f \frac{\phi_{Pcf}}{\phi_{P_cP_c}} + G_f \frac{\phi_{fPe}}{\phi_{P_cP_c}} \qquad (23)$	$\frac{\phi_{f_b} - \phi_{ff}}{\phi_{P_eP_e}} = G_f\bar{G}_f + \bar{G}_f \frac{\phi_{Pef}}{\phi_{P_eP_e}} + G_f \frac{\phi_{fPe}}{\phi_{P_eP_e}} \qquad (23)$

III

page 16 - 13th line from the bottom bution.....in Fig.13 for	bution ...... in Fig.6 for
page 17 - 8th line ask for.... - , or at the least few minutes, -....	ask for.....-, or at least several minutes, - ......
page 18 - 21st line Such filters,..... and timers switch area	Such filters,..... and timers, switch area
page 20 - 11th and 12th line in the...., Liapunov stability regions do not include all....	in the....., Liapunov's method does not determine all....
page 21 - 17th line from the bottom difficult to be integrated and......	difficult to be interpreted and......
page 22 - 11th line from the bottom So far, d.c.links have built only......	So far, d.c.links have been built only......
page 24 - 26th line from the bottom unit....to advise when a.....	unit,....to give a warning when a......
12th line from the bottom consequent considerable increase.....	consequent appreciable increase.......
page 26 - 16th and 17th line and fast.....be entered the controller design at least in constraint equations......	and fast.....affect the controller design at least through constraint equations......
page 27 - 7th line from the bottom is introduced by the......	is caused by the.......
page 28 - 9th line from the bottom tion in power plants........	tion of reactors in power plants.........

page 29 - 10th line On the other ......also proposed for....	On the other.....also been proposed for.....
page 30 - 8th line scarce availability.....	limited availability
page 32 - 5th line electronics for the controller-amplifier and....	electronics for controller-amplifiers and......
15th line on the response.....	in the response
page 33 - 6th line infite bus.	infinite bus.
7th line linearized system, with machine angle and generator voltage as	linearized system, with internal angle and output voltage as
page 34 - last and last but one lines remotely....and is possibly linked to station computers. -	remotely....; with possible link to station computers. -
References - page VI - n.102 QUAZZA, Modelli analitici delle caldaie a corpo cilindrico - Automazione e Strumentazione, Nov. 1968	QUAZZA, Modelli analitici delle caldaie a corpo cilindrico - Automazione e Strumentazione, Nov. 1968 and Febr. 1969
page VI - n. 101 STEPHENS	STEVENS
page VII - n. 105	TAKENOUCHI, Characteristics of once-through boiler for load change - Proc. on Int. Seminar on Automatic Control in production and distribution of electrical power, Brussels, April 1966 - ed. Dunod et Presses Acad. Européennes

G. Quazza

CONTROL PROBLEMS IN ELECTRIC POWER SYSTEMS

INTRODUCTION

1.1 The main applications of automatic controls to production, transmission and distribution of electric energy, as it has been quite clearly shown by B. Favez in his survey paper [1] at Basel IFAC Congress, stem from the basic requirements of quality of service and economy of electric power supply. In the following, a brief account is first given of the present trends in electric power system planning and operation, and it is shown how the growing demand for better security and continuity of service on one side, and investment and operating cost reduction on the other side affect the role of controls both in system and in station operation and design. The recent progress in each of the main areas of control technique applications is then outlined, more emphasis being laid on the use of computers and modern methods of dynamic analysis, optimization and identification.

1.2 Trends in power system planning : the problem of service continuity

Fig. 1b qualitatively shows how the overall investment and operating costs of large boiler-turbine generator units decrease with unit capacity. It explains why in the last years there has been a growing trend towards larger and larger unit sizes. The rate of unit size increase has been, infact, impressive, as Fig. 1a indicates. Although the installation of a larger unit in the system calls for more reserve, detailed planning studies - which are based upon highly sophisticated digital computer programs for calculating system availability at the peak load and deciding when to install a new unit - indicate that unit sizes of more than 5% of total system capacity, for reasonable values of power shortage risks and good unit forced outage rates, may still be convenient. In other words, a 1500 MW unit may be economic for a 30.000 Mw system. Indeed, units of more than 1000 MVA rating are already in operation, and turbine-generator manufacturers do not see, after having solved the problems of rotor conductor cooling, any unsurmountable difficulties in going further, except for transportation limits.

However, all the above progress has one drawback : larger units shows worse reliability, i.e. greater forced outage rate (F.O.R. in Fig. 1c). Why this can happen, it is open to question ; but is may not look so strange, even in the years of technological maturity, if it is noticed that the turbine-generator designer is frequently faced with studying the

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Giorgio Quazza is with Ente Nazionale Energia Elettrica - Direzione Studi e Ricerche - Centro Ricerca di Automatica, Milano design of a much larger unit when the previous smaller machine has not yet undergone enough experimentation.

Furthermore, improved materials and design methods have halved machine weight per unit output power, or increased turbine blade size by 50% in a few years; but often to the expense of safety margins, and in any case with consequent less inertia of rotating parts, lower metal capacity, lower water and steam volumes. The effects of disturbances are much faster and call for much more prompt action, to avoid serious faults and damages.

A rough idea of the role of unit F.O.R. upon reserve requirements is given by Fig. 1c : and it should be added that realistic figures for the F.O.R. in the first year of operation of a large unit are in the order of 8 to 12 %, while evidence is not yet available that after three years they may be better than 3 to 4%, for unit rating in excess of 300 MW. Nevertheless, the trend is towards larger and larger unit sizes.

Another good reason for this trend is the development of *interconnections* between power companies : indeed, it is obvious that a pool among several companies has a larger capacity than that of a single member, and as a consequence the largest unit becomes a smaller fraction of the total capacity, so that the overall % reserve requirements decrease. The investment-plus-operation-economy improves.

However, going too far in increasing unit size and decreasing overall reserve by pooling may be dangerous. A problem of system security may arise again, if the reserve is not suitably distributed in the pool. Tripping of a large power station when the available reserve is physically too far in the system may engender instability. The transient may occur when there is an unexpected overload for adverse meteorological situations, while many lines are on programmed maintenance, etc. : a risk of black-out appears.

The propagation of a large transient across the system is a real problem, as world-known cases [2] have shown. While it is impossible to have a reasonable estimate of black-out probability, and consequently design the power system with enough safety margins as to prevent collapse in such situations, it is imperative to study and apply any conceivable automatic control action that may save the system.

Just as the large and low-inertia boiler-turbine generator unit requires faster controls, better protections, automation of the too complex start-up and shut-down operations to reduce stresses through improved repeatability, power system security calls for centralized automatic controls and protections, pre-planned corrective actions, operator-guides for manual emergency interventions, continuous monitoring of system overload margins for possible contingencies, load-shedding, system splitting, installation of suitable direct current transmission lines to avoid transient propagation, system restoration procedures.

1.3 Role of automatic control techniques for system security and operating economy

In the preceding paragraph, emphasis has been laid upon the need for automatic controls as means to achieve the desired power system security. While security is certainly considered to be the most important aspect of quality of service, it must be remembered that controls play also a role in minimizing frequency and voltage variations , and their application to system operating cost reduction through centralized economic dispatching and station unit performance monitoring is becoming more and more widespread.

Actually, the influence of automatic control techniques upon electric power systems is even broader. Indeed, as long as they were directed towards the improvement of the response of single feedback loops, they were conceived only as means to obtain better operating performance from a given system, the design of which was made independently of the existence of controls and was quite often based upon static stresses.

Today, the "total system" viewpoint is accepted. It is understood that system structure and general features may limit the results which controls may achieve : why not accounting for the existence and the performance of automatic controls in the system design stage, so as to remove useless or economically unjustified constraints ?

The impact of modern control theory and methods, from multivariable system matrix analysis, optimization and identification, to computer predictive, adaptive, non-interacting sampled-data controls, while still relatively small in actual realizations, is very relevant in the basic engineering approach to system analysis for design and operation.

Accounting for network and plant dynamics, and adopting the total system viewpoint in the design of electric power systems poses, of course, heavy and delicate problems : system size and need for simulation, analytical vs. empirical models, need for statistical identification of system environment and load changes, centralized vs. decentralized control, partial automation and man-machine communication, predictive vs. feedback action, reliability vs. manual reserve, etc.

How far this integrated view has gone until now, we will somehow try to show in the next paragraphs. To be consistent with it, we will start with system problems, and then proceed to plant controls having in mind that the specifications of the single generating units should at least conceptually be established as a result of system requirements.

Following Dy Liacco [3] , we will distinguish three levels of power system control, with increasing degree of operator intervention : direct control, optimizing control, adaptive control; and for each level we will list the automatic and manual functions, whether the system is in normal operating conditions or in emergency.

"Direct Control" in normal operating conditions includes primary frequency control, tie-line power and secondary frequency control, generation voltage regulation, transformer tap changing, condenser and reactor switching, fault clearing and reclosing; while in emergency and restorative operation includes governor emergency biasing, load shedding, network automatic switching, out-of-step tripping, system splitting, automatic feeder restoration, automatic load transfer.

To "Optimizing Control" in normal or preventive conditions belong active power economic dispatching, voltage and reactive power centralized control unit commitment, hydro resource economic allocation, economy interchanges; while possible optimizing functions for emergency and restorative operation, are the determination of maximum acceptable load and the choice of an optimal dynamic restoration procedure.

As "Adaptive Control" functions we list here - besides some of the above quoted direct control emergency actions, which might also be called adaptive - relay setting changes, controller parameter and set point variations, security assessment and consequent network structure changes or generating power reallocation, constraint modification, reliability evaluation and stability analysis, fault location, reserve requirements, diagnostic analysis and touble-shooting.

A similar distinction could be made for controls of stations, substations an distribution systems.

The relative roles of automatic and manual controls in system operation and planning, with special reference to information processing and display will be illustrated for each of the above functions in the next sections.

II. CENTRALIZED OPTIMAL CONTROL OF ACTIVE AND REACTIVE GENERATING POWERS AND SYSTEM SECURITY MONITORING

II. 1 Optimum control of active and reactive powers in thermal production systems

As it is well known [1], an on-line automatic solution to the problem of minimizing operating costs of a thermal system was already available more than ten years ago. The numerous applications of relatively simple analog computers to the economic dispatching of active powers were all based upon the coordination equations [5] and quadratic formulas giving transmission losses as functions of the p generated active powers P_i.

Such formulas implied rather restrictive assumptions : constant voltages E_j, θ_j , constant ratio between individual loads and total load, constant ratio between reactive and active powers; and loss coefficients had to be re-calculated for each network structure change, or pre-calculated for several network states, with consequent adjustment of analog computer potentiometer settings. Furthermore, quadratic loss formulas were not al~~l~~ways suitable to describe the variation of losses with load for non-compact networks.

The advent of the digital computer has truly been a turning point in on-line and off-line economic dispatching. Not only because it has made it possible to remove all the above limitations, but also because it has offered a satisfactory solution to the problem of integrating the search for economic allocation of generated power with the preventive assessment of system security in front of possible line-or generator outages.

In addition, the more rigorous approach to the minimization of production costs, where also reactive powers are considered as variables and optimized, and constraints on line transits are accounted for, can be implemented. Application of Kuhn and Tucker theorem to the problem of

minimizing
$$F = \sum_{i=1}^{p} F_i(P_i) \tag{1}$$

subject to the static active power balance equation

$$g(P_1, \dots, P_p, Q_1, \dots, Q_p) = 0 \tag{2}$$

where :

$$g = \sum_{i=1}^{p} P_i - \sum_{j=1}^{n-p} C_j - P_L(P_1, \dots, P_p, Q_1, \dots, Q_p) \tag{3}$$

with given load active powers C_j and reactive powers D_j, and subject to inequality constraints, due to equipment limitations, - such as generating plant capacities, line transit capacities, bus voltage tolerances, - among which we list here for simplicity only the constraints on generated active powers :

$$P_{im} \le P_i \le P_{iM} \qquad i = 1, 2, \dots, p \tag{4}$$

leads to zeroing the derivatives of the function :

$$\phi = F + \lambda g + \sum_{i=1}^{p} \underline{\nu}_i (P_{im} - P_i) + \sum_{i=1}^{p} \bar{\nu}_i (P_i - P_{iM}) \tag{5}$$

with respect to the variables P_i, Q_i. The resulting equations :

$$\frac{dF_i}{dP_i} + \lambda \left(1 - \frac{\partial P_L}{\partial P_i}\right) + \sum_{i=1}^{p} (\bar{\nu}_i - \underline{\nu}_i) = 0$$

$$\frac{\partial P_L}{\partial Q_i} = 0 \qquad\qquad i = 1, 2, \dots, p \tag{6}$$

$$\underline{\nu}_i (P_{im} - P_i) = 0$$

$$\bar{\nu}_i (P_i - P_{iM}) = 0$$

yield the solution, if the expressions of the derivatives of transmission losses :

$$P_L = \sum_{j=1}^{n} \sum_{k=1}^{n} \left[P_j \alpha_{jk} P_k + Q_j \alpha_{jk} Q_k + P_j \beta_{jk} Q_k - Q_j \beta_{jk} P_k \right] \qquad (7)$$

$$\alpha_{jk} = \frac{r_{jk}}{|E_j|\,|E_k|} \cos\theta_{jk} \;; \qquad \beta_{jk} = - \frac{r_{jk}}{|E_j|\,|E_k|} \sin\theta_{jk}$$

can be obtained, as functions of active and reactive powers P_j, Q_j at all nodes, i.e. including both generator and load powers, with proper values for bus voltages E_j and phase angles θ_{jk}.

The second equation in (6) shows that minimization of production costs calls for minimizing transmission losses as functions of reactive powers Notice that the non-negative dual variables, associated with each inequality constraint, such as $\bar{\nu}_i$ or $\underline{\nu}$[illegible] may be interpreted [8] as the incremental costs of the constraint or the sensitivity of cost to the constraint value.
Indeed, notice that if the constrained optimum calls for $P_i = P_{iM}$, removing the constraint, i.e. letting P_i free to be incremented by ΔP_i, would yield a positive cost reduction $-\Delta F = \bar{\nu}_i \Delta P_i$.

The actual solution to (6) can be obtained by iteration, with relaxation between active and reactive power allocation [6]. Reactive powers are given by the reactive power optimizing subroutine, and enter the active power program as inputs. By iterating on an initially estimated value for λ , the active powers-as determined by the coordination equations with estimated losses-are derived. A load flow is calculated on the basis of such active powers, so as to obtain a corrected value for transmission losses and pursue iterations on losses until convergence is achieved. A sketch of an active power optimization flow chart [6] is given in Fig. 2, while Fig. 3 shows the flow chart for the reactive power part of the program, as based on a gradient method [6] :

$$\Delta Q = k^{(i)} \text{ grad } P_L^{(i)} \qquad (8)$$

where ΔQ is the p column-vector of manipulated reactive powers.
If voltage constraints are violated, $k^{(i)}$ is decreased : if a reactive power limit , say Q_{iM}, is exceeded, Q_i is kept fixed at Q_{iM}.
Computing times of about 1.5 min on a 360/50 IBM digital computer for a 176 buses, 268 lines, 25 regulated buses, 15 generating plants, 5-segment cost curves are reported [6] .

II. 2 Centralized control of reactive power

Reduction of computing time is essential, if such digital programs are to be implemented on an on-line computer. A remarkable progress has recently been made in cutting down load-flow digital program times, expecially by the use of the product form of the inverse system matrix with ordered triangularized factorization [10] : a complete load-flow for a 200 buses system may now take only a few seconds on an IBM 7040.

However, the 2n load-flow equations :

$$(P_k + jQ_k) - (C_k + jD_k) = E_k \sum_{i=1}^{n} (Y_{ki}\, E_i)^{*} \qquad k = 1, \ldots, n \qquad (9)$$

or, in equivalent but more compact form, without explicitly mentioning load active and reactive powers C_k, D_k and network admittances Y_{ki}, but introducing the manipulated P_j, Q_j vector U, and the bus voltage vector E (alternatively, the line transit vector), the system of equations:

$$G\,(E,\ U) = 0 \qquad (10)$$

need not necessarily be solved directly for the optimizing program.

It is enough, more frequently - both for constraint equations and coordination equations - to obtain the derivatives of (10), i.e. the Jacobian matrices G_E, G_U of G derivatives with respect to the components of vectors E and U. For example, minimizing losses vs. reactive powers should comply with the condition that bus voltages E remain close to their reference values, within a narrow tolerance. The linearized relationship is then searched between voltage variation ΔE and manipulated variable variations ΔU :

$$\Delta E = S\, \Delta U \qquad (11)$$

where :

$$S = -\, G_E^{-1}\, G_U \qquad (12)$$

is the sensitivity matrix. Calculation of G_E^{-1} is, by the way, greatly speeded up by the above ordered factorization, the efficiency of which is due to the sparse character of G_E.

Sensitivity matrix and Newton-Raphson methods with the product form of the inverse have greatly enhanced the possibilities of on-line fast programs. Indeed, the rigorous approach to active and reactive economic dispatching for thermal systems had already been stated by J. Carpentier [7] in 1962 with his "method of injections", but convergence difficulties and computing times had somewhat impaired its application. An important progress towards efficient programs, along somewhat different lines than in (1) ÷ (7), and more in accordance with the original injection method and the sensitivity concept, has been obtained by several authors [8, 9, 10] ; see expecially the methods of differential injections [11] and of total injections [12].

In the practical applications of on-line computers to control of voltage and reactive powers, attention must be given to the fact that the elements to be manipulated in order to effect the desired ΔU (or ΔQ) are the following :

1)- Load Tap Changer Controllers, for varying transformer turn-ratio where tap positions can only assume integer values ;
2)- Static Condensers or Shunt Reactors, where again the number of capacitors or reactors that can be switched on can only be integer
3)- Rotating Condensers or Generators with voltage or reactive power control.

The only item 3) can assume any value within its maximum-minimum limits, and then be suitable to the straightforward application of (1) ÷ (8) : actually, since 1) and 2) are quite effective elements to be used, the computer problem becomes one of partially integer quadratic programming.

One approach[13, 14], which has been employed for the Kyushu Electric Power Co. on-line computer installation, splits the optimization problem into two-phases : a) search for bus voltages which are compatible with constraints; b) minimization of losses. While for phase b) direct search methods are used, phase a) employs a multi-stage conjugate gradient-method, with approximate discretization of synchronous machine reactive powers, to minimize $\sum(\Delta E_i)^2$, where ΔE is given by (11) : the minimizing procedure is stopped when all voltages have come within their tolerance range.

If it is noticed that the overall economic objective does not call for frequent controlling element adjustments, say one every more than 15 min, it is understood that the reported[13] computing time of 8 sec on IBM 7090 may be adequate and allow enough time for other computer functions.

Indeed, the interest in on-line centralized voltage control, which is growing, in spite of the very small number of computer installations operating to day in the world, is justified when voltage control is only one more task for a dispatching computer, besides active power allocation and security assessment. Savings from transmission loss reduction cannot certainly be substantial. One important aspect of reactive power optimisation by minimizing losses is the fact that it offers a criterion for the establishment of a voltage pattern throughout the network and for the cost evaluation of voltage constraints.

II.3 Security assessment and active power dispatching

If the on-line digital computer is capable to compute loss coefficients by a load-flow program, it probably can handle on-line security assessment checks. Indeed, minimizing production costs subject to the constraints of not overloading lines and generators does not always yield a reasonably safe situation. If the current in a line is close to its rated value, an overload may result from tripping of another line in the same area, with possible relay switching and a sequence of interruptions, much before the computer or the operator may have had a chance to modify generating power allocation so as to suitably reduce the load on that line.

Timely account must be taken of possible single contingencies, such as tripping of one line or one unit, or perhaps double contingencies, by checking that no contingency can overload any line or generator. An essential task for the dispatching computer is then the calculation, on the basis of telemetered bus voltages and injected or transit powers, of network load flows for all major or credible contingencies, to insure that no overload may occur. Such calculation may imply hundreds of load-flows : no wonder that some users [15] prefer simplified d.c. load flows, and that so much work is done to obtain faster a.c. load flow programs. If, as a result, no evidence of overloads appears, the computed economic allocation of generating powers is judged as safe enough and confirmed : if some overload is shown, the operator - or, alternatively, the computer itself when properly instructed - suitably changes power allocation and possibly introduces other spinning reserve. Certainly, if off-line studies could discover an approximate relationship between the maximum overload caused on one line by the tripping of anyone else and the total system load - or may be a few other parameters - all the above checks would not be needed, with great savings. This is the reason why some utilities are making systematic investigations to determine the load increase caused on all other lines by the tripping of any single line. The above relationship would allow describing security by simply introducing, in the economy loading program, transit power limits, which are suitable functions of total system load.

Even if drastic simplifications may be hoped for, security assessment is certainly one of the heaviest tasks of the dispatching computer, which is still considered by many users as a powerful and sophisticated information display more than an optimizing or control apparatus.

E.d.F. Centre National du Dispatching [16] and CEGB National Centre [15] are equipped with CRT displays showing network diagrams, with active and reactive power flows, substation switching, plus much tabular information. Telemetering instrumentation reasonability checks are performed by the computer. The amount of fast pick-up reserve, which can be called in within 5 minutes, is displayed by Nixie indicators in several existing dispatching computers [16, 17].

Most USA digital computers still determine optimal active power allocation on the basis of equal penalty-factor-corrected incremental costs, by using quadratic loss formulas and no line-transit constraints [18].

Indeed, this approach may well be adequate for systems having no line bottlenecks, expecially if more rigorous new loss expressions [20] are used. Elsewhere [15], a merit order is enough to decide unit selection, but scheduling the economic loading on each of the not fully loaded machines implies recognizing the limitations on unit loading rate and hence using the computer to calculate the expected demand for 1 h ahead by a load-forecast program.

The increasing need for coordinating the economic operation of the members of a single large pool has suggested the installation of a central computer [19, 21] for determining inter-area transfers for minimum overall cost, with direct telecommunication link with area-computers : iterative [21] solutions to the minimization problem have been conceived, which call for computer-to-computer communication.

II.4 Variational problems in optimizing system operation

Other tasks, which are frequently assigned to the dispatching computer within the scope of economic operation and security checks, are the following :

a) unit commitment, usually in a predictive program, for the next day;

b) short-term hydroelectric resource allocation, on the basis of reservoir seasonal schedule ;

c) tariff computations for energy interchanges with neighbouring companies ;

d) periodic recording of measured and computed quantities.

Programs for unit commitment do not pose any special difficulty when selection is made on the basis of a priority list : units are ordered for increasing average operating costs. However, if start-up time and cost, which are functions of both the time elapsed after the last shutdown and the unit load before shut down are accounted for, the problems becomes considerably more complicated. Minimization of the integral cost during a 24 h period calls for a Euler coordination equation, whereby the best time for starting up a unit is obtained when its incremental start cost is equal to the incremental profit from shutting it down [23]. In other words, keeping a unit at its technical minimum for a longer time may cost less than shutting it down earlier, due to the higher cost of starting it up later in the following day [22].

The short-term optimal scheduling of a hydrothermal system, expecially for the case of complex valleys, i.e. hydraulically cascaded plants, with given water volume to be drawn from seasonal reservoirs in a given period, say 1 day, or 1 week, is an even more typical variational problem. The objective is a functional, the integral of the fuel cost in steam stations, while one of the constraints, on the reservoir water volume, is also of the integral type on water rate of flow : the optimal "trajectory" is given by the steam and hydro generator output power curves vs. time, which minimize the daily, or weekly, fuel cost.

Several optimization methods and digital computing procedures have been tried to solve the problem, from the older dynamic programming [26] and Euler coordination equation [27,29] approaches to constrained gradient [28] and more recently the maximum principle [30] and linear programming [31].

For the highly simplified case of single-reservoir constant head hydro-electrical units and steam units, with no other constraint than the requirements of coping with the demand and consuming the given water volumes, the problem is one of :

$$\text{minimizing} \quad \int_0^T F \, dt \qquad (13)$$

$$\text{subject to :} \quad \sum_{i=1}^{s} P_{is} + \sum_{j=1}^{h} P_{jh} - P_L - C(t) = 0 \qquad (14)$$

$$\text{and :} \int_0^T q_j \, dt = V_{jT} \qquad j = 1, 2, \ldots h \qquad (15)$$

with $C = \sum C_K$ total active load; and V_{jT}'s are established by the long-term hydrothermal system optimizing program which determines weekly outputs of hydroelectric stations for most economic yearly operation of the system, with due account for the random nature of hydrological predictions, load forecast, unit availability and the risks of peak power deficiency associated with emptying reservoirs [29,33].

If steam power P_{is} and water rates of flow q_j are chosen as variables, Euler equations become simply :

$$\frac{\partial L}{\partial P_{is}} = 0 \quad ; \quad \frac{\partial L}{\partial q_j} = 0 \qquad (16)$$

where :

$$L = \sum_{i=1}^{s} F_i(P_{is}) + \lambda(t) \left[\sum_{i=1}^{s} P_{is} + \sum_{j=1}^{h} P_{jh} - P_L - C \right] + \sum_{j=1}^{h} \mu_j q_j \qquad (17)$$

i.e., if $\lambda(t)$ is eliminated in the "coordinating equations" resulting from (16), the following relationships are obtained :

$$\frac{1}{1 - \frac{\partial P_L}{\partial P_{is}}} \cdot \frac{dF_i}{dP_{is}} = \mu_j \frac{1}{1 - \frac{\partial P_L}{\partial P_{jh}}} \cdot \frac{dq_j}{dP_{jh}} \qquad \begin{matrix} i = 1, 2, \ldots s \\ j = 1, 2, \ldots h \end{matrix} \qquad (18)$$

$$\frac{\partial P_L}{\partial Q_k} = 0 \qquad k = 1, 2, \ldots (s + h) \qquad (19)$$

When linear programming is used, the period T is subdivided into a suitable number of time intervals of duration T_i. both objective function and volume constraints are discretized, a linear approximation for losses vs. active and reactive powers is accepted, and P_{isk}, q_{jk} relative to interval k are treated as positive variables different from P_{isw}, q_{jw}, $w \neq k$. By this token, since T_i's are known constants, the problem becomes one of linear programming, and ample opportunity is given to introduce inequality constraints and exploit the wealthy set of elaborate techniques and routines available for large-scale optimal linear programs.

However, if the number of time intervals in which T has been subdivided is high, the number of stations and hydraulically cascaded plants is large and losses are taken into account, the overall number of equations, inequalities and variables may become excessive even for large computers.

Simplifications are then needed. One of them [31] consists in suboptimizing each "valley" separately from the remainder of the system, say maximizing its output energy for a given shape of its load diagram versus time : hydroelectric units take up on themselves most of the variable part of the load curve. The resulting optimization is not rigorous : but each valley is dealt with to a greater detail, allowing for water transport delays in open-air canals, small intermediate pondages, constraints on levels and rates of flows, etc. Alternatively, the rigorous approach is followed, but "valleys" are replaced by an "equivalent" hydroelectric unit, with some sacrifice in establishing the equivalence, and need for checks on admissibility and consequent corrections.

A further interesting but simpler example of variational optimization is offered by pumped-storage station operation. Indeed, while such stations are meant to generate electric power at the daily peaks, and pump water from the lower reservoir at night, the problem arises as to choose time intervals and water flows for generation and pumping such as to minimize the overall cost of pumping, and maximize fuel saving during generation. It can easily be derived from (13) to (19) that the condition for optimum is that pumping is scheduled such that water incremental cost dF/dq is constant along all the duration of pumping, and likewise the incremental fuel saving dS/dq during generation is constant, while of course the saving must exceed the cost :

$$\left(\frac{dF}{dq}\right)_{\text{along pumping}} = \text{const} = \mu \quad ; \quad \left(\frac{dS}{dq}\right)_{\text{along generation}} = \text{const} = \nu \qquad \mu < \nu \qquad (20) \; .$$

To solve (20), knowledge of incremental cost of steam power at the pumped storage station node vs. time is needed, although the required timeliness and accuracy are not so critical as to impose an on-line automatic solution. Also hydrothermal and valley optimization problems do not strictly belong to the realm of on-line automatic controls, since hydroelectric station scheduling is generally prepared once a day, for the following day, on the basis of load forecast and unit availability reports and is only exceptionally corrected during operation, as the search for the true optimum would call for. Nevertheless it has been felt that hydro-thermal system optimization has to be legitimately quoted here, because it may be thought as an example of predictive control, where modern control methods and techniques are widely employed.

At present, valley suboptimization is generally obtained either manually or by off-line computers. but may become the task of regional computers, when the system size is such as to suggest the centrally coordinated regional organization. The central computer, which would of course take care also of security monitoring, would then be responsible for the "instantaneous" optimization of the thermal system, with values of hydroelectric station hourly outputs given by the regional predictive scheduling. Notice that "instantaneous" means that the computer repeats its calculations, on the basis of the total generated power plus the "area requirement", every 3 to 15 minutes.

II. FREQUENCY CONTROL OF INTERCONNECTED SYSTEMS AND DYNAMIC SECURITY

III.1 Power system dynamic models

The generation-demand balance equations (2), (3), or (14), and likewise power-flow equations (9), hold only when system frequency is truly constant. Such condition cannot be fulfilled in practice : indeed it is just on the basis of frequency deviations from a reference value that a measurement of the unbalance between turbine power outputs and generated electrical powers - i.e. also load demand - is obtained, and secondary frequency control and governing actions are taken, to maintain frequency and generation-demand balance.

A very accurate economic optimization would then require corrections to account for system-and unit-dynamics. Under transient conditions it is no longer true that steam unit heat consumption is only a function of its instantaneous electrical output power : dynamics of boiler, turbine, cycle and their controls play a relevant role. Secondary frequency control may in each instant establish the amount of regulating power to be added to the predictive unit schedule, which was based on highly accurate load forecast. The desired values of such regulating powers may be included in $\sum P_i$ equation (3), and this is in fact ugually done : but the achieved economic operation is still not perfect, due to the limited speeds of response of the regulating units, and the dispersion of their characteristics.

On the other hand, searching for such an ideally economic instantaneous operation is not even realistic : transducer and telemetering errors inaccuracies in incremental cost data, and their variations with plant conditions, limit the attainable overall accuracy. Therefore, economic control is intended only as a "tertiary" control, i.e. relatively slow, as already pointed out at the end of the preceding paragraph, and consequently be based upon a quasi-static description of the generation-demand situation.

A "quasi-static" description of the system behaviour has already been considered as acceptable in II.3, in connection with "static" security assessment. While reallocating generation may already be required in a preventive stage to avoid overloads in case of single contingencies, the actual occurrence of a double-contingency fault may well engender an overload on some lines, and if so action must be taken before line temperatures become excessive. In the fortunate situation, when no protection has tripped yet, the line thermal time constant allows at least a few minute time for effecting the correction, more or less depending upon ambient temperature and line load before the emergency.

The required action is not likely to be the switching a new line on the network : in general, if some lines are not in operation, the cause is maintenance outage. There may be enough time to start up a hydro-electric unit, or a jet turbine; but in general reallocation of generating powers is needed.

Clearly, line heating phenomena are slow enough, as to allow use of a quasi static mathematical model, accounting for line thermal time-constants, unit loading rate limits, short-term pick-up reserve and the like : at most, load frequency response times.

On the other hand, a better description of system dynamics, with a reasonably good approximation in the frequency range below 0.5 cps, is required when the behaviour of secondary frequency and tie-line power control is studied.

A further step, say by one decade, towards higher frequencies is needed in system dynamic modelling for the analysis of electromechanical oscillations and stability. Finally, the last stage in dichotomy of system transients vs.time, or dynamic response vs.frequency, is the description of traveling waves of surge voltages along lines and transformers : no account of it will be given here, in spite of the relevant role of automatic protections, because the contribution of modern control techniques in this field as yet is not very significant.

III.2 Statistical identification of power systems

Since the number of generating units in most existing systems is very large, and reliable information on the response of their governors is available only for a few of them, there is little chance of obtaining the system injected power-to-frequency transfer function by analytical means. Experimental measurements are necessary.

Step responses of an isolated system to disconnection of a large generator - see [35,34] for the effect of reactive power on the equivalent active power step - or of a heavily loaded line, or to a command signal from the central dispatcher to regulating stations, do not give a wholly satisfactory answer. In order to obtain clearly interpretable responses,- see the exceptionally good recording in Fig. 11-, large steps are required, and consequently frequency deviations during the test far exceed normal operating deviations. Therefore, much more control action than governor dead bands normally allow is evidenced : conclusions on "available regulating energy" are optimistic. Furthermore, the measured step response corresponds only to the specific network structure at the moment of the test, and no information on the continuously varying system response is given. No quantitative indication is offered on the load disturbances which act on the system.
Therefore, statistical identification methods have been tried. [34,36,37].
The basic difficulty here is the impossibility of measuring load or, more generally, injected power-variations, so as to obtain the transfer function $G_f = \Delta f / \Delta P$ as a spectral ratio of input-output cross correlation function to input autocorrelation function. Several methods have been proposed to circumvent this problem. A simple one consists in comparing system responses in two different conditions but presumably with the same spectrum of load variations $\phi_{P_c P_c}$: elimination of $\phi_{P_c P_c}$ yields an equation in G_f.

With reference to Fig. 12, where P_c, P_e, P_R indicate variations in load, exported power, secondary control power out of regulating stations, the two conditions to be compared are :

a) interconnected system, measurement of f and P_e

b) isolated system, measurement of f;

both with disconnected load frequency controller, i.e. $P_R = 0$.
If f_b is the frequency variation in case b), f in case a), one can write :

$$\phi_{PcPc} = G_f^{-1} \bar{G}_f^{-1} \phi_{ff} + G_f^{-1} \phi_{Pef} + \bar{G}_f^{-1} \phi_{fPe} + \phi_{PePe} \qquad (21)$$

$$\phi_{Pcc} = G_f^{-1} \bar{G}_f^{-1} \phi_{f_b f_b} \qquad (22)$$

hence :

$$\frac{\phi_{f_b f_b} - \phi_{ff}}{\phi_{PePe}} = G_f \bar{G}_f + \bar{G}_f \frac{\phi_{Pef}}{\phi_{P_e P_e}} + G_f \frac{\phi_{fPe}}{\phi_{P_e P_e}} \qquad (23)$$

Equation (23) establishes a relationship between the real and the imaginary parts of $G_f(j\omega)$ for each ω . If the structure of G_f is known or assumed, and contains n unknown parameters, it is enough to write (23) n times, for n properly chosen values of ω . Criteria for finding the best estimate of such parameters, i.e. by maximing a suitable functional, are suggested by the theory of estimation errors. One obvious disadvantage of the above method is the need for a special operating condition, i.e. disconnection from neighbours. Other methods [34,36] have been proposed in order to avoid this disadvantage, such as the recording , under normal operating conditions, of interchange powers among the two or more regions in which the system has been divided, then assuming that load fluctuations in the various regions are uncorrelated and solving the spectral equations yielded by such assumption.
By this method one might feel that the goal of obtaining a continuous indication of system transfer function along the day is achieved, provided the rather heavy computations involved in solving the above equations are performed. However, some short-comings still prevent obtaining satisfactory results : a) the contrast between the need for long records, say several hours, to reduce truncation errors, and the non-stationary character of the power system; b) the existence of many non-linearities, such as dead bands, voltage and frequency-dependence of loads, while the main assumption of the above statistical analysis is that the system must be linear and stationary; c) the inaccuracies associated with separation of very low frequency non-stationary components; d) the too small amplitude of higher frequency components in the excitation signal, i.e. in the load change spectrum; e) the heavy computational work required. When the above difficulties will have been overcome, or their effects quantitatively evaluated, it will be easier to collect experimental evidence both on system responses and on load change probability distribution. At present, a behaviour like the one indicated in Fig. 13 for frequency autocorrelation function, even if system transfer function is assumed to be known, does not allow a clear cut determination of statistical load pattern vs. time : indeed, measurements do not distinguish load changes from generation programmed variations as effected by operators. Consequently , the basic exponential Poisson distribution is heavily altered.

III 3 Matrix analysis of interconnected system control

The growing size of interconnected systems has greatly simplified the task of secondary frequency and tie-line power control in normal operating conditions. Infact, it is reasonable to assume that loads in different areas are statistically uncorrelated, and as a consequence the overall load variance is proportional to $\sqrt{P_n}$. if P_n is the total system spinning power. Since the governing action is roughly proportional to P [illegible], the standard deviation of frequency decreases with increasing system size, even if no secondary control is applied. In other terms, there is a "natural" compensation of load changes in interconnected areas, since they do not occur simultaneously.

On the other hand, no stringent requirement of response speed is posed on exported power control, since inter-member negotiations only ask for complying to 1 hour -, or at the least few minutes, - interchange-energy obligations.

Nevertheless, the contribution of modern control approaches to the multivariable system study has been valuable. For example, the well known quasi-static Darrieus condition for non-intervention has received a more general and rigorous reformulation by means of transfer-matrix analysis [38]. With reference to Fig. 9 and 10, the requirement that each area take care of its own load changes has turned into the "autonomy" criterion :

$$G^*_{R_j} = G_{R_j} G_{f_j} \qquad (24)$$

relating exported power controller transfer function $G^*_{R_j}$ to frequency controller transfer function G_{R_j} by the above-defined area transfer function G_{f_j} (see III. 2). This stemmed from the diagonality of GP, G being the controller transfer matrix, and P the transfer matrix of the "process", i.e. the interconnected system with primary governing. Likewise, systematic transfer matrix analysis of the n-variable system has yielded criteria for equitable participation of areas in frequency and tie-line control [39]. For example, each member should choose its controller $G^*_{R_i}$ such that the system frequency deviation due a load change in his area is the same as that produced by an equal load change in another area : the whole system would suffer from the relative "weakness" of one of its members. The resulting condition is very simple :

$$G^*_{R_1} = G^*_{R_2} = \ldots\ldots = G^*_{R_n} \qquad (25)$$

As to the choice of structure and parameters of secondary controllers, analytic optimization methods, as based upon an assumed Poisson distribution for load variations and an evaluation of frequency and tie-line power r.m.s. errors vs. controller parameters, with constraints on control power, or control power rate, have proven to be useful [34,40,41].

III. 4 Centralized adaptive control and dynamic security

While the choice of secondary controller parameters is not at all critical under normal operating conditions - as a proof of this statement, notice the very good performance of existing large interconnected systems,

where several partners do not know their G_{f_i} well enough to cope with (24) -, insuring an effective aid to a member who is in serious trouble for an emergency poses more difficult and important problems to centralized control.
Logic-adaptive controllers incorporating emergency actions, such as starting and loading fast pick-up reserve, calling for normally unavailable reserve as extraction-closing in steam units, coordination of load-shedding, have been advocated and studied [42, 43].
They could also inhibit frequency and exported power errors if all lines are working far from security limits, while they would exercise full control action if the load on a line is relatively high. On the other hand, they could introduce an automatic limitation of the assistance action to an adjacent area in case of large unbalance and consequently great frequency deviation : this is to avoid tie-line overloading and untimely tripping. Finally, they could incorporate the suitable logics for tie-line opening , and system sectioning.
The idea of avoiding - to the benefit of efficiency and machine life - unnecessary secondary control power variations when frequency and tie-line power errors are small enough and follow a normal random pattern has been realized also by means of suitable rejection filters [44].
Such filters, including rectifiers, comparators and timers switch area control error ε into the controller if and only if the value of $|\varepsilon + k\int\varepsilon\, dt|$ has exceeded a given threshold for more than a given time. They may reject short-duration deterministic signals as due to synchronizing oscillations, . periodic load changes , start-up of large machines, or Poisson-distributed random errors with "normal" average time between zero-crossings. They are also intended to recognize when valve characteristics or dead zones have too much degraded the system gain by seeing when the error remains off longer than the expected time : in such case they increase controller gain, for compensation.
Other selective actions have been proposed in order to increase overall efficiency under transient conditions, such as discriminating among secondary control units according to their dynamic response and efficiency, by the introduction of high- pass filters for high dynamic efficiency units, low-pass filters for high dynamic cost units [45].

III. 5 Electromechanical oscillations and stability

In the preceding paragraph, the possibilities of adaptive controllers for emergency corrective actions have been briefly recalled. It should be here stressed that such actions are not generally intended to control the first tenths of a second of the electromechanical transient, but rather intervene later, when hopefully synchronizing oscillations have died out, and it is already reasonable to speak of a single system "frequency".

However, the first swings after a fault may determine whether the system is going to survive, or at least whether any unit will lose synchronism. Expecially for networks including long transmission lines this problem is very important.

It can be reddily recognized that system response to such transients cannot be described in terms of transfer function G_f : indeed, f can no longer be considered the same throughout the whole system, due to the relative oscillations of synchronous machines. A more complete and detailed model is then required, where angular positions of machine rotors are among the dependent variables.

While synchronous machine dynamics is well known - although it is often difficult to obtain a quantitative evaluation of the effect of damper windings and of the solid rotor - its complete description implies a system of non-linear equations. Even if the analysis is limited to "steady-state stability", so that small perturbation linearizing is accepted, transfer functions appear to be relatively complicated. The case of the single machine connected to an infinite bus, or to a reactive load, is still reasonably simple, see Fig. 9.a, and can be investigated by conventional frequency response methods or Routh criterion : but the two-machine situation, see Fig. 9.b, is already difficult.

The real network, which is certainly a multi-machine system including lossy transmission lines, transformers, voltage and frequency sensitive loads, induction motors, governors, voltage regulators and protective devices, can only be studied by digital or analog-hybrid computers. Powerful digital programs [46,47,48,49] have been developed for the study of multimachine system electromechanical transients, with special reference to short-circuit faults, circuit breaker opening and fast reclosing. Some of them [47] can include protection relay operation and may accept several types of perturbations, like periodic load variations, loss of lines, generators, loads : they are then suitable to simulate emergencies, or "black-outs", and study system sectioning, protection coordination, load shedding, system restoration.

However, such digital programs are very heavy, imply the use of large and costly computers, are not too adequate for covering relatively long transients as it may be needed when steady-state stability is nearly marginal. Therefore, other ways are being searched to obtain a synthetic answer to the question whether the system is stable or not without simulating the whole transient , or to the question as to what reclosing time is necessary to maintain stability.

Liapunov-criteria for stability have been applied [50,51,52,53,54] to this purpose. The case of the single synchronous machine connected to an infinite bus has been extensively studied, and a Liapunov function

has been found for the 6th order machine including two damper windings and a first linearized approximation of the speed governor. Quadratic terms due to "relative" kinetic energy and flux linkage energy with respect to the steady-state situation, plus elastic energy integral terms, appear in the Liapunov function : which can find an explanation in terms of the early "energy integral" approach [55], but is not exactly , however, an expression of total system energy.
The problem is one of finding the regions of equilibrium, and checking whether the system point at the instant of after-fault-reclosing is within the borders of one among the several stability regions. Even in the simple case of a single machine, however, Liapunov stability regions do not include all existing stability regions. Such limitation exists, a fortiori, for the multi-machine problem, which is far from having obtained a satisfactory solution. Most studies are based upon the assumptions of a lossless network and non-regulated second-order n synchronous machines : Liapunov functions and sufficiency conditions for the linearized system - i.e. the Jacobian matrix of machine electrical output powers vs. relative angular displacements must be positive definite - can be found [53], and the stability regions for the nonlinear system determined, for any n . Other authors [51] have included viscous damping and a crude linearized description of speed governors, while voltage regulators have not been considered, pushing the generalization, with some sacrifice in rigour, to the case of 4 machines.
Altogether, much more research is still needed before digital programs based upon Liapunov criteria become really useful tools for multimachine system stability studies. Even when regulators, governors, saturation, lossy lines will be included in Liapunov functions, there will still be a chance that the stability region determination will not be complete and that the complexity of the required digital computer programs will discourage on-line investigations and make transient simulation programs still preferable. However, the subject is a challenging one and interesting contributions are expected from further research.
While practical results from the application of Liapunov methods have still been scarce so far, conventional criteria have been applied with success in many cases to describe small perturbation stability in the parameter space, i.e. for variable working point [59,60]. Consideration to sophisticated machine dynamic models, to the voltage-dependence of load [61], to several means to widen stability margins - such as excitation forcing by suitable feedback from angle, electrical power, speed, acceleration, current and voltage and their derivatives, or electric resistance braking, hydraulic turbine supply pressure variations, etc. - to asynchronous operation, to excitation

control of synchronous motors [62] - has been given in analog-hybrid and digital-computer studies. We will not try here to describe the outcome of such investigations, which often get to very accurate and valuable results in particular and relatively simple cases, but fail to achieve enough generality in the multimachine situation. Certainly the time when it will be possible to use an on-line computer to predict the transient behaviour of the system after a fault in a 100 : 1 faster-than-real scale and then follow a suitable logics to control the system so as to avoid instability [64], is still far to come.
On the other hand, simulation of the transient response of a few-machine system, when perturbations are small enough as not to exceed the linear range, is well within reach of present digital computers even if boiler controls, not only governors and voltage regulators, are accounted for. An application of state-space analysis to multilevel control of a three-machine system, using linearized synchronous machine Park's equations, high-order matrix representation for boilers, and decomposition into optimally controlled subsystems, with a central controller for optimizing the integrated overall control has been reported [65]. However, when the system includes a large number of machines, which is the usual case with today's pools, its detailed description far exceeds the capacity of existing computers, may require unvailable data on machine dynamics or control performance, and it is well possible that the study becomes so complex and dependent on the numerical values of many parameters, that it's results are difficult to be integrated and generalized, and are not accurate enough. Therefore, the development of approximate dynamic "equivalents" for large sections of the network is advocated, so as to reduce the whole system to very few, and possibly just one or two, equivalent machines with respect to the point of fault [66]. Further, the choice of a suitable type of perturbation, e.g. a three phase short-circuit with subsequent circuit-breaker opening and reclosing, is suggested for the convenience of the controlled machine designer.

III.6 Direct current transmission control

As already noted above, clear assessment of the question whether there is any technical or economical limit to the size of a.c. network pool's, or conversely what the dimensions should be of the single regions in which a system is to be splitted under emergencies, has not been reached yet. However, the danger of colossal "black-outs" as may be caused by propagation of large transients along interconnecting tie-lines has spurr attention on the use of direct-current links instead of a.c. transmission lines for connection of large systems.

A second reason for favour towards d.c. is the need for limiting the natural growth of short circuit power level with growing size of the pool.

Whether d.c. links are really competitive with a.c. lines to day is still a controversial matter - indeed very few d.c. transmission lines are operating as yet in the world - and authoritative experts [66] see no other limit to the increase in a.c. pool sizes than natural barriers between continents. However, at least it has been proven that an improvement in system transient stability can be obtained by control of a d.c. line in parallel with the a.c. line [68].

If the differences between the instantaneous frequencies and phases at the a.c. line terminals are suitably used to control the d.c. transmission, satisfactory and adjustable damping of a.c. line swings can be accomplished, and the a.c. circuit breaker reclosing time after a fault can be made considerably longer. Analog, hybrid and digital computer studies [69, 70, 71, 72] confirm the above d.c. line beneficial effect on stability.

As an indication to the achievable performance, notice that the constant-current firing-angle control loop in the transmitting converter has usually a very rapid response, e.g. 10 cps bandwidth, and the inverter constant-extinction angle control loop [79], though it requires the computation of a firing angle on the basis of d.c. current, its rate, commutation voltage and reactance, is likewise very fast.

Further progress, in terms of reliability by use of digital control [73], harmonic suppression [74], equipment simplification [75], and integration with the convertor protective system [76], has recently been made, so that the d.c. link availability, although still lower than the one shown by the a.c. line, is now approaching acceptable values.

When the control system calls for remote action or feedback, overall availability becomes of course dependent upon fast and reliable telemetering.

So far, d.c. links have built only with one transmitting and one receiving station. Considerable attention is being given, in view of future expansion of the use of d.c. transmission, to multi-terminal system modelling and control [77, 78]. Both for this case and for the two-terminal link, basic studies cover balanced and unbalanced steady-state situations, dynamic stability and fault conditions, low and high frequency transients; while there is still justification for network analyzers, analog models, simulators, there is a growing trend, as elsewhere, towards the use of powerful digital computers. Digital computers are also advocated for on-line control of firing angle and expecially for some centralized control of multi-terminal systems.

III. 7 On-line digital computers for power system dispatching control

In Chapter II the use of on-line computers for automatic dispatching and security monitoring has been repeatedly mentioned. While most of the earlier applications of digital computers to power system dispatching included only a very limited contingency analysis [18, 84, 86]; recent installations are more security-oriented [15, 80, 82, 83].
Sometimes, and expecially in Europe, security monitoring has been the main scope, and automatic economic dispatching has been confined to inter-area flow transfer setting, in the case of a central computer coordinating area-controllers [15, 80] or area satellite computers. On the other hand, U.S.A. systems have retained automatic dispatching among the essential tasks for the computer.
Two solutions have been given to the problem of integrating economic loading with load-frequency control : the digitally-directed analog or "hybrid" control [19, 18, 82, 83, 84, 87] and the all-digital control [81, 86], see Fig. 10 and 11.
In both cases load-frequency command signals are issued at a quite higher rate - say every 2 sec in the case of all digital control, continuously in the hybrid case - than economic dispatching orders, which are updated every few minutes. While marked advantages do not appear today in favour of the all-digital solution, because its load-frequency program does not yet include any elaborate actions more than the conventional controller, and an analog back-up is recommended, it is safe to say that technological feasibility is now well proven and the further steps to adaptive control will certainly be easier for the digital computers. It is envisaged that some operator-guide functions, such as fast pickup reserve display, or line-overload monitoring, can be better turned into automatic corrective actions by digital computer control.
As far as hydroelectric system automatic dispatching is concerned, it is perhaps worthwhile mentioning that several computer systems have been installed for pumped storage station scheduling, hydraulically interconnected plant operation optimizing, and optimum power dispatch of two rigidly cascaded stations where water level control was required.[88]
A lot more is expected from future on-line computers in terms of emergency - and system restoration - control. Whether the on-line computer will actually analyze a large transient, predict its behaviour and command suitable corrective actions, or it will store the results of previous off-line studies, and have access at them on the basis of key events ; whether it will coordinate protective relay settings, command system splitting, trip tie-lines in dangerous situations, it is still too early to say. At least, it is very likely that it will be used to offer the dispatcher a better guide for dynamic security control.

IV. STATION CONTROLS

IV. 1 The influence of system security and service continuity requirements on unit control specifications

We have already pointed out in the Introduction, sec I. 2, that along with the increase in turbine-generator ratings there has appeared a deterioration in forced outage rates, while the improvement in machine materials and design has caused a marked reduction in unit relative inertia. At the same time, the need has been felt for better service continuity, and consequently better unit availability and flexibility. Therefore, all possible means have been searched to reduce instantaneous and integral material stresses, increase unit start-up speed and loading rate, avoid unnecessary unit tripping.

Most developments in boiler and turbine control equipment and instrumentation originate from the above requirements. Sophisticated sequence of events recorders, with memory of what happened just before the accident, are employed in order to analyze faults and study appropriate remedial actions. Complete monitoring of single unit performance is intended to advise when a dangerous situation arises, or material deterioration starts and maintenance is needed. Wired logic or computer sequence control insures good repeatibility of unit operations which imply relevant material stresses, such as lighting burners, bringing turbine up to speed, generator loading, unit hot-restarting and shutting down. Fast and optimized boiler-turbine electronic controls and better protections enhance unit speed response to dispatcher command signals and filtering of internal disturbances.

On the other hand, the improvement of operating efficiency calls for faster and more accurate controls, to keep controlled variable transient deviations as small as possible. For example, if maximum superheated steam temperature transient deviation can be reduced by 1°C, temperature set point can be increased by 1°C, with consequent considerable increase in unit efficiency.

Notice here that transient deviations may be due to unexpected accidents, as loss of a fan, or a coal mill, and in these conditions a high response speed of the feedback loop is the only answer : but may also be caused by a programmed input command variation, such as start-up or loading, and then a suitable choice of the input variation vs. time and an adequate feedforward action would substantially reduce the stress on the feedback control loop and consequently controlled variable deviations.

Therefore predictive feedforward and coordinated boiler-turbine controls are employed. Their design implies a good knowledge of unit dynamic response : experimental identification and analytic mathematical modelling become a necessary prerequisite.

At the same time, it is realized that the steam-boiler or nuclear reactor turbine-generator unit is a multi-variable system, to which modern control methods of analysis and synthesis can be applied in view of improving upon the results of empirical approaches, avoiding interactions, trying some degree of invariance, optimizing controller parameters, introducing adaptive features. Broadening unit operating range, by making low-load operation more stable, is possible if controller parameters are automatically adjusted as functions of load. In this connection, and not merely as equivalent alternatives of analog controllers, computers and direct digital controllers may find their justification in the next future.

At present, about 500 digital computers are on order or installed in electric power stations, and the rate of growth in the past six years has been about 30 % per year [91]. However, very few of them include d.d.c. or any control task during normal operating conditions . less than 10% have been given the task of automatic start-up and shutdown; while the vast majority has supervision and performance monitoring functions. The reasons for the scarce and as yet not growing development of computer control applications will be given in a following paragraph : the general feeling is that more research on mathematical models is still needed. To this purpose existent on-line computers may well provide a good source of operating data for identification of unit dynamics.

The computer tasks of alarm monitoring, trend recording, performance calculations, event recording and post mortem review fault analysis, load runback, operator guide display directly originate from the search for better system security, i.e. unit availability. Since the time for completely automatic operation is far to come, operators and control panels are still required. The increase in unit size and complexity would call for very big centralized control and annunciator panels, with great difficulty for a single operator to watch so many instruments at the same time. The computer and its peripherals, such as electric typewriters, nixie indicators, cathode-ray-tube screens, is intended to simplify man-machine communication by displaying only the essential information - after proper processing and reasonability checking - and in a more readable form.

The other obvious steps to enhance security and centralized control, such as letting automatic control replace manual interventior as much as technically and economically possible, are effected by high reliability wired logic sequential controls and protections - see automatic burner lighting transistorized subloop [133, 134, 135], load runback protective devices for loss of auxiliaries, combustion system protections - or by feedback loops, such as coordinated boiler-turbine control system, hydrogen cooling and lube oil temperature local controls, air-heater and water-heater controllers.

On the other hand, unit prompt response and better availability both in normal conditions and under load-frequency control, with broadened operating range, i.e. wider reactive power limits or higher active power maximum loading rate, are the main motivations for developing - with the help of refined design methods and better components - more reliable, flexible, accurate and faster automatic voltage regulators and speed governors.

IV. 2 Mathematical modelling and identification of steam power plants

While the most ambitious studies of conventional steam and nuclear power plant dynamics aim at calculating transient stresses in pipes, waterwalls, superheaters, reheaters, turbine, the usual scope of power unit dynamic analysis is limited to providing an approximate mathematical model as a basis for predictive control system synthesis. Actually, transient stresses, and perhaps their time-integral, should be the main concern during start-ups, shut-downs and fast load variations and consequently be entered the controller design at least in constraint equations. However, their detailed calculation is too complex to be accounted for in control studies. Therefore they are entered as admissible start-up procedures and maximum loading rates, to be established on the basis of off-line computer transient stress evaluations and direct measurements on the unit.
The need for simpler models for control purposes is dictated not only by the size, accuracy and setting-up time of available analog computers or by the programming effort and computing time of digital computers, but also by the inherent difficulty in applying both conventional transient response simulation methods and analytic optimization procedures to a too large system. Sensitivity analysis becomes too complex, state variable approaches may suggest too elaborate controllers, with consequent heavy problems of parameter search : and understanding of physical phenomena in the plant is made less intuitive. Furthermore, fitting a high order model to an experimental response, at the final phase of identification, poses another annoying difficulty in the multidimensional parameter optimization.
For these reasons, most analog-computer-oriented studies of drum-type boilers 98÷103 and of once-through boilers 105, 106, 110 are limited to linearized descriptions of the unit around a given operating point, and accept lumped-parameter approximations of the distributed system, even when - as in superheater temperature transients - many cascaded cells are required to have a reasonable fitting to actual response.

A wide variety of analog models, employing from 50 to over 200 operational amplifiers, have been proposed. So far, the evidence of a satisfactory check between calculated and measured responses of drum-type boilers is still scarce [101], while doubts exist whether neglecting not well understood phenomena in drum steam condensation is legitimate [103]. Drum level behaviour is qualitatively explained, but quantitative checks are often unsatisfactory [103, 108].

Better results have been obtained with once-through boilers [107] even when the essentially non-linear fluid behaviour in the evaporation zone [104] has been disregarded [106, 107], by choosing enthalpy and pressure as variables, with no reference to changes of state in the fluid.

Digital computers have been preferred for mathematical modelling when further detail was sought in plant description. Examples of the state variable approach, with due consideration to reheater, water-heaters, economizer, extractions, are reported [95, 96, 97]. However, since evidence of agreement with experimental results is still missing and boiler circulation loop equations are not any more elaborate than in analog models, while lumped approximations are accepted to avoid solution of partial differential equations, the improvement with respect to the above studies may have been not so relevant. One definite advantage lies, anyway, in the more accurate computation of steady-state heat-balances and pressure-flow relationships.

Resorting to digital or analog computers - and sometimes hybrid computers when partial differential equations are retained, for heat exchanger or parallel channel thermohydraulic instability analysis - is needed for any numerical investigation of specific cases.

Nevertheless, it is perhaps worth mentioning that the problem of determining drum boiler-turbine transfer matrix has also been tackled by purely analytical means [102], with all parameters being kept in their literal symbols. Retaining closed form expressions of transfer functions, where gains, poles and zeros are literal algebraic functions of boiler and turbine dimensions and fluid average properties and conditions gives a better insight into plant behaviour and enables desk determination of the influence of plant design on dynamic performance. This may not be immediate, however, since the above algebraic functions are often cumbersome. On the other hand it has been proven [103] that no appreciable loss of accuracy is introduced by the simplifying approximations introduced by the "analytical" transfer function model, in spite of the several refinements of the reference model with respect to conventional descriptions of the circulation loop.

The check with experimental trials is sometimes impaired by unsatisfactory behaviour of existing transducers or by difficulties in assessing plant steady-state before impressing the perturbing signal, or in detecting response out of internally produced noise.

Several methods have been used for experimental identification; conventional open-loop step [103, 108] or single-or double pulse responses, frequency response with suitable noise rejection by correlation or r.m.s. computation, random pulse response with input-output correlation analysis [112]. While no relevant problem of interpretation exists with oil-fired units, and step responses are quite satisfactory, coal irregular supply generates a heavy low-frequency noise which makes step response almost uninterpretable. Double-pulse tests are not very good either, since perfect symmetry is difficult to achieve, and slow plant drifts may be present. Frequency response would be the best, should it not require too long time for exploring the low frequency range. Multi-level noise generators have been used for random signal testing : identification has been achieved by fitting the coefficients of a transfer function of a given form into the output autocorrelation function by means of multiple linear-regression analysis.

Other deterministic methods imply the numerical inversion of the input-output convolution integral, where the input is plant noise plus a superimposed ramp, or a suitably shaped pulse. The shape of such pulse is chosen such that its amplitude-spectrum is nearly flat in a wide enough frequency range : notice that the step function spectrum amplitude is inversely proportional to frequency and appears therefore less adequate for a uniform accuracy in determining frequency response.

Statistical identification has been tried also by using spontaneous random plant variations [111], with reference to the analysis of combustion behaviour. As an interesting by-product, this approach determines plant disturbances, in the form of noise spectral distribution characteristics.

The above remarks apply to conventional steam plants. As it is well known, the interest in an accurate description of their dynamic response is recent, perhaps because empirical solutions for boiler controls had proven to be satisfactory enough in the past. On the contrary, nuclear reactor dynamics has been the subject of deep concern and thorough studies much before actual installation in power plants. Analog and digital computer models have been developed through several years, and comprehensive books and surveys published to describe them (see, for example, [115, 116, 117]). Parallel channel flow instability, steam void dynamics in boiling water reactors, burn-out transient and many other phenomena, which have received little attention in steam plants, have been extensively treated [118, 119, 120]. Published evidence is still scarce, however, on experimental identification of nuclear plant dynamics.

IV.3 Coordinated boiler turbine control

Nuclear engineering research has taken a lead also in the application of modern theory approaches to nuclear power plant control system synthesis. State space analysis and control optimization for nuclear reactors are already the subject of textbooks [116], while integrated reactor-turbine and non-interacting control schemes are being considered for new plants [121, 122], and plant controllability and optimal neutron flux distribution control are being studied in terms of multivariable system theories [123, 124].

On the other hand, significant new ideas have also proposed for coordinated boiler-turbine control in conventional steam-plants. By using plant direct and inverse models and suitable feedback loops an approximate "invariance" of controlled variables with respect to unmeasurable disturbances is achieved [125]. Load-adaptive multivariable controls are optimized by minimizing an integral performance index [126], noninteraction between temperature and pressure controls is searched [127], secondary variables are used to improve control [128]. A more general approach to optimizing control of the non-linear boiler-turbine model has been proposed [132].

The concept of coordinated control has been widely accepted in practice for once-through boilers. Major manufacturers have adopted it, with suitable dynamic "characterization" of feedforward command signals, such as to achieve simultaneous and well balanced energy supply to the boiler-turbine unit when the dispatcher demands an electrical power output variation [129]. By this means, and by suitable transient decoupling of pressure and temperature controls, the disturbance on regulated variables due to dispatcher commands is minimized, and the task of feedback loops is made easier.

The real merits of the above feedforward-feedback, noninteracting invariant control schemes have not been clearly assessed yet ; some authors [131] credit to model-based-controls using heat flux computers a several-degree decrease in superheated steam transient deviations, with consequent possible raise in temperature set-point and considerable efficiency improvement.

IV.4 Computer control of start-up and direct digital control

As it has been pointed out earlier, only powerful and fast digital control computers can fully exploit the sophisticated adaptive techniques as proposed by modern theory. There is a widespread belief, however, that the advantages to be gained by such techniques are not worth the effort to apply them.

Indeed, the rather frustrating experience of the early projects of full start-up and shut-down computer automation has somewhat cooled down the enthusiasm of pioneers. Trasducer, limit stop and electronic hardware malfunctions are no longer a problem as they were a few years ago, nor is noise filtering : but the need for substantial flow-chart changes from design to commissioning stage, the time for program developing and on-line debugging, the scarce availability of the new very efficient plant for final testing, the size of the project with its analog and on-off inputs by the hundreds or thousands, and the associated dispersion of energies are still sources of difficulties.

Four or five years, or even more, are required to go from the initial preliminary study to the first meaningful operating results: only very few applications have already been completed at present and most of them have included turbine run-up and loading, but not boiler start-up [136-140]. The time will soon come, however, when enough experience will be available to judge about the validity of such computer application and say a final word on the comparison between wired logic sequential systems and computer control.

On the other hand, although with less optimism on the break-even point of economic justification, all the anticipated reasons for using the computer still hold to day. The needs for a high number of checks before each single operation is effected, for fast and almost simultaneous actions, for perfect repeatibility of start-up and shut-down procedures, for memorizing many programs to suit the different normal and emergency situations, appear truly to be beyond operator's capability when the plant is large and complex. The reduction in material stresses, which can be achieved by automatically following optimal procedures, with consequent improvement in plant safety, availability and life is certainly a goal worth being pursued.

Therefore, the digital computer - or suitable wired logic equipment - as a means for achieving such objectives through automatic control of normal and emergency start-up and shut-down, has so sound motivations as to justify further intensive efforts to overcome all technical and organisational difficulties.

Another chance for the digital computer is direct digital control of both minor and major slow-response loops in the steam plant. When fast response is needed, as in some conventional control loop and expecially in turbine governors, multiplexed d.d.c. becomes im - practical, due to the too heavy requirements in computer time and scanning rate : analog subloops are still preferable.

After the preliminary experience at Sterlington Station, Louisiana Light & Power Co., where digital computer direct control was ap - plied to three minor cooling loops of the turbine-generator, several other applications have been reported [142, 143, 145].

Cases of d.d.c. for 20 minor slow temperature control loops [142], and for the three major feedwater, temperature and combustion loops [143,145], as back-ups of analog controls, are quoted.

While computer remarkable logic-handling capabilities are largely exploited to effect on-off or adaptive actions, as switching on a pump or a fan, or changing the sampling period, when load or temperature gradients exceed preset limits [145], dynamic control action does not usually go beyond transposing PID controller into a digital form.

Here, choice of control algorithms, whether of the positional or the velocity type, of scanning rate, of dead zone to avoid limit cycling due to quantization, is often done on the basis of a hybrid simulation study. Practical implementation of more elaborate control algorithms, such as flat response optimal correctors [144], has not been started yet : and little has been done to design and realize digital versions of adaptive feedforward and non-interacting control schemes, although it is often stated that the best justification for digital computers steam power station control lies in their ability to embody sophisticated control structures. Even if this will not be confirmed by experimental results, it is likely that more and more interest will be aroused by the adaptive logic actions, the trimming corrections to optimize combustion, the computation of non-linear characterizing functions, the indirect measurements, the integrated protective system which can be incorporated in digital computer control.

On the other hand, digital computers have already been accepted in many power stations for supervision and performance monitoring, as it has already been pointed out. While there are still doubts as to their objective justification for conventional medium-size plants, acceptance is general for nuclear reactor power stations. Security checks and the heavy calculations of neutron flux distribution in the core call for use of digital programs.

Nuclear plant security has also suggested resorting to computers for operator training. Digital simulators [147,148] have been developed, which include a detailed representation of the nuclear unit, with spatial models, dynamics and control logics, both for off-line study of transients and for preliminary and permanent operator training.

Finally, it is worth mentioning that a great aid to speed up digital computer programming has come from development of standard subroutines and programs for scanning, alarming, logging, etc., of specialized languages for start-up and shut-down automation, and of more general process-oriented languages.

IV. 5 Progress in voltage regulators and speed governors

Though surprisingly late, electrohydraulic speed governors are finally winning consumers' and turbine-manufacturers' favour not only for hydroelectric stations, but also for steam units.
The combined merits of electric transducers plus solid-state electronics for the controller-amplifier and high-pressure oil hydraulics [149, 150] for actuators, with respect to conventional mechanical or hydraulic solutions, yield much smaller governor dead-bands - with better primary frequency control -, easier remote control from the dispatcher, improved dynamic response, faster and safer protections, better integration with digital computer or analog coordinated boiler-turbine control. Use of electric power output feedback - or impulse chamber pressure feedback - allows eliminating the effects of governor valve non-linearities on the response to dispatcher's commands. The more than 10 years experience with electronic governors in hydroelectric stations stands for their reliability and remarkably small drift in performance.
Automatic voltage regulators have also largely profited from the improvements in solid-state technology. Power semiconductor progress has made static excitation of a.c. generators possible [153]. Field current is supplied from the generator output terminals through a saturable transformer and a silicon diode bridge rectifier, or alternatively from a shaft-driven a.c. generator through silicon controlled rectifiers. By fast semiconductor control all lags except main generator field time constant are practically eliminated. Faster overall response in voltage control both for small perturbations and for large transients is then achieved.
No reference will here be made to the problems of negative voltage forcing and underexcitation, field winding overvoltages, unbalanced fault harmonics, limits in supply voltage transient variations, which are certainly relevant in determining the design of the excitation system and the choice of rectifier bridge connection 154, 155.
Attention will be limited to the question how to improve the small perturbations "steady-state" stability limits by introducing suitable actions or feedback signals into the voltage regulator. The stability region in the active vs. reactive power plane ought to be widened such as to include the unit thermal-limit region
Lead-lag networks on the voltage feedback signal, field current minor feedback loop, proportional-integral actions on an electric power output feedback signal, speed and acceleration feedback loops, generator current derivatives feedback signals have been employed with some success [59÷63, 156, 157, 158].

No general conclusion has been reached yet on what is the best among such additional signals for improving small perturbation stability without hindering voltage regulation.
An interesting application of Kalman's optimal control is reported[159], for the simplified case of a single machine connected to an infite bus. The machine is studied as a two-controlled variable linearized system, with machine angle and generator voltage as variables. By proper choice of state variable weights in the performance index to be minimized, the optimal controller matrix K - which satisfies Riccati equation - is determined. Governor and voltage regulator are treated as a single two-variable controller, where the "additional" feedback signals enter as "states", to be multiplied by matrix K constant elements.
The above approach must, of course, be checked against validity of performance index weighting coefficients, saturation in manipulated variables, measurability of states, variation in operating point, response to dispatcher's commands and primary control requirements, possible contrast with large signal transient stability.
All solutions, indeed, should be verified against transient stability: but here static excitation is generally preferable just because it forces the excitation voltage to reach its ceiling sooner.

V. CONCLUSIONS

In the above, only the highlights of the impact of modern automatic control methods and techniques on operation and design of electric power systems have been given. Not all the aspects and the recent developments of automatic control applications in this field have been quoted. For example, no mention has been made of the progress in measuring instrumentation, in spite of the fundamental role of the more accurate and faster digital-computer compatible sensors now available and of the new means to obtain a direct or indirect measurements of basic quantities like quality of service, heat flux, combustion efficiency, thermal stresses. Nothing has been said about numerous interesting tasks for the computer in a power station or in a dispatching center, like indirect improvement of sensor accuracy by heat and mass balances, multiple-path comparison, reasonability checks, or running of instrument maintenance routines. No detail has being given on the developments in wired-logic equipment for measurements and control, like sequential event recorders, with or without post-mortem review facilities, computer-compatible digital tape recorders of analog quantities, statistical correlators, alarm scanners and data loggers, sequential control systems for burner lighting, coal handling, soot blowing, ash handling, water demineralizing, lubricating oil or condenser circulating pump start-up, steam turbine automatic start-up and shut-down[160÷163], pump and generator start-up, shut-down and switching in a pumped-storage multiple-unit hydroelectric station.

Entire chapters have been ignored, as electronic protections, remote controls, data transmission, automatic reading and processing of energy meter data, computer stock control and management information systems.

Finally, no account has been given of progress in substation control equipment and use of digital computers for control of distribution networks, although this type of application, which includes monitoring and remote-controlling of many substations from a central station, has already proven to be economically competitive with conventional wired-logic solutions, and is encountering wider and wider acceptance. 164, 165, 91.

In spite of all these omissions, it is hoped that enough evidence has been offered of the wide range of problems where advanced control theory and practice play a relevant role in the electrical supply industry. The power system is a typical large-scale distributed system, where the operation of individual subsystems must be separately optimized for maximum efficiency and fast, accurate, stable response, but must also be integrated for optimum economy, best quality of service and highest security of the whole system. No wonder then that refined optimization methods, identification techniques, multi-variable coordinated control approaches find here wide application and integrated control has been pushed so far as to suggest hierarchical control computer systems, where a central on-line computer automatically coordinates regional dispatching computers, and each of these remotely controls power stations and substations and is possibly linked to station computers. -

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FIG. 1.a

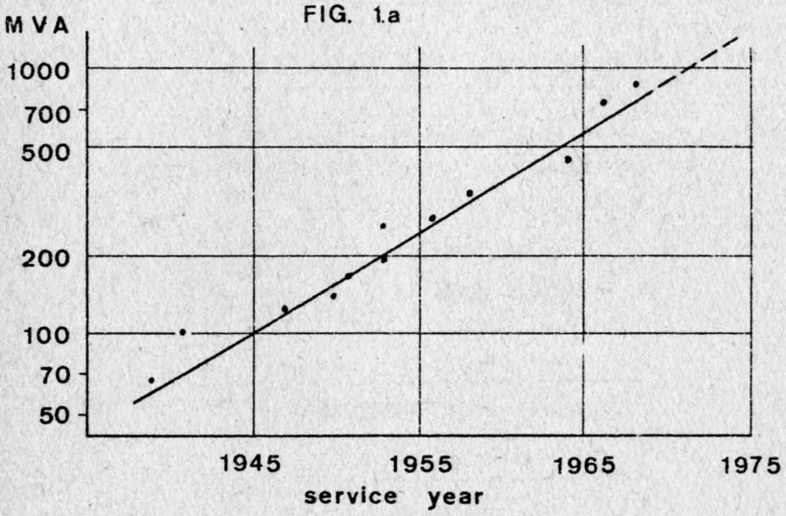


FIG. 1.b

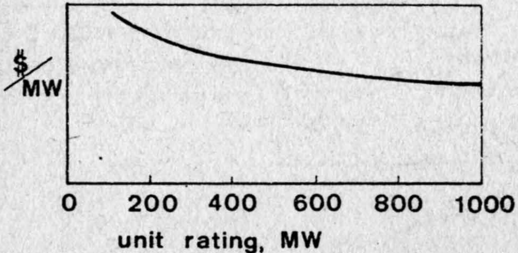


FIG. 1.c

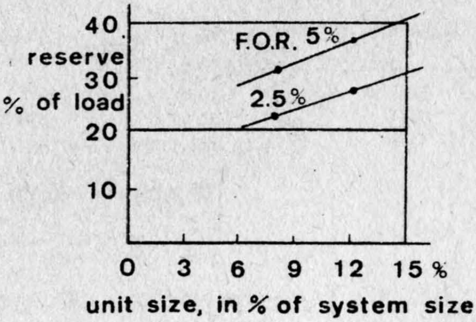


FIG. 1 - GROWTH OF TURBINE-GENERATOR RATINGS AND RESERVE REQUIREMENTS

a. Growth of steam turbine-generator ratings
b. Investment and operating costs
c. Reserve requirements

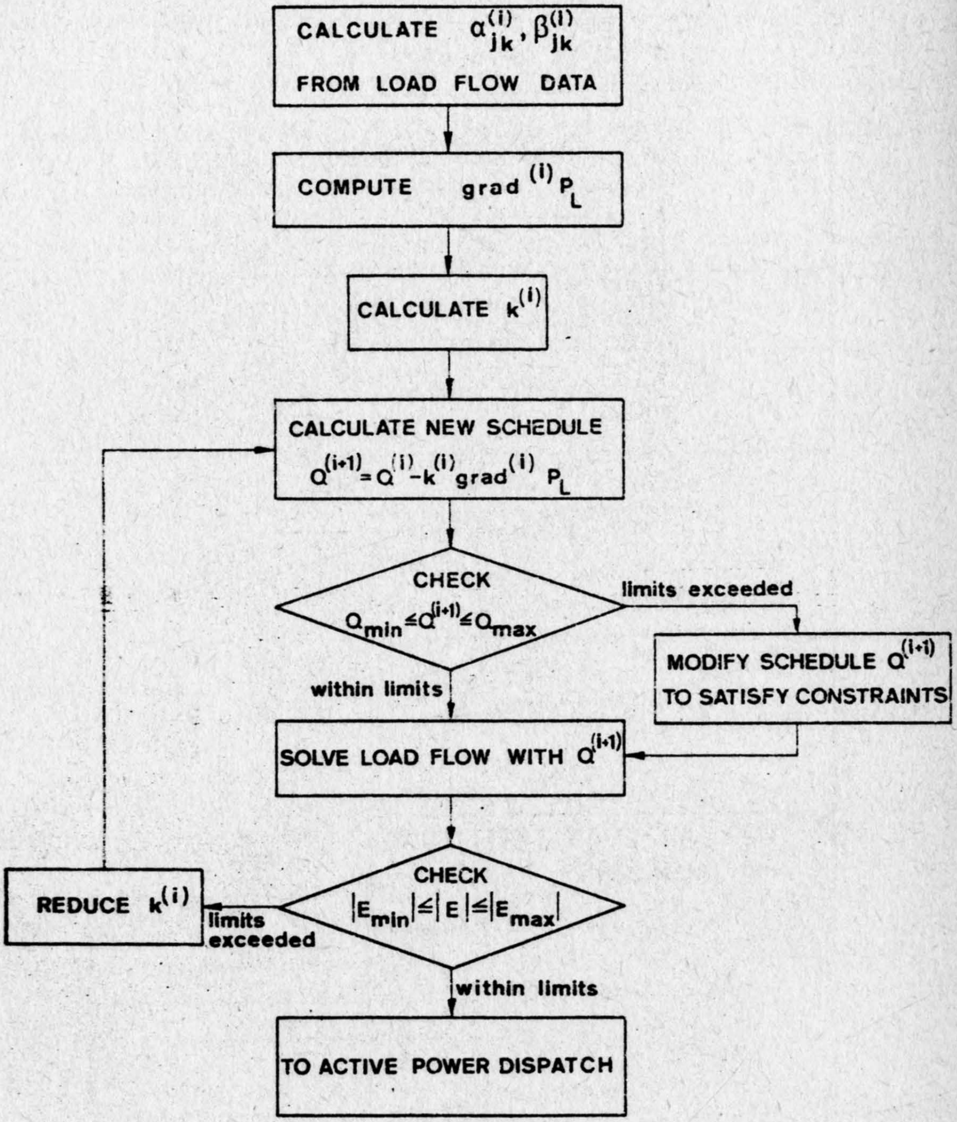


FIG. 2 - FLOW CHART FOR REACTIVE POWER OPTIMIZATION

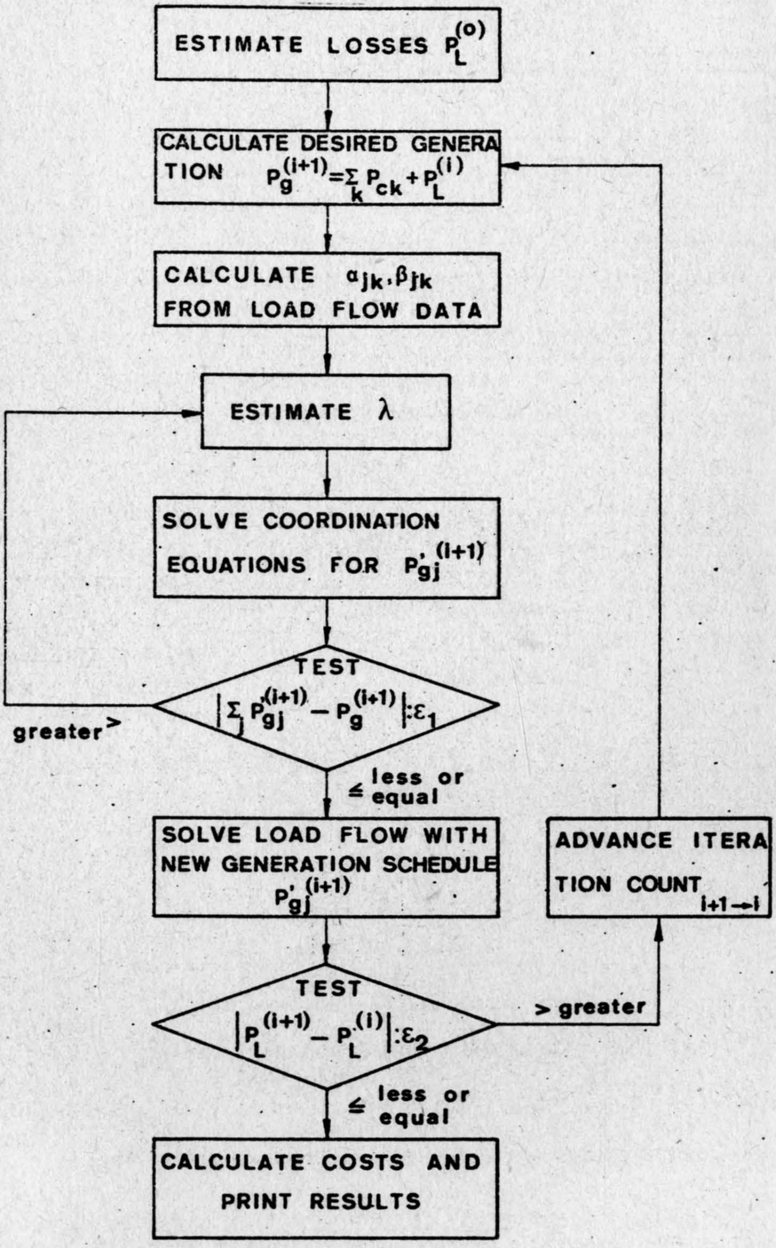
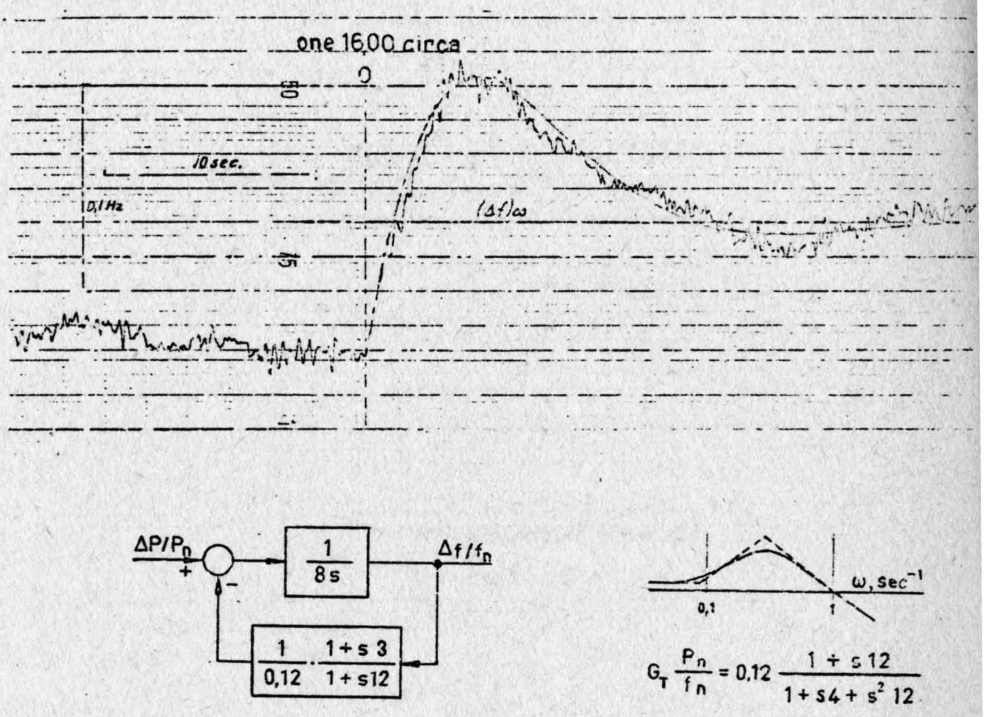


FIG. 3 - FLOW CHART FOR ACTIVE POWER OPTIMIZATION



$$G_T \frac{P_n}{f_n} = 0{,}12 \, \frac{1 + s\,12}{1 + s4 + s^2\,12}$$

FIG. 4 - INDICIAL RESPONSE AND TRANSFER FUNCTION OF ITALIAN ELECTRIC POWER SYSTEM

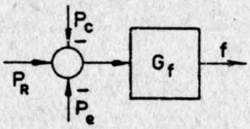


FIG. 5 - BASIC BLOCK DIAGRAM OF POWER SYSTEM

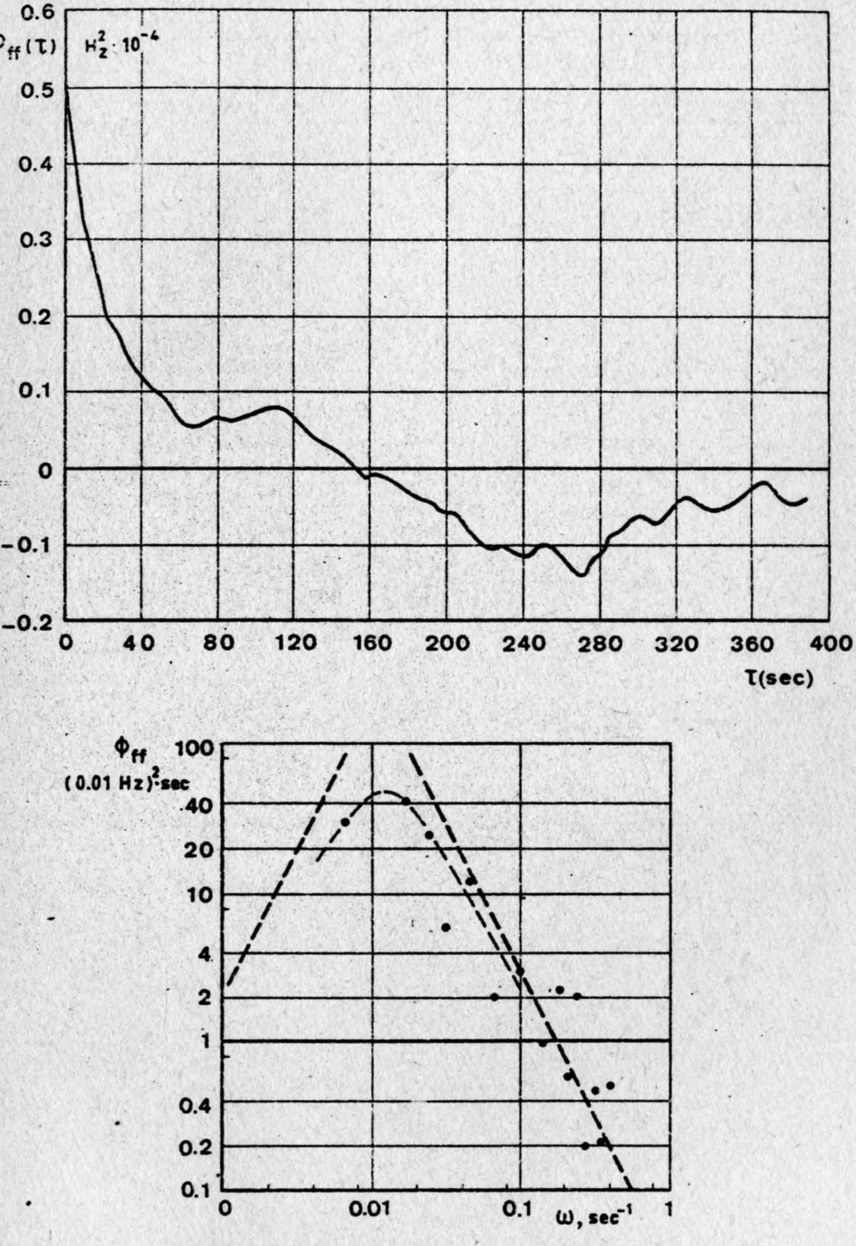


FIG. 6 - AUTOCORRELATION FUNCTION AND SPECTRAL DENSITY OF WESTERN EUROPE POWER SYSTEM-FREQUENCY

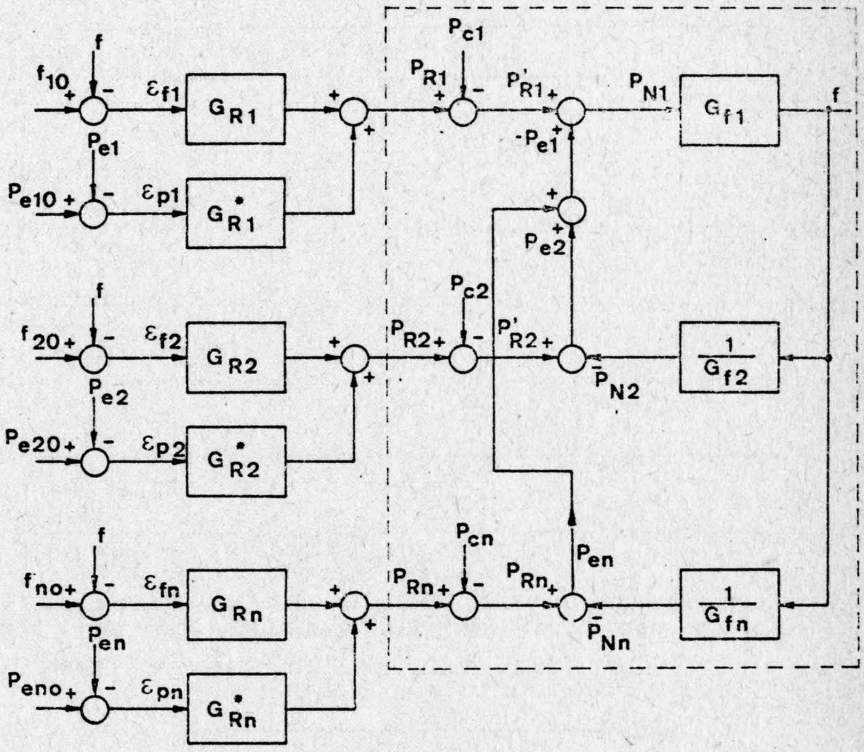
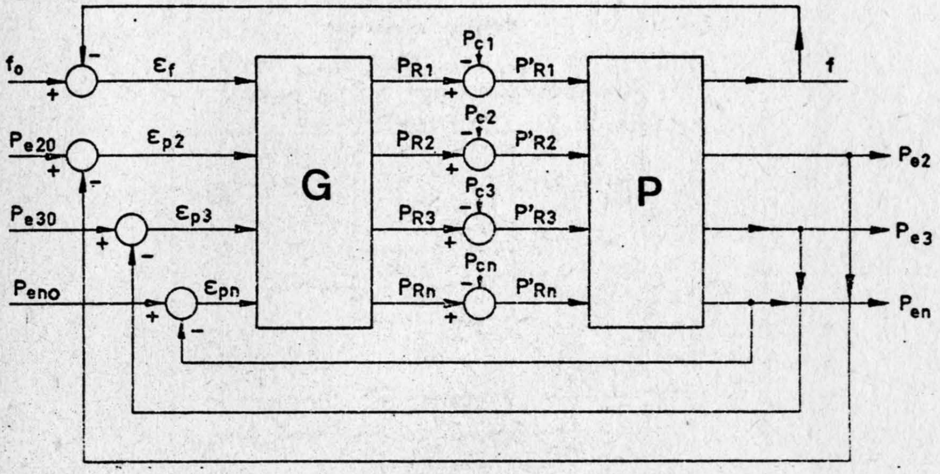


FIG. 7 - FREQUENCY AND TIE-LINE POWER CONTROL IN AN n-AREA INTERCONNECTED SYSTEM



$$P = \begin{bmatrix} G_f & G_f \ldots\ldots & G_f \\ -\frac{G_f}{G_{f2}} & (1-\frac{G_f}{G_{f2}}) \ldots & -\frac{G_f}{G_{f2}} \\ \ldots & \ldots & \ldots \\ -\frac{G_f}{G_{fn}} & -\frac{G_f}{G_{fn}} \ldots & (1-\frac{G_f}{G_{fn}}) \end{bmatrix}$$

FIG. 8 - TRANSFER MATRIX BLOCK DIAGRAM OF INTERCONNECTED POWER SYSTEM POOL

FIG. 9.a

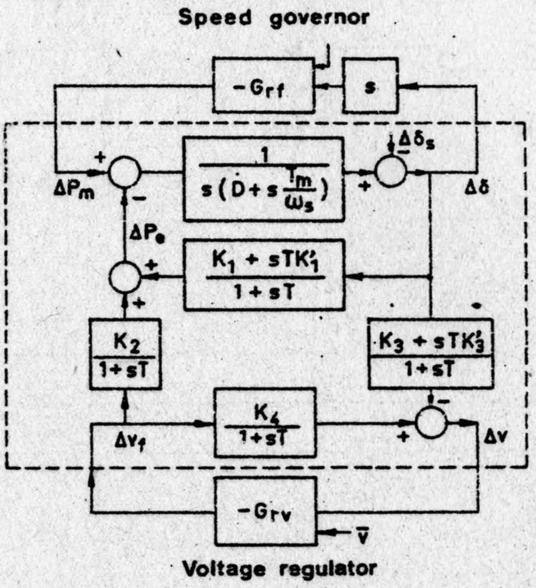


FIG. 9.b

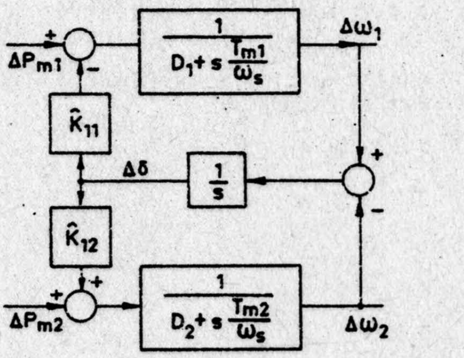


FIG. 9 - BLOCK DIAGRAM FOR STABILITY STUDIES
a. Block diagram of synchronous generator connected to infinite bus
b. The "two-machine" problem with "ideal" voltage-regulators

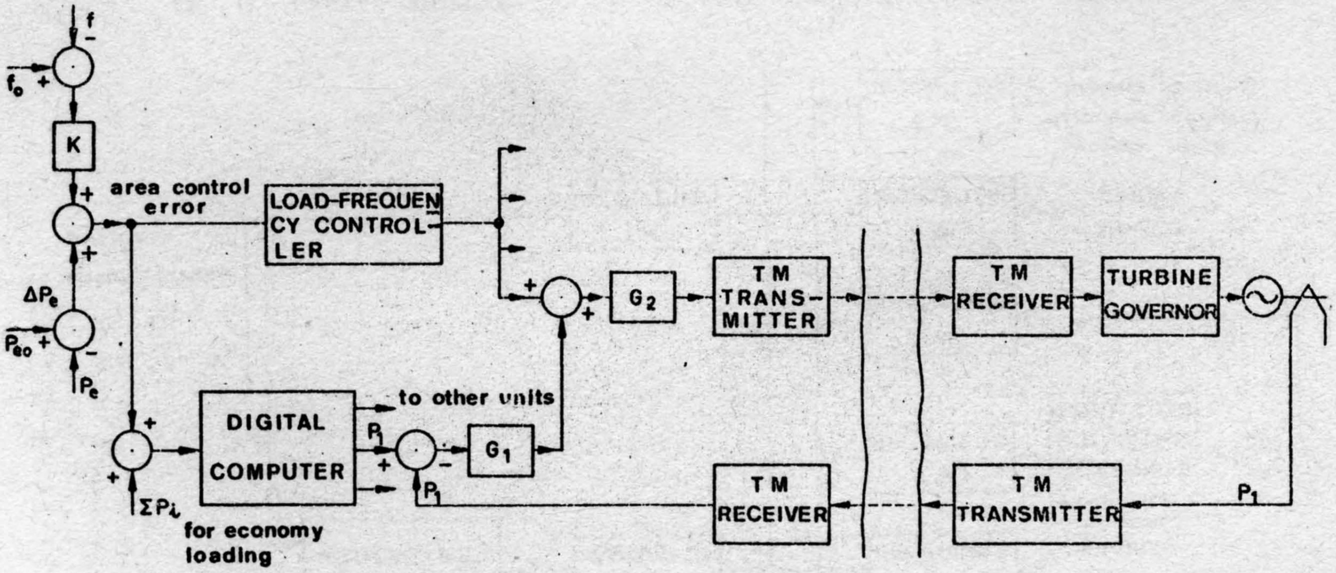


FIG. 10 - DIGITALLY-DIRECTED ANALOG SYSTEM FOR LOAD-FREQUENCY CONTROL AND ECONOMIC DISPATCHING

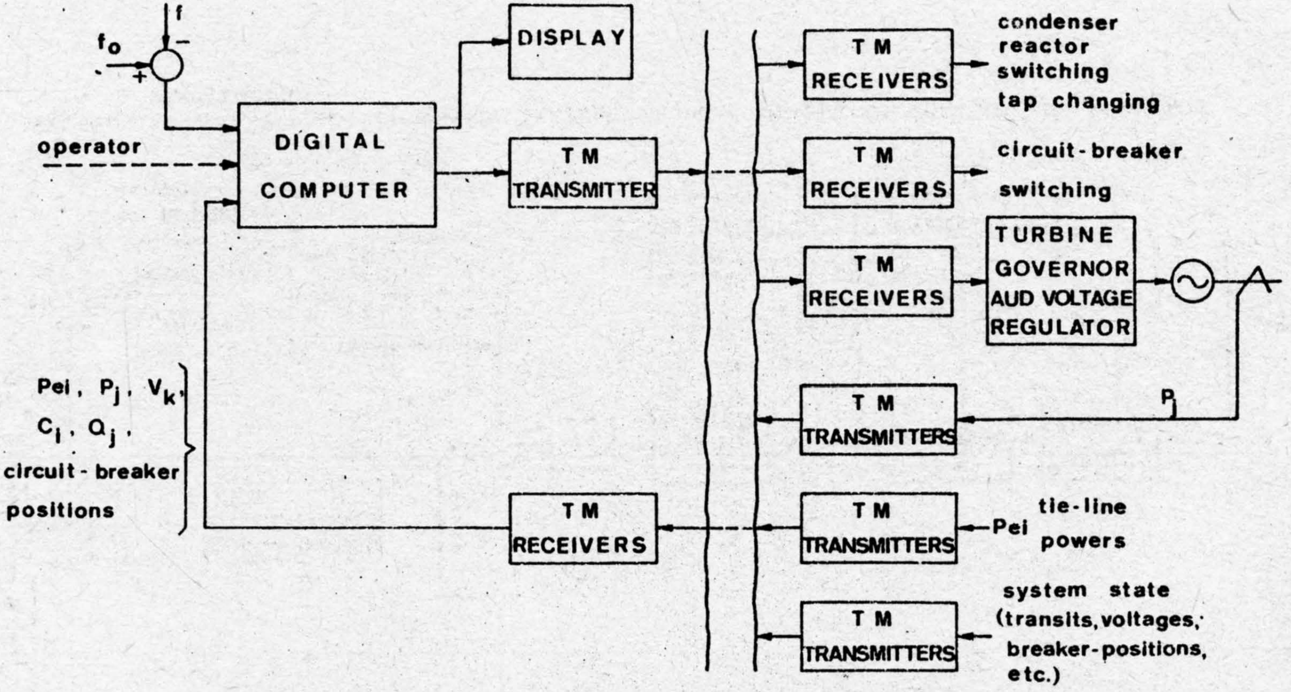


FIG. 11 - DIGITAL COMPUTER SYSTEM FOR LOAD-FREQUENCY CONTROL, ECONOMIC DISPATCHING OF ACTIVE AND POSSIBLY REACTIVE POWERS, AND SECURITY SUPERVISION AND CONTROL