# The Adaptive Reliability Control System

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*Abstract*—**Considerations necessary for the design of a total control system for the improvement of the reliability of the generation–transmission system are discussed. The control system is made of automatic functions, human participation, and an information system.**

**In the first part of the paper the framework of the design is established and the basic overall strategy for maintaining reliability is described. The second part describes the thinking and the work being done at Cleveland Electric Illuminating (CEI) Company for the practical implementation of the design concepts on the CEI system. The primary purpose is to contribute an organized approach to the solution of the problem of control for improved reliability. The aim is to be as comprehensive as possible so that all of the requirements within the framework of the approach are covered even though not all of the solutions have as yet been formulated. In the process of describing how the requirements may be met, major difficulties are pointed out as an aid in identifying areas where research in depth would be of value. Mathematical formulations are not used, but a discussion of the mathematical treatment of some aspects of the control system will be written in a separate paper.**

## Introduction

THE ELECTRICAL operation of the generation–transmission system may be viewed as a series of control actions taken to maintain continuity of service at standard frequency and voltage.

The control actions, manual or automatic, are dictated by various decision-making processes based on available system information, environmental data, engineering knowledge, experience, and intuition. It is evident that under certain circumstances, decisions made may not be the best from a desired performance viewpoint, and may in fact worsen instead of alleviate an emergency. In general, the importance of a correct decision is greater with actions which should be carried out immediately than with those where urgency is not paramount. The two requirements, speed and correctness of action, practically rule out manual action in favor of automation.

Automation has always been integral to a power system in the form of governor action, voltage regulation, and protective relaying. Further automation has been achieved in the form of load-frequency control and economic allocation of generation and in power plant operation. Outside of these automatic systems, all other control functions have been done, or have been expected to be done, manually.

In recent years the rapid expansion of power systems plus the installation of high-capacity generation, EHV transmission, and more interconnections have led to operating decision problems much more complex than those which existing automatic devices, let alone human operators, can cope with successfully. Many of these problems are forestalled by sound system design. There are, economic limitations to how much security can be designed into a system. Furthermore, techniques for evaluating trade-offs between risk reduction and investment in equipment are lacking in the area of transmission design.

There is, therefore, a need for an overall electrical operation control system which would make optimal day-to-day operating decisions but which also would recognize emergencies when they do happen and provide the necessary control action to resolve the complex emergency situation. The design of such a control system from a total systems viewpoint has been the object of study over the past 18 months at the Cleveland Electric Illuminating Company.



### *The ARCS Project*

In considering the addition of more automation for improved reliability of the CEI generation–transmission system, it was realized that in view of the extreme difficulty of making operating decisions in the time available under critical emergencies, the ultimate goal was the automation of all transmission substations. Although there were established principles for automating individual substations, there was as yet no fundamental set of design criteria for the automation of the entire system.

In 1964 a Company research proposal on system automation was evaluated and approved. The purpose of the project was two-fold:

1) to develop concepts and plans for the effective automation of all transmission substations

2) to develop a control system to improve the reliability of customer service and especially to minimize system catastrophes.

To start the research work, a joint study was undertaken with the Operations Research Group of the Case Institute of Technology. Specifically, the study team worked on the identification of the operating decision problems and on the development of suitable mathematical models for analytical study and for possible on-line application later. The result of this joint study, after one year, was the development of a mathematical model for emergency operation.[1] The project is continuing in CEI, at present without outside participation, and a program has been laid out for its development over a five-year period. The project has been called ARCS (Adaptive Reliability Control System).

This paper discusses the basic concepts for the ARCS design and also describes the current stage of development of the design.

Paper 31 TP 66–524, recommended and approved by the Power System Engineering Committee of the IEEE Power Group for presentation at the IEEE Summer Power Meeting, New Orleans, La., June 10–15, 1966. Manuscript submitted June 29, 1966; made available for printing February 21, 1967.

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### *Scope of Control System*

Before proceeding with the discussion of concepts for the control system design, three important aspects of the term *control system* should be noted:

1) Control system includes both the control function and a necessary supporting information system.

2) The control function includes both automatic and manual processes.

3) *Control* is used in its broad sense of decision-making. Thus control could take the following forms: immediate and direct manipulation of equipment based upon the decision made; deferred changes in device settings; revision of operating limits, parameter values, procedures, computer programs, etc.; determination and display of a decision for information purposes only.

## Design Concepts

### *Multi-Level Approach to the Control Problem*

A control approach that has been proved useful and effective in the power industry and in other large, complex processes is the so-called multi-level concept.[2] By this approach the overall, complex problem is divided into simpler subproblems. The interactions among so utions to the subproblems are then coordinated to achieve the overall objective. This procedure is often referred to in control terminology as *decomposition*.

Basically the decomposition of a complex process is done in two ways: 1) the process is decomposed into a number of subprocesses each with its own control system; and 2) each control system is decomposed into levels of control functions each contributing to the realization of the control objective. The various control solutions are then coordinated for the *best* solution to the overall control problem.

One example of multi-level control in the power industry is the *process* of transmission protective relaying. The transmission system is decomposed into subsystems, i.e., circuits, using circuit breakers, and each circuit has its own protective relaying. The protective relaying of each circuit is in turn decomposed into two levels of protection—primary and backup. The interaction among the various relayed circuits are coordinated via proper relay settings.

In the ARCS project the *process* we wish to control is the electrical operation of the generation-transmission system. The complexity of the operation problem rules out consideration of a single control approach. The implementation of a single total control is impractical for the following reasons:

1) The overall problem is too complex and too highly dimensioned to be handled analytically on one level.

2) The instrumentation, communication, and computer requirements would be too great.

3) Even if the foregoing difficulties were overcome a single control would still be inadvisable for reasons of reliability of the control system itself.

As an illustration of the third point, we might use again the example of transmission protective relaying. As an alternative to the present multi-level relaying control system, it is quite conceivable, as has often been suggested, for all the relaying and tripping control decisions to be made by a central computer. Relaying measurements from various points in the transmission system could be sent to the computer where they would be processed and trip signals could then be sent out to the proper breakers. Assuming that the practical problems of communication, relaying logic, and computer availability could be overcome it would still be ill-advised to have the entire system protection depend on a single relaying control scheme.

The multi-level approach provides the framework for the control strategy that makes the ARCS project realistic and within the realm of practical on-line implementation.

### *The Three Operating States*

The electrical operation of the generation-transmission system may be decomposed into three modes of operation or operating states. These states will be designated as:

preventive
emergency
restorative.

The preventive operating state is usually known as normal. The designation preventive is used, however, to stress the system security aspect of normal operation. In the preventive state, the generation-transmission system is being operated so that the demands of all customers are satisfied at standard frequency and at desired operating voltages. The control objective in the preventive state is to continue indefinitely the satisfaction of customer demand without interruption and at minimum cost. Since continuous supply of energy is predicated, it follows that no electrical component of the system shall be operated beyond its safe thermal limit. It is also implicit that the electrical system will not go unstable for minor or routine disturbances. These requirements are usually satisfied by engineering design. The control action is one of a defensive character. That is, the control system will recognize electrical system and environmental changes, will evaluate the effect of uncertainties, and will take courses of action to prevent, as economically as possible, the impairment of satisfactory service.

The emergency operating state comes about when some component emergency ratings are exceeded or when the voltage at a customer cannot be maintained at a safe minimum or when the system frequency starts to decrease toward a value at which important motors will stall, or when the electrical system is in the process of losing synchronism. The control objective in the emergency state is to relieve the system distress and forestall further degradation while satisfying a maximum of customer demand. Economic considerations become secondary.

The restorative operating state is that condition when service to some customer loads has been lost. Usually this is the aftermath of an emergency. The control objective in the restorative state is the safe transition from partial to 100 percent satisfaction of all customer demands in mini-

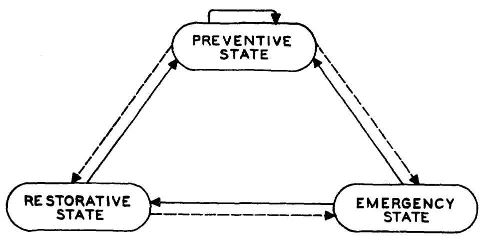


Fig. 1 Operating state strategy

mum time. From the standpoint of real customer satisfaction, restoration of interrupted supply in as short time as possible is of crucial importance.

*The Overall Problem and the ARCS Strategy*

From the foregoing discussion of operating states the performance of electrical operation is measured by how well it can meet the various optimum requirements. As power system and environmental conditions change, the optimum requirement could be any of the following:

1) minimum operating costs at a desired level of service reliability

2) maximum satisfied demand without exceeding constraints

3) minimum duration of customer outage.

The overall problem is to develop a control system which will adapt to the changes in optimum requirements and which can effectively influence the electrical system so that departures from continuous reliable operation (i.e., the preventive state) will be as infrequent as possible.

The ARCS control strategy is illustrated in Fig. 1, where the solid arrows indicate the change in state by planned control action and the dashed arrows indicate the change in state resulting from unavoidable circumstances or from incorrect control action.

The overall control objective is to try to keep the power system operating in the preventive state. This is shown in Fig. 1 by the solid arrows directed to the preventive state. While in the preventive state, some preventive actions may be too costly to implement and some set of events will be completely unforeseen. Thus it is expected that some disturbances could create an emergency which cannot be avoided by the preventive control. In this case the emergency control would take over. The emergency control would try to take the system back to the preventive state. Failing this, it would try to satisfy as much customer demand as possible with the emergency condition corrected. The emergency control will be designed to handle most emergency conditions but there will be some situations which cannot be taken care of because of additional complexity and will result n losing more customer load than is necessary. This situation, too, will be planned for by having the restorative control bring the system back to the preventive state as fast as possible.

The ARCS control strategy aims to meet the two-fold purpose of the project, particularly the second part, "to improve the reliability of customer service and especially to minimize system catastrophe." The strategy guarantees to provide the best control actions so that no major system shut-downs can occur.

Actually, we should go back a step to emphasize that a good engineering design of the power system itself is predicated. This premise reduces the burden and therefore the complexity of the preventive control for reducing the set of circumstances which could create an emergency.

*The Three Control Levels*

The practical realization of the control objective in each of the three operating states may be effected by a hierarchy of three control levels. Adopting the terminology used by Lefkowitz[2] we will refer to the first, second, and third control levels as *direct control, optimizing control,* and *adaptive control,* respectively.

*Direct Control:* The first level, or direct control, performs high-speed decisions using logic or a logical decision process and carries out directly the necessary control action. This level of control will be predominantly located at local points within the system rather than at a control center. As much as possible the logic used at a given location would make use of local information and would be kept fairly simple. An example of the simplest form of logic is a sing e relay operation. A less simple form of logic may require one or more pieces of local information plus some other external information from the control center. Although level 1 decisions should have a minimum of dependence on central processing, there would be some decisions which have to be done at the control center. Whether done locally or centrally, the distinguishing features of level 1 control are its high-speed and the use of logic programming.

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

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

In the ARCS design there will be a direct control level and an optimizing control level for each of the three operating states. The adaptive control level will be common to all three operating states and, in effect, will perform the necessary coordination of the solutions for the three states.

*The Information System*

The various control functions cannot be fulfilled without a supporting information system. The principal role of the information system is to determine the operating conditions of the system and provide the necessary information inputs to each control level. In addition, the information system will provide the link between the power system and the human operator, giving him information on request by a prearranged plan.

The information system will be made up of the following subsystems:

measurements
communication
information processing
information display and reporting.

Measurements include data obtained from the power system and from the environment. The environment represents the sum total of all factors external to the power system which affect or have potential to affect the electrical conditions of the system. In the ARCS project the identification of the optimum set of system and environment measurements to be made is one of the major tasks. During the process of developing the on-line control models, the problems of measurement and their hardware and communication aspects will have a decisive influence on the structures of the models.

The communication subsystem provides the information paths from local stations to the control center and the control paths back from the center. The communication requirements for ARCS will be integrated with those for relaying and other data-acquisition systems independent of ARCS.

For the sake of efficiency of communication and of reducing the complexity of the processing logic, the information processing subsystem will be decomposed into two levels. The first level processor will have immediate access to the system measurements and will act as a filter for information going to the second-level processor. For simple cases of system disturbances the first-level processing would usually be complete and no further processing would be necessary to obtain a dependable information for use by the control subsystems. The second-level processor will use for inputs the outputs produced by the first-level plus some selected direct measurements. By using the 2-level approach, the logic statements used in processing would be kept as simple as possible.

Most of the results of the information processing subsystem would be fed in directly as inputs to the various control functions. There will be other pieces of information, processed or not, which would need to be communicated to the system operator in the form of information displays and reports.

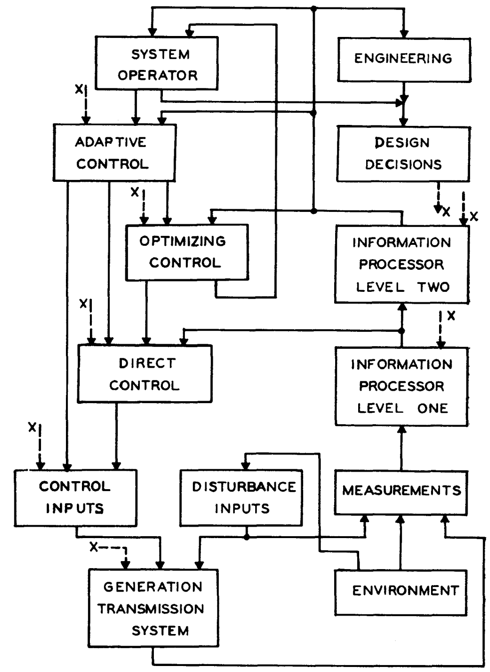


Fig. 2 Organization of ARCS multi-level control

Improved methods of displaying information should be developed which would be highly effective in conveying to the operator the significance of the information.

*Overall Organization of ARCS*

Figure 2 represents of the overall organization of ARCS according to the concepts described. Subsequent discussions will be made with reference to this figure and the details will be explained according to the present stage of design development. Certain features of Fig. 2 need some brief explanation in advance of the discussions.

The generation-transmission system has two sets of inputs. The first set, control inputs, is deterministic and is subject to regulation by the control system. The control inputs are MW generation, system voltage, and breaker positions. The second set, disturbance inputs, is uncertain and is not, except in a limited sense, subject to regulation by the control system. The disturbance inputs are loads, tie-line flows, and faults and other malfunctions.

The system operator is represented in Fig. 2 by a separate block, although conceptually some of his functions are part of the adaptive control. If we consider the system operator as representing electrical operation personnel, his other functions constitute, with engineering (also shown in Fig. 2 as a separate block), another level of control.[1] At this level, design decisions are made based on accumulated experience with the control system and better knowledge of the power system. These decisions are implemented as changes in the structures of the lower-level controls and of the information system. These are indicated n Fig. 2 as input sets $x$ to each of the three control levels. The input

[1] The term *self-organizing* is used by Lefkowitz[2] to characterize this control function.

sets will include such things as revised control logic, new procedures for abnormal operation, relay system changes, preferred one-line diagram, additional measurements, new information outputs, better modelling, modified optimum criteria, new operating limits, etc. This last level of control is outside the control system proper and will not be discussed further in this paper. It is shown in Fig. 2 for the sake of completeness of the overall concept since every control system must have some kind of feedback action in order to maintain good performance.

The discussion up to this point has been on the concepts guiding the design for ARCS. In the remaining portion of this paper, specific ideas for the application of these concepts will be presented. These application ideas have been incorporated into various work activities which made up the ARCS project.

## Direct Control Functions

The direct control level obtains information from the system, via the information processor level 1, and by simple logic automatically performs control actions on the system. As described before, most of the controls are localized. However, the direct control, as shown in Fig. 2, also acts in accordance with instructions from the upper levels.

Table I lists the automatic subsystems at the direct control level for each of the three operating states.

### *Direct Preventive Control*

In the preventive state the direct control subsystems are all existing and presently rendering satisfactory performance on a local basis. In the ARCS design, what is significant is that the functions of these existing controls will be extended and improved on a system basis by the addition of *instructions* from the higher control levels. We already have an example of this in economic dispatch where optimal raise and lower signals determined by an optimizing model are applied to the turbine governor control. While presently some form of manual adjustments are made on the existing control subsystems as system conditions change, some of these adjustments are generally arbitrary and not necessarily the results of objective decision processes with definite goals.

For the purposes of the ARCS plan a review will be made of the performance of each existing subsystem to insure that the operating principles, control logic, response rates, and other characteristics are compatible with the higher level requirements.

TABLE I
Direct Control Functions

| Preventive | Emergency | Restorative |
|---|---|---|
| Load-frequency control | Essential load protection | Automatic feeder restoration |
| Turbine governor control | Generator shedding | |
| Generator voltage regulation | Automatic switching | Automatic load transfer |
| Transformer tap changers | Out-of-step tripping | |
| Capacitor switching | System splitting | |
| Fault clearing and reclosing | | |

### *Direct Emergency Control*

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

1) *Essential load protection (ELP):* This automatic control function, consisting of both local and central logic processes, drops load (not necessarily optimal) from the system, or from an isolated area of the system, so as to save the system from a partial or total shutdown.

Local logic may be based on any of the following options:

under-frequency plus under-voltage
rapid rate of decay of frequency
under-voltage plus some other local information or possibly system information received from the control center.

ELP relays capable of carrying out any or all of the above logic are already available. Another type of logic may be based on the overloading of a transformer bank with no relief capacity immediately available. Essential load protection may also be initiated by a central logic program. This will be discussed later along with other control alternatives determined centrally.

2) *Generator shedding:* Some emergency cases leading to instability may be contained by direct emergency control using local logic at generating stations. For example, if a plant at full output suddenly loses three out of four outgoing transmission circuits the plant will fall out of step and the loss of the entire output will be thrown as a burden upon the interconnection. Rather than tax the interconnection in this manner which could lead to complications it would be better to recognize, by logic, the situation at the plant and automatically drop enough generating units to maintain stability with the available transmission.

3) *Automatic switching:* By means of local logic at substations, automatic switching sequences may be made to correct an emergency situation. For example, in a customer station fed by two transmission circuits with two transformer banks on one circuit and a third transformer bank on the other, loss of the 2-transformer circuit would result in a critically low service voltage. This situation may be handled by an automatic switching scheme which would transfer one of the two unloaded transformers to the circuit remaining in service.

4) *Out-of-step tripping:* Presently on the CEI system, distance relays are permitted to trip at locations close to the point of zero voltage during severe swings. For slight to moderate swings instantaneous relay trippings are blocked by means of out-of-step relays. A modification of this practice will be considered which would deliberately

split the system at a desired location or locations when the system is in the process of falling out of synchronism. The splitting of the system will be designed to result, as much as possible, in generation matching load in each area. The splitting of the system on out-of-step at desired locations rather than by independent distance relay action will have the advantages of: minimizing the shock to the interconnection; maintaining as much area load as possible; and placing the system in a good position for quick restoration later.

5) *Direct emergency control using central logic:* In this category are those control alternatives which depend upon central information processing Because of the speed requirement, the processing would be a straightforward logic program. Essentially the decision-making would be based on the identification of information patterns. A set of direct emergency contro' rules would be developed beforehand and stored. Based on the structure of the emergency condition or on a programmed interrogation by the information processor the proper emergency control would be selected and carried out. For example, if the emergency is due to loss of generation and there is no time to wait for the best solution, the information processor knowing the specific area[2] where there is a deficiency and knowing the magnitude of the load in that area will forward the information to the direct emergency control. The emergency control would then, according to the set of rules, carry out the required essential load protection by dropping load in the area identified. Another pattern of events may call for a decision to split the system and thereby separate an area in trouble from the rest of the network. The area having been split off and its interconnection to the outside world also tripped automatically, the ELP relays in the isolated area would be depended upon to drop load in that area.

### *Direct Restorative Control*

At the direct control level automatic restoration of load may be accomplished by local logic subject to commands from the higher control levels. Although the desired functions are easy to identify, namely, automatic feeder restoration and automatic load transfer, feasible alternatives for the logic processes to initiate such actions still have to be searched out.

## Optimizing Control Functions

The optimizing control obtains information via the information processor, level 2 (see Fig. 2), and solves for the combination of operating decision variables which minimizes or maximizes an objective function subject to constraints of service continuity and to instructions from the upper levels. As mentioned previously, the optimization will be done via suitable and practical mathematical models. The main research endeavor will be to develop such models capable of on-line implementation. Table II lists the optimizing control functions planned for each of the three operating states.

[2] The *area* concept will be discussed in a subsequent section.

### *Operating Decision Variables*

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

units on line
MW output of generators
interchange schedule
system voltages
system load connections.

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

### *Service Continuity Constraints*

All solutions to the optimization problems should satisfy a set of service continuity constraints which consist of the following:

network equations
MW and MVAR demands at substations
MW and MVAR limits of generators
thermal ratings of equipment
interconnection limits
generator voltage limits
substation voltage limits
stability loading limits
service reliability factor.

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

The fact that the decision variables and the constraints are the same for all three operating states (with only a few changes from one state to the next) suggests that one basic optimization procedure may be applicable to all three states. That is, mathematically, the objective function to be minimized or maximized over the set of decision variables and subject to the given constraints could be that associated with either the preventive or the emergency or the restorative states. The optimization routine would be basically the same.

TABLE II
Optimizing Control Functions

| Preventive | Emergency | Restorative |
|---|---|---|
| Unit commitment<br>Economy interchange determination<br>Economic generation dispatch<br>System voltage control | Maximum load solution | Dynamic restoration procedure |

*Optimizing Preventive Control*

In the preventive state the function to be minimized is the operating cost, subject to the given constraints which, as listed above, include reliability. Usually, because of system design standards and favorable operating conditions a great many of the constraints, such as the thermal and stability constraints, will not be binding and need not be considered in the model. In such a case the computation time for optimization would be greatly reduced. Assuming that a model has been developed, the third and fourth control functions in Table II, (economic generation dispatch and system voltage control) would be determined on a minute-to-minute basis and automatically implemented by the first-level controller. The other two functions (unit commitment and economy interchange) would be determined on a less frequent basis and the solutions made available to the operator for manual execution. Between changes of the values of these variables they become part of the constraint set.

Historically, optimization methods have been applied to the subproblems of MW dispatch, unit commitment, and interchange scheduling. System voltage control has been handled independently though not necessarily on an optimal basis. However, two factors are not being adequately taken into account in the present solutions of these subproblems. One of these factors is the interaction among their solutions and the other is the consideration of the service continuity constraints and especially of service reliability.

In ARCS, one of the major study activities is the consideration of generation dispatch and system voltage as a combined problem of minimization of operating cost subject to continuity constraints. Optimal solutions would be carried out by sending control signals to the direct controllers. The end result would be the most economical combination of system watts and vars and all constraints satisfied.

*Maximum Load Solution*

Some emergency cases will result either in overloads or in voltages below desired limits, or in both. Such emergencies could be the result, for example, of a loss of generation or of a major transmission circuit when the system is not normal. Assuming that the system is stable and that the system remains tied to the interconnection, the optimizing control will be called upon to correct the emergency. (It should be recalled that instability and under-frequency would be handled at the faster-acting direct control level.) The optimizing control will solve for the combination of generation and load so that the total demand satisfied is a maximum and the overload or low voltage conditions are corrected. In Table II this function is referred to as the *maximum load solution*.

The maximum load solution is obtained by going through a mathematical optimization procedure. The preliminary mathematical model so far conceived[1] requires for inputs the following information: identification of generating units on line and their operating limits, latest changes in network configuration, the individual substation loads, individual tie-line flows. All of this input data would be provided by the information system. A complete network representation would be in storage and corrected for the actual state of the transmission system. The model does not require generation data or system voltage data to calculate the optimal solution. The outputs of the optimization process would be MW and MVAR generation, desired connected load at specified substations, and amount of interchange to be negotiated and with whom. The optimization could be constrained so that only some substations can have their loads reduced or so that the interchange would remain as originally scheduled.

The preliminary model uses a nonlinear programming technique[3] for optimization. The nonlinearity, which is a familiar aspect of network analysis problems, arises from the fact that the network equations are expressed in terms of powers. The speed of computation by a mathematical programming method is highly dependent on the way the problem is formulated, on the optimizing method used, on the dimensions of the problem, and on the computer program itself. To improve computational speed, efforts are being directed to developing a final model which would require a minimum number of variables and constraints, and whose computer program would be as efficient as possible. This aspect is more of an engineering problem than strictly mathematical one since knowledge of network theory and of the CEI system's characteristics is being used to great advantage for *streamlining* the model.

Techniques for handling large networks by piecewise analysis[4] could be successfully applied for reducing the dimensions of the network that has to be considered for a given situation. Under consideration is the subdivision of the CEI network into areas and the treatment of loads, generation, and tie-line flows on an area basis. For a given emergency it may be necessary to look just at one or two areas in detail and have the others represented at their tie-points. Knowledge of the system's behavior would indicate what areas are relatively insensitive to changes under a given situation. Given an area representation and the flow into the area it should be possible to get an approximation via piecewise analysis, of the initial flows and voltages within the area. The use of experience and knowledge of a specific power system, that is to say the use of heuristics, has tremendous value in the successful development of a practical model for on-line use. Heuristics for example, should help identify what lines or equipment should be included in the set of thermal constraints for a given situation as it would be obvious that there are many lines which do not have to be checked for an overload for that situation.

The area concept results in another form of decomposition when applied to a very large system or when extended to a pool of several utility companies. Each area would be large enough to have its own control subsystem, each structured into three operating states and each having three control levels. There would then be a central control level coordinating the actions of the area control subsystems.

*Dynamic Restoration Procedure*

The prompt restoration of service to customers is the object of the dynamic restoration procedure. Although we can state informally that our objective is to restore service in minimum time, mathematically, it does not appear practical to formulate a suitable time function which would be minimized. The difficulty lies in the fact that after loads have been dropped by emergency control action, there are only a few alternate ways to choose from with varying restoration times. The alternatives available differ only in the sequence by which loads should be restored. One sequence appears equally good as another provided the restoration can proceed smoothly without encountering overloads, low voltages, or instability. Thus we might say that service may be restored as fast as possible, limited only by the rate of generation pickup, as long as the sequential switching on of loads can be accomplished without violating the system constraints. On this basis a dynamic restoration procedure may be built around the same optimization routine used in the emergency control. In restoration, load is to be picked up; in emergencies, load is dropped.

Under the service continuity constraints, the maximum amount of load with a given generation availability could be calculated. The next step in the sequence could then be similarly figured out subject to the rate of generation increase, and so on. The entire sequence may be predetermined or one step may be carried out first and then new calculations made for the next step.

The modelling of the restoration procedure at the optimizing level is the most difficult of the three operating states. Heavy reliance will have to be placed on the adaptive control level in the event of an actual transmission system shutdown. The difficulty of the restoration problem stresses the importance of the overall strategy which aims to keep the system operating in the preventive state.

In determining how much load could be picked up, estimates of the demand will have to be relied upon. Here, the area concept will also be of value as the area load prior to the emergency would be known and the process of estimating would have a base to work from.

## Adaptive Control Functions

The purpose of adaptive control is to adjust the settings, logic, and parameters for the first and second levels, to compensate for conditions not considered in those levels, and to coordinate the solutions for the various operating states.

As shown in Fig. 2, the adaptive control level obtains information via the information processor, level 2, and then makes decisions which are sent to the lower levels. These decisions are listed in Table III as adaptive control functions.

Some of these functions are almost self-explanatory, i.e., regulator and relay setting changes, integrated control error, constraint values, and lower-level logic. These functions represent the frequent up-dating of various parameters and logic used by the lower levels of control.

*Load Estimates*

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

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

The prediction process for load estimating will be programmed for the computer.

*Tie-Line Flow Model*

A method of prediction would also be of great value in representing the interconnection. The handling of the interconnection behavior is one of the more difficult aspects of the optimizing control models. In the optimization problem, the decision variables are generation and load, and in seeking an optimum solution the changes in tie-line flows have to be taken into account. Although it may be possible to develop a good network equivalent to represent the interconnection, the adaptive problem is to keep this equivalent up-to-date under all system conditions. Measurements of actual tie-line flows would be readily available at the control center. What is also required is a fairly accurate estimate of what the flows would be as changes are made in the CEI generation, load, and network configuration.

The problems of representing the interconnection for on-line operating purposes are different from that of representing the same network for off-line planning purposes. For load-flow studies, it is difficult and time-consuming to develop interconnection equivalents for different load levels and network conditions, but it can be done, given enough time and cooperation from other companies. The easier alternative is usually chosen of securing detailed data and using as large a load flow program as is available. For

TABLE III
Adaptive Control Functions

| Preventive | Emergency | Restorative |
|---|---|---|
| Regulator and relay setting changes<br>Integrated control error<br>Constraint values<br>Lower-level logic<br>Load estimates<br>Tie-line flow model<br>System reliability evaluation<br>Stability analysis<br>Fault locator<br>Switching operations<br>Manual intervention | Constraint values<br>Lower-level logic<br>Tie-line flow model | Constraint values<br>Lower-level logic<br>Tie-line flow model |

on-line operating analysis the second approach is obviously impractical and the first approach presents problems of accuracy and up-dating. The standard network equivalent is only as good as the assumptions used. The interconnection model required should be dynamic, i.e., capable of updating as internal and external conditions change.

It appears that the key to an up-to-date interconnection representation lies in the tie-line flows themselves. We could view the external network beyond the boundaries of our power system as an uncertainty whose structure at any given time is not completely known. However information is being communicated all the time from this uncertainty in the form of the actual interactions with our system, i.e., in the form of tie-line flows. This information is automatic and the most up-to-date concerning the state of the interconnected network. It appears reasonable to assume that a dynamic tie-line flow predictor could be based on the most current tie-line flow information.

Research will be required to pursue the feasibility of this idea. For example, it is known from experience that the MW flow through each tie-line is, to a high degree of approximation, linearly related to the net MW interchange. Theoretically any two sets of tie-line readings, moments apart, should yield the constants of the linear functions. Practically, the tie-lines could be continuously monitored and a prediction routine could make use of, taking the latest 4 or 5 sets of readings a minute apart and generating the linear functions. This approach has value in that the effect on tie-line flow behavior by changes in the interconnection is immediately known without having to know what the changes are. At any rate, new ways of representing the interconnection by a dynamic model have to be sought out.

### *System Reliability Evaluation*

In the two sections immediately preceding we discussed the disturbance inputs of loads and tie-line flows and how prediction methods could be applied. In this section we consider the most uncertain disturbance input, namely, faults. A fault could be any external event which could result in the temporary or permanent disconnection of a generation-transmission system component or of a load. The effect of a fault depends on the pre-fault condition of the system. Thus adaptive control should assess the reliability of the system under prevailing conditions and determine what changes should be made to the generation, transmission, or the control system so as to maintain service continuity at least until the next decision time.

We view system reliability as being synonymous with service continuity at standard frequency and voltage. We would consider prevailing system conditions as risky if the next fault disturbance could result in significant reduction of frequency, loss of electrical connections to a load, instability, thermal overloads, or below standard voltages at some locations. Because of the several ties to the interconnection we can rule out consideration of frequency in our preventive decision-making. This leaves us with four consequences to consider.

Reliability mathematics using probability and statistical methods has been applied to simple networks by considering the various ways by which all electrical paths from the sources to a load may be lost. Results so far developed are of no significant value to our problem for the following reasons:

1) Loss of load connections is perhaps the least likely to happen of the four consequences mentioned above because of the way the network is built. In the CEI system as many as four loop circuits feed a given load point.

2) To simulate the loss of all electrical paths to a load, very many combinations of events and their probabilities have to be considered and assumptions have to be made as to which events are independent and which are dependent. The probability calculations become too numerous and complex.

3) Even if the probability expressions can be written out and data obtained, the results would still be meaningless because the network equation constraints are not taken into account. That is, although on paper there may still be a path remaining which can be traced from a source to a load, in reality such a path can not meet the requirements of network laws and of other electrical constraints. Extension of present-day reliability mathematics to conditions of low-voltage, thermal overloads, and instability poses a formidable if not an impractical task to perform.

There have also been some suggestions for applying techniques which have been developed for maximizing flow[5] through networks such as transportation and communication networks. These methods however are not directly applicable to power system networks, again because of the disregard of electrical circuit laws.

Due to the major difficulties involved, we should not employ probability methods alone to the exclusion of other approaches even though, traditionally, probability has been associated with reliability calculations. We should consider the feasibility of logic or of a logic-oriented approach. The logic would be based on experience and knowledge of the system. We had already made appeal to this approach (see the section, *Maximum Load Solution*) and had used the word *heuristics* to designate this decision-making process. This approach leads us to the concept of adaptive preventive control as being based on the recognition of information patterns. If the existing pattern of system conditions of load, generation, and transmission network can be recognized as a danger situation, then preventive measures may be taken to improve the pattern. Because of system design, an emergency is never due to a single contingency on a normal system and seldom if ever due to two contingencies. What generally happens is that a single contingency is added to a combination of two or more previous non-normal situations. Thus if situations are prevented from adding up, the occurrence of emergencies would be in theory eliminated. The main problem is the identification of symptoms or patterns or situations which require corrective action. The selection of patterns will be limited to next-contingency considerations only. Many of the adaptive actions are part of present-day standard operating procedures developed over years of experience with the system. Hence, a good source from which examples of recognizable danger patterns may be obtained is the experience of operating personnel. Other sources are engineering analysis and simulation studies. Research also may disclose that patterns of system parameters, such as phase angle patterns, yield measures of system reliability.

### *Stability Analysis*

One of the information patterns which should be recognized by adaptive control is that which could lead to instability of the system. The more stable the system is at any time the more effective will the control system be in maintaining reliable service. One factor working in favor of adaptive control is the time element. In direct control, action must be done in cycles or seconds; in optimizing, control action may be delayed by a few minutes; in adaptive control, no emergency has happened yet and there is little pressure from real time. Thus there should be ample time and opportunity to evaluate and correct system conditions by shifting generation, speeding up or deferring maintenance work, modifying relay settings, or modifying the logic of the direct emergency control subsystems designed for handling instability. To facilitate the recognition of basically unstable patterns, improved techniques of stability analysis will be explored. Methods based on such techniques will take advantage of the characteristics of the CEI system.

### *Fault Locator*

After a line has been faulted, one of the adaptive control functions is to locate the fault so that repairs if needed could be made as soon as possible. Again the motivation is the prevention of the piling up of contingencies. Two approaches to fault location may be considered. One approach is to provide adequate system oscillography and procedures for fast processing and analysis. Oscillograms may be quickly interpreted in terms of miles to the fault from a given station with the aid of a computer either for information retrieval or for simulation purposes. The procedure would be speeded up further if direct recording oscillograms were used. The other approach which is a matter for further research is the installation of an automatic fault locator system.

### *Switching Operations*

Some adaptive preventive decisions have to do with switching operations for reasons of maintenance work or for improving loading distributions or for improving the overall reliability picture. If the effects of such switchings are questionable, they could be analyzed by the system operator with the aid of a computer program tailored for operating use.

### *Manual Intervention*

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

## Development of the Information System

The information system for ARCS cannot be completely designed until all the requirements of the various control subsystems are adequately identified. However, as the development of the control models progresses certain aspects of the information system take form and design work on them can be started. The following sections describe progress in some areas of the information system.

### *Communications*

The concept of an operating control center which is integral to ARCS has been studied and recommended for implementation by the Operating Department. Following this, a task force has been organized by the System Planning Department with members from various engineering and operating elements to identify the location of the control center. A primary consideration for choosing the location is that of communication. The CEI generation-transmission system is now almost completely covered by a microwave communication system for the primary purpose of transmission relaying. The addition of communications for ARCS will require the extension of the microwave network to the few remaining parts of the system which at present do not have microwave. A problem with the existing communication network is that the paths from transmission stations, having been put in for relaying, do not all terminate at one location which could automatically be the control center. Investigation of the communication problem aspects of alternative locations is being conducted.

### *Automatic System Trouble Analysis*

One of the functions of the information processor is to perform a quick and correct diagnosis of a case of system trouble. The information so developed would be fed into the control models so that the network representation may be updated and control decisions made. The result of the diagnosis would also be displayed to the system operator to help him make adaptive control actions if required. The diagnostic procedure is referred to as *Automatic System Trouble Analysis* (ASTA).

The ASTA design is based on the decomposition of the information process into two levels. The first level, or *circuit diagnosis*, is the determination of what has taken place within a circuit or to a system component. The second level, or *system diagnosis*, is the processing on a system-wide basis by coordinating various information from various circuits. ASTA takes advantage of the built-in diagnostic logic already designed into the protective relaying subsystem.

If a fault were nonpersistent and all automatic sequences operated correctly to clear the fault and restore facilities to normal, ASTA would simply identify the faulted circuit and indicate whether ground was involved or not. No action would be required for this fault except later when the results of the fault locator (see the section, *Fault Locator*) are known. On the other hand a persistent fault or malfunction of one of the protective sequences will require a more involved analysis to identify promptly the nature of the resulting system condition and of the fault. Since it is the function of the protective relaying system to identify precisely which circuit or component is faulted, it is logical to look to the primary relaying to provide the information for diagnosis. Likewise, when a protective malfunction occurs, the backup relaying has been designed to identify such failures so that backup trippings can take place. By monitoring the performance of the relaying system, the complexity of the diagnostic logic will be reduced considerably.

The logic for ASTA can be further simplified if the fault locator were made automatic. Since an automatic fault locator, if feasible on the CEI system, would still take some time to be developed and implemented on the system, the ASTA logic is being designed on the basis that breaker and relaying operations are the only available input data. The role of ASTA would be to provide enough *digested* information to the control system (which includes the system operator) so that proper control decisions may be made promptly.

ASTA will be primarily a software package for the control computer. By designing the logic as a computer program, changes in logic occasioned by changes in relaying and by power system evolution would be accomplished very readily as a program modification.

### *Computer and Software Requirements*

All throughout this paper it has been taken for granted that there would be a computer at the control center. Before we can go out and rent or buy a computer for system reliability purposes we should first have a fairly developed plan as to how we would use the computer. This means that the ARCS design should have progressed to the point where preliminary models of most of the control functions, especially those in the preventive states, have been formulated and tried out on at least some sample networks. We estimate it will take us two more years of research and engineering before we can translate the computer needs in terms of type, speed, memory size, languages and peripheral equipment and also all the other components of the information system. However, it may be possible to identify the nucleus of the computer configuration much sooner if a workable model for the optimizing preventive control can be developed early enough.

There are certain things which we can say now about some features which would be required of the central computer. The computer should be capable of real-time application. The computer should have a high availability rate, i.e., the down-time should be minimal. The programming language of the compiler type should be fast and should be able to accept directly complex variables and logic variables. The computer should have real-time clocks to provide time sequences for some of the logical decision processes.

We plan to do most of the programming for the computer and this represents a major task not only in terms of actual programming man-hours but in the prerequisite steps of acquiring and training qualified specialists. Based on the control function requirements shown in Tables I, II, and III the following computer programs would have to be developed:

direct emergency controller
unit commitment
economy interchange
economy dispatch and voltage control (subject to service continuity constraints)
optimizing emergency controller
dynamic restoration procedure
adaptive controller
load estimator
tie-line flow predictor
system reliability evaluation
stability analysis.

There will of course be other programs, not needed by the control system, but which may be run on the computer on a time-sharing basis. These other programs will be for off-line routine calculations of operating or engineering problems.

Some of the working computer programs which have been developed by the power industry will provide some basis on which to build the software as indicated in the list above. The fact that many computational routines have been tried and tested by the power industry in working out its successful programs will reduce the programming task for ARCS to some degree.

## Concluding Remarks

For the successful management of a project as large as ARCS, a PERT diagram of the various research and engineering activities should be drawn up at the start. The PERT diagram for CEI's ARCS project has a total of over 60 activities and includes, in addition to those related to the control functions, such activities as initiation of individual substation automation work, preparation of operating guides, development of software, debugging, training of operating personnel. The total duration of the project covers a period of over five years. However, in the course of the project, design intermediate results will become available for *manual* use even before the control system is in complete service. Thus, for example, results of research and analysis in the modelling of the preventive control functions and the development of logic for the information system may be adapted to immediate operating use in the form of guides or off-line computer programs.

In conclusion the following remarks are offered:

1) A unified control system for generation–transmission reliability is feasible via the multi-level approach.

2) The control system is characterized by a combination of man and machine functions, a combination of local logic and central computer processing, and a communication via an information system between the system-environment complex and the control center.

3) The structure of the ARCS design provides a unifying medium for coordinating various operating control functions so as to achieve the overall objective of service reliability. Many of these functions have been known to the industry in some form or other but hitherto their applications have been for isolated objectives and have not been necessarily coordinated in terms of a total system design.

4) The control strategy attempts to contain emergencies in two modes. First, if an emergency has not happened, by reviewing the prevailing state of the system and taking adaptive measures to prevent emergencies, especially for the types that leave very little time for corrective action. Second, if an emergency has happened, by using direct control action if time is not available; and by using optimizing control action if time is available.

5) There is a need or a motivation for research study in the following areas:

- dynamic interconnection representation
- system reliability analysis possibly using heuristic programming
- new approach to stability analysis
- automatic fault location
- extension of Kron's piecewise analysis for problem reduction and computational efficiency
- nonlinear programming techniques which insure convergence for electric-power-oriented functions
- improved programming language for power system operation problems.

The above list is by no means exhaustive.

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## Discussion

**John R. Linders** (Consulting Engineer, Cleveland, Ohio): One of the more unusual aspects of this paper is that it is being offered now, before all of the problems have been resolved rather than five or six years hence, after more of the practical aspects of the theory had been confirmed. Mr. Dy Liacco's positive expressions of things to be done to automate a power system, in fact, are an inspiration to anyone who has an interest in this field. And yet there is a question in my mind as to whether the paper will be sufficiently understood to make its mark in the annals of IEEE.

Manuscript received July 22, 1966.

I have this question because I cannot focus on the person in a given company who would act on these integrated control concepts and bring the described system into being. The system planner is usually quite divorced from control problems. He considers them in the domain of the substation engineer. But the substation engineer is more concerned with component control than the optimizing of a system for restoring service to the maximum number of customers in a minimum of time. Mr. Dy Liacco makes frequent mention of the relay system, yet the relay engineer is mostly interested in clearing faults, not in controlling buy-sell decisions on the interconnections.

My point is more clearly made by referring to the sections on load shedding. This is only a small part of ARCS. But following the November 9, 1965, Northeast blackout, very few rushed forward to claim responsibility for implementing the load shedding part of the FPC report. With the emphasis on operations which followed the November 9 blackout, perhaps the needed leadership for moving such an across-the-board program forward lies in the operating arm of the utilities. But such heavy engineering responsibilities do not usually reside in operations.

With respect to the vendors' organizations, they are largely oriented toward selling hardware. Whereas this project, in its present state, is in need of systems concepts and software.

Thus there appear to be few organizations which can successfully move into the program Mr. Dy Liacco has outlined without a major revision of classic ideas of responsibility and division of labor. But I do believe in the ideas expressed and in the soundness of the IEEE for disseminating current thinking. So I am confident that my question once raised will be satisfied.

From a technical standpoint, I am sure that many readers will inquire as to why this or that idea is considered new or novel when it has been common practice for many years. What is new is the concept of doing these things in the context of a complete integrated system. For example, the arguments over ultra-high speed reclosing frequently being self-defeating vanish with these adaptive control concepts.

When relaying and trouble locating (which are both done today) are truly integrated, the system operator will be promptly informed by a computer print-out, if he should send a line crew to repair a break at tower No.——— or a maintenance crew to a specific terminal to repair a malfunctioning circuit breaker or relay, and if he should make a change in any operating plan. Thus the significance of doing these things in the context of a complete system takes on a new dimension.

Most of the tools which the project visualizes for metering and observing the system are in existence today. This is seriously restricting the fundamental thinking on this project, but it is about the only way to get started. It would be quite impractical to complete a project of this nature with a ten-year gap waiting for someone to invent the needed tools. Hence care must be exercised to interpret this report in the broadest sense. Because, once these concepts are accepted, there should be no question that improved tools will proliferate, and improved methods for reaching the desired ends will automatically follow.

Mr. Dy Liacco mentions that improved decisions on various engineering trade-offs will result from these concepts. These concepts will also provide the system planner with new insight into how the system functions and what his real needs are. It is important to recognize that this project, for practical reasons, is oriented toward the problem of automating a system which was largely designed for manual operation. The impact of these concepts on the design of the system itself has yet to be analyzed. As mentioned in the paper, the industry has evolved to where we know how to automate individual substations (and plants) but we have yet to learn how to automate a complete power system. This paper is the first recorded effort directed toward this larger problem.

The present evolution of power systems has brought us EHV and pooled interconnected operations. As great as these changes are from systems of 15 to 20 years ago, this adaptive system control concept will cause at least as great an impact on future system design and operation. We are already painfully learning that electrical network theory recognizes no legal boundaries. The area concept mentioned in the paper must be developed to understand how a given power system may electrically lie half in one area and half in another, even though the legal and operating relations may be entirely different. In fact, the trend toward massive interconnected systems is futile without these concepts. November 9, 1965 demonstrated this.

The paper is organized around the basic aspects of the control hierarchy and properly so. The need for this total control integration can be further understood if one tabulates why systems get into trouble. In addition to the usually recognized component failure, system upsets can occur because of:

1) a fallacy in the system plan
2) an improper execution of the plan
3) misunderstood operational limits.

And with EHV interconnections, these situations two or three companies removed can cause your system to go down. This is a timely paper.

**George C. Barnes, Jr.** (Department of Electrical Engineering, Virginia Polytechnic Institute, Blacksburg, Va.): Mr. Dy Liacco has done an admirable job of explaining a most comprehensive and sophisticated control system concept. This concept is timely in the light of the rapid growth of our energy networks with continued pressures for proliferation of interties. He has also properly referred to the ARCS project as one of design, with perceptive suggestions relative to a minimum of eight areas of needed research in improvement of systems controls of preventative, emergency, and restorative functions in maintenance of optimum energy supplies.

As one engaged in education, the piecewise analysis in approach to design is particularly pleasing to me. It is in contrast to the too-often encountered philosophy of total consideration in today's education. The approach is through a study and understanding of components, too often neglected. Dy Liacco also pictures the energy system for what it is—a total system involving energy conversion, circuitry, measurements, communications, information processing and reporting, and, finally, optimum control function which does not exclude the intelligence, knowledge, and experience of man. His references to economic considerations are also pertinent and timely.

As one who has found continued effort necessary in maintaining student interest in the most basic and important of our electrical endeavors, our energy supply, it is felt that the paper is an excellent exposé of the engineering excellence required in the maintenance of that supply. Because of this exposé, and because of the totality of application of knowledge to energy systems indicated, I suggest the paper be published in the *IEEE Student Journal* regardless of other dispositions of it.

Manuscript received July 5, 1966.

**Sanjoy K. Mitter** (Systems Research Center, Case Institute of Technology, Cleveland, Ohio): Mr. Dy Liacco is to be commended for his timely paper on the systems approach to power systems design and control. As he points out, the approach suggested is an application of the multi-level concept for the solution of system engineering problems.

Manuscript received July 22, 1966.

I would like to point out three areas where research is being done and where some progress has been made.

1) The problem of allocation of power and load shedding under emergency conditions can be formulated as a nonlinear programming problem. It is thought that the SUMT procedure due to Fiacco and McCormick[1] is probably most suitable for solving the nonlinear programming problem.

2) One of the problems of large-scale systems is to characterize the properties of the overall system from the properties of the subsystems and the nature of the interconnections. It is thought that the problem of stability of a power system could be solved in a decomposed fashion.

3) Pattern-recognition techniques are probably most appropriate to determine the security of the network.

[1] A. V. Fiacco and G. P. McCormick, "Computational algorithm for the sequential unconstrained minimization technique for nonlinear programming," *Management Science*, vol. 10, July, 1964.

**D. N. Ewart** (General Electric Company, Schenectady, N. Y.): The work which Mr. Dy Liacco and his associates at CEI have undertaken has the potential of showing to the industry where the next great strides are to be taken in terms of power system operation and security.

This paper must be viewed as providing the framework about which a pattern of power system automation can take place. What makes the structure which Mr. Dy Liacco has formulated so appealing is that it stresses the *evolutionary* rather than the *revolutionary* approach to automation. This structure encompasses all the functions presently being performed by automatic equipment, from the simple overcurrent relay to the complex analog and digital computers being used to operate today's power systems. This unifying concept is one of the most valuable contributions made by the paper.

I have only a few specific comments and questions relating to the paper.

First, the necessity of providing adequate operator displays was mentioned in the paper and this point cannot be overstressed. Although many of the operating functions can be and are being automated, the human operator must be maintained as a vital link in the system at all times. His adaptability to unpredictable circumstances cannot be matched by any computer envisioned today. Thus, the role of the computer must, in many areas, be restricted to digesting and presenting information to the operator for his action. As time goes on, we will see more and more advanced and imaginative methods of communication between the computer and the operator being used. Along these same lines, the paper states that the information system will provide the operator with information on request. This should not preclude the function of keeping the operator routinely and continuously informed of the normal and abnormal system conditions as they develop.

We cannot fail to see the importance of developing rapid means of estimating load flows for use in several areas of system monitoring and optimization. Work in this areas as reported in the paper is most gratifying, and several recent papers devoted to this subject attest to the attention being given to it by the industry.

The comments regarding the inadequacy of present efforts to apply reliability mathematics to system continuity are, I feel, too harsh. The data presently being gathered will be just as useful for the estimation of thermal overloads, instability, or of substandard voltages as they will be for the estimation of the absolute loss-of-service continuity.

Manuscript received July 29, 1966.

Last, I notice that the Essential Load Protection Function is not triggered by simple underfrequency but by a combination of underfrequency and undervoltage or by other means. This load shedding function has a great deal of significance to system security and must be coordinated within interconnected pools if tie-line overloads are to be avoided. I would be interested in Mr. Dy Liacco's comment on how this coordination might be assured within the framework of his plan of automation.

**H. L. Smith** (Westinghouse Electric Corporation, East Pittsburgh, Pa.): The author has presented a very unique, but complete, analysis of the problem of system operation control. It is interesting to note that many of us have been working toward the system described here on a step-by-step basis without defining it. This discussion consists primarily of comments relating the work that has been done to the control system described in this paper.

The author describes a preventative control state and relates it to normal system control. I feel his title is far more descriptive and should be considered for use by all of us. Most of the activity on system operation computers to date has been confined to this area.

This control state is then divided into three levels. Direct control is comprised of actions performed by all operating systems today, as pointed out by the author. However, he suggests there should be an overriding control on these actions by a central computer. I think most people who have worked with digital system operation computers have this in their minds as a long-range goal, and are working gradually toward that goal. Many already perform circuit breaker monitoring and they could be expanded to circuit breaker control if desired. Also, with the recent purchase of seven small computers by a large western utility for installation in transmission substations, I feel that we will see the control of some of these functions on an area basis in the near future.

The optimizing control level of preventive control as presented by the author is now performed by most system operation computers, except for system voltage control. However, there have been discussions on this subject and, in fact, one session of the 1966 IEEE Summer Power Meeting dealt with the planning and control of var supply. Control in this area will undoubtedly appear in the near future.

In the area of the adaptive control level of preventive control, some functions have been discussed only, other have been implemented, and still others are being developed. For example, some operating system operation computers have used constraint values to match subarea load and generation. Almost all operating system operation computers provide the capability of forecasting the next day's loads, and several Westinghouse systems provide a static tie-line flow model. Several systems now being developed will provide system reliability analysis.

For the other two areas of control, emergency and restorative, little if anything has been done. However, I feel the progress made by the industry, as just pointed out over the last three or four years, is very commendable. This brings me to two questions.

The author points out that the development of the proposed control system will require five years. My question is, does he feel it is better to develop this ultimate control system immediately rather than use the step-by-step development, as has been done to date? I personally feel that the step-by-step development is safer, but it may require a longer time delay than the immediate development.

The author also states that the programming required will be performed by CEI. My question is, aren't there definite economies available by using, where possible, programs developed by the computer supplier?

Manuscript received August 2, 1966.

**H. J. Sutton** (Gulf States Utilities Company, Beaumont, Texas): The author is to be commended for this paper. The paper is rather hard reading because a full understanding of the implications requires a comprehensive understanding of system operations and a working knowledge of computers.

A first impression might be that the author is unrealistic, but when I think of how we are using a computer in connection with our analog load control system for economic dispatching and how this scheme takes into consideration line losses as well as incremental generating cost in loading up our system, together with other information which is made available hourly, Mr. Dy Liacco's proposed control system appears to be just a more comprehensive system. When we think that our systems are doubling at the present rate it is not too soon to be thinking of the hardware and software that will be required to handle the systems which we expect to exist within ten years.

Manuscript received August 10, 1966.

**T. E. Dy Liacco**: I thank all the discussers for their encouraging words of commendation and for their perceptive discussions of my paper. Their comments attest to the growing recognition in the utility, manufacturing, and educational fields of the need for solving the system operating problem described in the paper. Each discusser dwells upon different facets of the problem and yet in the overall it is gratifying to realize how well the discussions add emphasis and perspective to the structure of the ARCS design. Mr. Linders' discussion is particularly helpful in establishing the background and the context in which the need for a total control system should be viewed.

One of the purposes of the paper was to identify special problem areas so as to motivate further study by research-oriented groups and by educational institutions. Thus it is particularly gratifying to take note of Professor Barnes' positive reaction to the paper as a suitable reference for evoking student interest in power system problems. Professor Mitter's observations on the multi-level concept and on approaches to the problem of nonlinear optimization, stability, and system security are indicative of the type of contributions that the industry can look forward to from the universities. The Systems Research Center of Case Institute of Technology has been engaged for some time now in research on the control of large complex systems. Following Professor Mitter's suggestion, the present formulation of the nonlinear program will be compared with the alternative formulation according to Fiacco and McCormick. Both formulations are similar in that the optimization of the objective function subject to constraints is transformed into a problem of unconstrained minimization. However, the Fiacco-McCormick method has definite advantages which would facilitate fast convergence to a solution.

One problem area pointed out in the paper is that of evaluating system security in the preventive state. Mr. Ewart is correct in stating that current reliability methods may also be applied to situations of overload, instability, and substandard voltages. In the paper however, I meant to point out that this approach could lead to a brute force application of probability which would be impractical to implement unless it is modified by experience and knowledge of the specific power system behavior. I also wanted to warn against the application of methods which violate Kirchoff's voltage law. The feasibility of basing decisions on information patterns, as mentioned in the paper, should be studied since the approach offers promise of practical, on-line application. As Professor Mitter suggests in his discussion, it may be possible to formulate the determination of system security as a pattern-recognition problem.

Manuscript received September 19, 1966.

Mr. Smith's question as to the desirability of a step-by-step development is in effect answered in the *Concluding Remarks* section of the paper where it is stated that, "In the course of the project design, intermediate results will become available for manual use even before the control system is in complete service." This development is what Mr. Ewart refers to as being evolutionary. Mr. Sutton has undoubtedly the same thing in mind when he looks at the proposed control system as being just the ultimate development of existing control. As we see it at CEI, the development of the control system over a period of years will be one of continuous development. Initially, the amount of automatic functions will be minimal with the rest of the operating decisions being done manually as they are at present. As results are obtained from the ARCS project the scope of manual operation will be progressively reduced to the ultimate man-machine balance desired.

Mr. Linders directs a fundamental and very important question to the industry in general as to how a project such as ARCS may be effectively carried out. The same question would apply to other endeavors whose scope and concepts are new to a utility in the sense that they do not clearly fall within traditional areas of responsibility and work assignments. The answer, of course, is as Mr. Linders points out—"a major revision of classical items of responsibility and division of labor." This could be accomplished overnight, such as for example, the creation of a research-oriented entity within the utility, or come about as an evolutionary process. It seems to be Mr. Linders concern, which I share, that although no successful organization is static, changes by evolution may not be fast enough for the demands of present and future power system problems. At CEI, the planning of a system for reliability has been a function of the System Planning Department. Historically, a system one-line diagram is planned to be operable within a given set of conditions and provided prescribed automatic functions are carried out as part of the plan. As mentioned in the paper, the automatic functions required for the reliable operation of the system are in a state of change. Thus, the system planning function should in itself evolve, recognizing the changes in reliability requirements and in emphasis on automation.

At CEI, the responsibility and leadership for the ARCS project lies within the system planning function. However, the ARCS design is a system engineering problem and as such can not be worked out from the narrow field of any given specialty but rather as a team effort of various specialists. The present ARCS team as constituted possesses a collective background in: power system planning, protection, control, and operation; communications; systems engineering; mathematical programming; and modern control theory. An aspect of the problem raised by Mr. Linders is that granted that talent is available, how is the team going to carry out its task? We still have difficulties at CEI in this regard, the main reason being that the specialists qualified for contributing to ARCS are also those with other high-priority assignments. This is a manpower problem that is gradually being rectified.

Mr. Ewart wonders about the Essential Load Protection function which combines underfrequency with undervoltage or other conditions. Coordination within the interconnection is definitely required. Basic to load shedding is the idea that load should be automatically dropped in the area where there is a deficiency in generation. This could be required on a total system basis in which case the necessary information should be coupled with the underfrequency condition; or on an area basis in which case an undervoltage situation could be used with underfrequency. The undervoltage setting could, of course, be set at 100 percent if this control is not desired for a specific installation.

With regard to Mr. Smith's question on the development of computer software; CEI will establish the algorithms, the program specifications, and at least the initial flow charts. The actual coding and debugging may be done jointly with the computer supplier. In fact, the computer supplier will have to be available on a continuous consultation basis. There may of course be economies by using programs developed by the supplier. However, because of the need to adapt such general-purpose programs to the specific needs of the ARCS design there might still be a lot of work required on the part of CEI's specialists.

# Design of the First 500-kV Substations on the Southern California Edison Company System

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*Abstract*—**The design of two new 500-kV substations has been completed and is discussed in this paper. The discussion of the design covers first a description of the 500-kV grid of transmission lines and substations that will serve as a support for the existing 220-kV system. Following the description of the new system is a discussion of the substation design criteria. The areas covered are insulation coordination, line and bus arrangement, bus conductor selection, and equipment requirements. The paper concludes with a description of the stations.**

Paper 31 TP 66-102, recommended and approved by the Substations Committee of the IEEE Power Group for presentation at the IEEE Winter Power Meeting, New York, N. Y., January 30–February 4, 1966. Manuscript submitted October 29, 1965, revised May 2, 1966; made available for printing July 14, 1966.

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SIGNIFICANT advances have been made in the development of 500-kV technology in the United States in the past three years. The Southern California Edison Company has been a participant in this development and has completed the design for an initial 500-kV system. Previously published information on the Southern California Edison 500-kV system has included general information on substation design. Since the substation design is complete and construction is in progress, it can now be discussed in detail. This paper covers the planned 500-kV system as related to the substations, followed by an analysis of the substation design criteria and a description of the substation facilities.