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Hierarchical System Theory and Electric Power Systems

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SUMMARY

Hierarchical, multilevel control theory is a rapidly expanding but still immature field. In some respects, the theory is actually "behind" practice as many "newly developed" concepts of hierarchical, multilevel theory are already being used in electric power systems. However, an understanding of hierarchical concepts, as they exist at present, can help to clarify some of the many possible trade-offs in the control and operation of electric power systems. Furthermore, the available theory can be directly applied to some existing problems and hopefully the class of applications will expand as the theory itself expands.

In this paper, we will discuss some of the basic aspects of hierarchical systems, namely

(1) types of decomposition,
(2) control structures,
(3) information structures, and
(4) data flow.

These basic ideas will be related to a limited class of bulk electric power problems associated with real-time control (computer and operator) for economic and reliable operation. No attempt will be made to survey all available theory and power applications, or to give detailed mathematical results and descriptions of specific applications.

1. INTRODUCTION

Most complex systems consist of many interacting subsystems. Due to economic, political and social constraints as well as consideration of complexity and reliability, some "decomposition" of the over-all system to achieve "decentralized" control is almost mandatory. Hierarchical system theory deals with problems associated with such a decomposition and the resulting need for coordination between the many individual controllers.

From a hierarchical system theorist's point of view, electric power systems are perfect examples of applications of the theory. However, the electric power system of today has evolved to its present stage on the basis of need and good engineering practice and was not really conscientiously designed using hierarchical theory. In fact, in some respects, the theory is still trying to catch up with practice. Nevertheless, an understanding of hierarchical theory can clarify many of the trade-offs that are possible in electric power system control and operation and can point out new applications of practical value. In this paper, we attempt to provide such understanding. In the interest of keeping the length of the paper within reason, we discuss only general aspects of hierarchical theory without including mathematical details. We should also emphasize that there is no widely accepted definition of what hierarchical system theory really is. Hierarchical theory is sometimes considered to include only decentralized optimization techniques for a deterministic situation but we are taking a broader point of view which also includes uncertainty and information concepts.

Because electric power systems have a multifaceted character, we are forced to confine our discussions to limited aspects of the over-all system. We have chosen to concentrate on electric bulk power system problems associated with the real-time control for economic and reliable operation. We will consider "system levels" ranging from individual power plants and substations up to an interconnected system. We will concentrate on problems associated with system response times varying from about one second to several hours.

Hierarchical system theory can in principle deal with both competitive and cooperative situations. Since we are concerned with interconnected power systems we have a cooperative situation in mind. In a cooperative situation there may be a single goal or many goals. For an interconnected power system we are really in a single goal situation, *viz.* to satisfy customer demands at lowest cost subject to the system being sufficiently reliable. However, since a certain amount of decentralization is mandatory for an interconnected power system, the goals of the individual subsystems may be somewhat conflicting. A certain amount of conflict may also be introduced by decomposition.

This paper is divided into seven sections. In §2 we discuss three different ways in which a system can be decomposed: by level, by time and by mode. In §3 we consider the concept of information structure. In §4 we discuss the "main" problem of this paper: coordination of "decentralized" controllers which control the individual subsystems of the decomposed system. In §5 the problems of data flow, routing and coding are considered. Section 6 is concerned with trade-offs in the design of hierarchical systems. Section 7 contains a brief summary.

2. DECOMPOSITION

Decomposition is a key concept in hierarchical theory and there are many types of decomposition depending on the system and problem of interest. Three types of decomposition are considered in this paper:

Level decomposition
Time decomposition
Mode decomposition

These appear to us to be the most important decompositions relative to electric power systems but other possibilities do exist, *e.g.* it is possible to decompose the control function into automatic and human control. We will discuss these three levels primarily by use of examples. Precise scientific definitions will not be attempted.

2.1 *Level decomposition*

Decomposition of power systems according to level is usually a geographically related or spatial concept. Level decomposition is decentralization as understood in classical economics. It is often motivated by a desire to retain local autonomy as much as possible. An example of a three-level decomposition is:

Level 1: Power plant–substation level
Level 2: Individual system level
Level 3: Interconnected system level

In this case, there may be, for example, one interconnected system level (Level 3) which covers a large geographical area (say 10^6 km^2). Within this single highest level there are many (say 10) individual power systems (Level 2) which cover smaller areas (say, on the average, 10^5 km^2). Within each individual power system there are very many (say 50) individual power plants and substations (Level 1), each of which covers a very small area (effectively a point). Obviously, still higher and lower levels could also be defined. Decomposition by level gives rise to the "pyramidal" structure illustrated in Fig. 1.

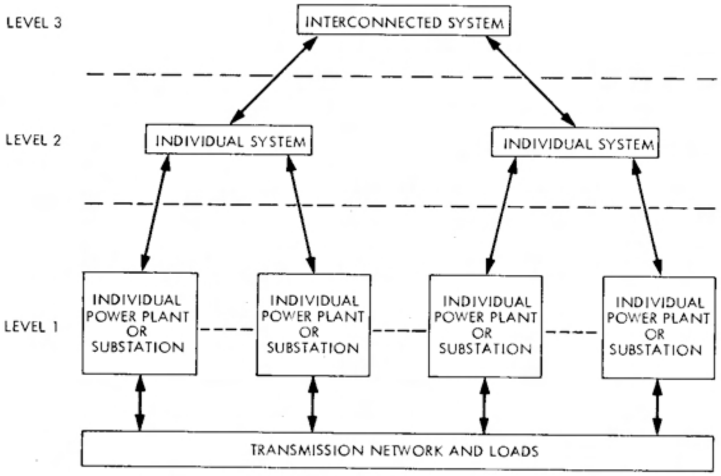

Fig. 1. Level decomposition (pyramidal structure).

Another example of level decomposition for power systems is in terms of the "bulk system" level (generators and EHV transmission networks, 230 kV and above) and the "distribution system" level (138 kV lines and below). However, we are confining our discussion to bulk systems so this type of level decomposition is not discussed further.

2.2 Time decomposition

Decomposition by time arises naturally because of the extremely wide range of response times inherent in an electric power system. Time decomposition is almost always motivated by a desire to subdivide a difficult problem into smaller subproblems.

An example of time decomposition is the control of individual power plants' real output as follows:

Control functions	*Time scale*
Unit commitment	hours
Economic dispatching	minutes
Load-frequency control	many seconds
Governor action	fewer seconds

There are still slower and faster functions than the above time decomposition, *e.g.* "maintenance scheduling" has a time scale of days while "relay action" is faster than governor action. Decomposition in time can be envisaged in terms of the sequential structure shown in Fig. 2.

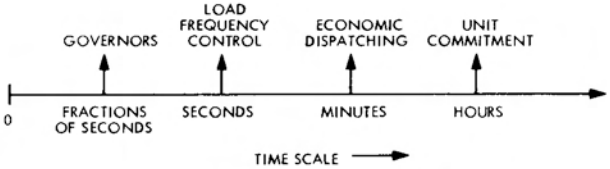

Fig. 2. Time decomposition (sequential structure).

It often happens that control functions at a higher level take place with a slower time scale than control functions at a lower level. An example of this is:

Unit commitment	Interconnected systems level
Economic dispatching Load-frequency control	Individual systems level
Governor action	Individual plant level

This, however, is not a general rule. For example boiler control done at the power plant level can be slower than load-frequency control done at the systems level.

2.3 Mode decomposition[1]

Analysis of system stability, load flow conditions, etc. yields certain "conditions of operation" (in the sense of continuous operation) for the power system. The need for decomposition by mode arises from a need to control the power system in all conditions of operation. Since the control strategies for different conditions of operation are likely to be qualitatively quite different, mode decomposition helps one to subdivide the over-all problem into subproblems dependent on the operating states. For power systems we consider the following mode decomposition:

(1) Normal mode
(2) Preventive mode
(3) Emergency mode
(4) Restorative mode

In the normal operating state the power system is being operated so that the demands of all customers are satisfied at standard frequency and voltage. Moreover the contingencies that are likely to occur in the immediate future are not likely to change the operating state to an emergency mode. An example of a control strategy for the normal mode is:

Keep frequency at approximately 60 Hz
Keep tie-line flow at about schedule
Meet power demand at minimum cost

If a contingency is likely to occur such that the system may not be able to return to the normal mode of operation, then the system goes to the preventive mode of operation. The assumption here is that by taking corrective action in anticipation the system can be made to remain in the normal operating mode. An example of a control strategy for the preventive mode is:

Keep frequency at approximately 60 Hz
Keep tie-line flows at about schedule
Meet power demand at minimum cost subject to constraint
    on amount of spinning reserve

It is possible and often desirable to combine the normal and preventive modes into a single mode.

If a contingency has occurred such that the customer demand cannot be maintained at prescribed voltages and frequencies, then the system goes to the emergency mode of operation. Here economics is completely sacrificed. An example of an emergency mode control strategy is:

Try to keep frequency at approximately 60 Hz
Maximize the amount of demand being met

Once the system has gone into emergency mode (*i.e.* a contingency has occurred) then the system has to be brought back to the normal or preventive operating mode via the restorative operating mode. The mode decompositions and mode transitions are shown diagrammatically in Fig. 3.

Note that decomposition by mode does not have a pyramidal structure as in level decomposition nor a sequential structure as in time decomposition. In general, mode decomposition has no correlation with time and level decomposition.

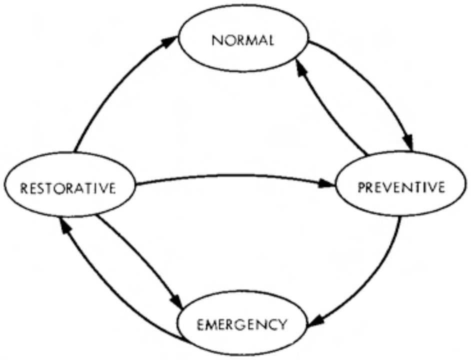

Fig. 3. Mode decomposition (interactive structure).

2.4 *Amount of decomposition*

The "amount" of mode decomposition is specified (by our definition). However, the amount of decomposition by level (*i.e.* number of levels and subsystems within each level) and time (*i.e.* number of time intervals) has not been specified. We will briefly discuss this subject because the choice of amount of level and time decomposition has a major effect on the over-all hierarchical system performance.

A fully integrated system is the limiting case where there is no level or time decomposition. For example, in a fully integrated system, instantaneous valve openings at the individual power plants would be determined at the interconnected system level by a computer program which explicitly considered unit commitment problems when computing turbine valve commands. Such a fully integrated system is not desirable (as it is not needed). Obviously, the other extreme of too many levels and time intervals is also undesirable.

There are many "natural" constraints on the choice of amount of decomposition. Level decomposition cannot ignore existing political, social and ownership conditions. The maximum amount of time decomposition is dictated by the natural response characteristics of the power system itself. Unfortunately we know no general rules for choosing from the various possibilities that lie within these constraints. All we can say is that the amount of time and level decomposition is one of the important trade-offs (see discussions in §6).

3. INFORMATION STRUCTURE

Consider a system which has been decomposed (by level, time or mode) into various subsystems. Each of these subsystems will have a certain "amount" of information of different "types" available to it for its decision-making process. The term "information structure of the hierarchical system" refers to both (1) the amount and type of information available to individual subsystems, and (2) the degree of coordination of information. In order to clarify these general ideas, we begin in §3.1 by considering "types of information". In §3.2 and §3.3 we then discuss the concepts of "amount of information" and "degree of information structure coordination". In §3.4 we point out the difference between usable information and inherently available information. Finally, in §3.5 we briefly discuss sources of information.

The term "information" is used here in a general sense with only limited correspondence to the formal mathematical definition used in communication–information theory.

3.1 Types of information

There are two basic types of information we will consider:

(1) Numerical values:
    system parameters
    state variables
(2) System structures.

After discussing these two types, we will consider the use of equivalents.

Numerical values of system parameters and state variables (and other variables) can be obtained either by direct observation or by estimation. Direct observation is essentially as its name implies—actual values that are the result of direct observation. For example, a watt meter provides a direct measurement of the real power flow on a transmission line. The "name plate" data for a generator provides a direct observation on inertia, etc. Estimation is a more general concept that involves the use of one or several direct observations to compute an estimate of the desired actual values. Such estimation can take many forms. For example, the real power flow on a given line can be estimated from direct measurements made by watt, var and volt meters located elsewhere on the transmission system. Future load demand can be estimated (predicted) by using past and present direct measurements. Response "time constants" of a boiler–turbine system can be estimated (identified) by using observations on how the system actually responds to inputs.

The second type of information is information on the structure of the power system. For example, the specification of a transmission network graph and the assumption of a "pi equivalent" for each transmission line constitutes a structural model (the values of the impedances are "actual values" and not part of the structural model). A special case of a structural model is structural information about the control strategies being used in different parts of the power system. Information on system structure is usually obtained by analysis (which can be viewed as a type of direct observation). However, it is also possible to obtain some information on system structure by estimation techniques using measured data.

It is important not to confuse the concept of the "information structure of the hierarchical system" with "information on the structure of the power system". One type of information in the "information structure" is "information on the power system structure".

The concept of an equivalent is very important when considering information on parameter-variable values and structures. Consider the level decomposition of

Fig. 1. It could be desired that each of the individual systems (Level 2) has equivalent models for the effect of the interconnected system as "seen by looking out through" the tie lines. Examples of equivalents are:

(1) network equivalents,

(2) spinning reserve equivalents (no dynamics),

(3) dynamic spinning reserve equivalents (effect on average system frequency behavior following major loss of generation) and

(4) transient stability equivalents.

3.2 Amount of information: uncertainty

As mentioned earlier, we are not using a formal mathematical definition of information so we have no quantitative measure of amount of information. However, in a general qualitative sense, the amount of information available is inversely related to the amount of uncertainty associated with the parameter-variable values and the system structure.

The amount of uncertainty can be measured by use of probabilistic–stochastic models or by use of unknown but bounded (set theoretical) models. Some possible approaches are briefly summarized in Fig. 4.

	Uncertainty in Parameter Values	Uncertainty in Structure
Probabilistic–Stochastic Model	Random vector with specific mean and covariance matrix	Hypothesize extra uncertain input modeled as stochastic process
Unknown but Bounded–Set Theoretic Model	Values lie within some set such as $2 \le x \le 4$	Hypothesize extra uncertain input modeled as unknown but bounded process; i.e. $2 \le x(t) \le 4$ all t

Fig. 4. Examples of modelling uncertainty.

In practice, models as in Fig. 4 for the uncertainty are usually not available. Often power system decisions treat (explicitly) values and structures as if they are exact and the uncertainty is ignored. This can be satisfactory if the actual uncertainty is small and its effect is implicitly considered when decisions are made. However, the uncertainty itself is always there and can have a major influence on the over-all performance. In the design of hierarchical systems, the amount of information available (*i.e.* the amount of uncertainty) is often a key and sometimes a limiting factor.

The use of the term "equivalent" in §3.1 is unfortunate as, except in rare cases, an equivalent is not truly equivalent. An equivalent such as one of the four examples of §3.1 usually introduces some uncertainty in addition to that in the complete representation itself. Sometimes this uncertainty can be completely neglected. However, in some cases the uncertainty can dominate even to the extent that the entire equivalent consists only of a model for the uncertainty. For example, one possible transient stability equivalent could consist only of false generators at each of the tie lines when the generator's real and reactive outputs are modelled by an uncertain process, either stochastic or unknown but bounded. Even when better (*i.e.* less uncertain) equivalents are available, the use of such uncertain equivalents can result in a major simplification in the computation and communication costs.

3.3 Degree of information structure coordination

Thus far we have discussed individual subsystem information structures, *i.e.* the type and amount of information available to the individual subsystems. The total amount of information in the whole system is the "sum" of the information available to all the subsystems. We now consider the "degree of information structure coordination" which determines how much of the total information is available to the individual subsystems.

Consider level decomposition as in Fig. 1. Each level and each subsystem at a given level has its own individual information structure. For example, if there is one subsystem at Level 3, 10 at Level 2 and 50 at Level 1 for each at Level 2, then there are $1 + 10 + (10)(50) = 511$ individual information structures. The information structure of the over-all system is said to be completely coordinated if all 511 individual information structures are the same, so that "everybody knows everything anybody else knows". The system information structure is completely uncoordinated if all 511 individual information structures are different. In general completely uncoordinated information structures cannot happen if the power system itself is interconnected. Even if there is no data flow between subsystems (see §5), the same power system is still "observed" and this provides some degree of information structure coordination.

The degree of information structure coordination must be viewed relative to the type of decision being made. For example, an almost completely coordinated information structure might exist for economic dispatch while the information structure might be completely uncoordinated relative to spinning reserve contingency evaluation.

The concept of equivalents is important when evaluating the degree of information structure coordination. For example, consider the problem of information (structure and values) on the network of the interconnected system. A completely coordinated information structure (relative to this problem) could exist if each individual power system (Level 2 of Fig. 1) had an equivalent impedance matrix looking out through its tie lines; complete detailed knowledge of the whole network is not required.

It is important not to confuse the concept of amount of information (*i.e.* degree of uncertainty) with the degree of information structure coordination. An increase in coordination will decrease the uncertainty but even a completely coordinated information structure could have a lot of uncertainty (*i.e.* a small amount of information).

3.4 Inherent versus *usable information*

There is an important difference between inherent information and the information that is actually usable.

Consider a transmission network with watt, var and volt meters on some but not all busses and lines. As a first example, consider a transmission line whose real power flow is not metered. The other metered values might be sufficient to allow the unmetered flow to be estimated so that information on the unmetered flow is inherently available. However, if the estimation is not done, this inherent information is not considered to be in a usable form. As a second example, assume the over-all network is an interconnected system containing many individual systems (decomposition by level). Assume each individual system has complete data on the structure and impedance parameter values of the whole interconnected network which could be used to compute an equivalent impedance network "looking out" from its tie-line interconnections. If some such computation is not made, the inherent information available in the network data is not considered to be in a usable form. As a third example, consider the same interconnected system but now assume data on the structure and impedance values of the whole network are not available to the individual systems. It is conceptually possible for one individual system to compute an estimate of an equivalent impedance network "looking out" by using just its own meter readings taken over a period of time when sufficient changes in tie-line flows have occurred. The inherent information available in these meter readings, of course, may not be used[3].

The earlier discussions on amount of information (uncertainty) and degree of information structure coordination have referred to the usable information rather than the information that is inherently available. Thus an information structure can be greatly changed by introducing extra computation facilities to convert inherent information into usable information.

3.5 Sources of information

Consider one subsystem of a system decomposed by level. Two sources of information for this subsystem are

(1) measurements made by the subsystem itself, and

(2) information externally transferred to it from other subsystems by a communication system.

These ideas are implicitly implied in the preceding discussions. We repeat them here to emphasize an important point. Even if there is no external information transfer by a communication system from other subsystems, the measurements made by the subsystem on itself provide some inherent information about the other subsystems because all the subsystems are interconnected. Of course this inherent information may not be converted into usable information but it is always there.

4. COORDINATION*

Thus far we have discussed decomposition and information structures. We now

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* The concept of coordination has been considered by Mesarovic *et al.*[2] Their view is somewhat different in the sense that the role of information and information structure is not given the emphasis that we give it here.

discuss the main problem of interest: coordination (or coordination of control). Assume that for a given decomposition (by level, mode or time) the individual subsystems are controlled in a decentralized manner, so that each subsystem controller acts to some degree in an independent manner. The basic problem is to provide some degree of coordination between the decisions of these individual controllers.

4.1 Types of coordination

Two ways of improving the coordination between individual subsystem controllers are

(1) to increase the degree of information structure coordination, and

(2) to give one subsystem controller "superior" status so that it "coordinates" to some degree the other subsystem controllers.

As long as the individual subsystem controllers have a common goal, an increase in degree of information structure coordination will improve over-all performance. A prime example of a superior subsystem is in level decomposition where (Fig. 1) Level 3 (the interconnected system) assumes partial responsibility for coordinating the Level 2 (individual systems) controllers by furnishing them direct commands, goals or constraints. Examples of possible Level 3 coordination are when Level 3 tells one of the individual systems at Level 2 to

(1) increase base load generation by 500 MW (a direct command);

(2) increase base load generation by at least 400 MW but not more than 600 MW (a constraint);

(3) attempt to reach and maintain an increased base load generation of 500 MW (a goal).

Note that the concept of a superior controller furnishing goals or constraints to other subsystem controllers can be viewed as the transfer of another type of information that was not discussed in §3.1.

We now look at the coordination process in a little greater detail by considering Figs. 5–7. Let us consider level decomposition. Figure 5 represents the complete interconnected system. We now assume that the system has been decomposed by level and we consider two subsystems of the decomposed system and their control (Fig. 6). The final process of coordination is shown schematically in Fig. 7.

Figures 5–7 are for level decomposition but the same ideas hold for time decomposition.

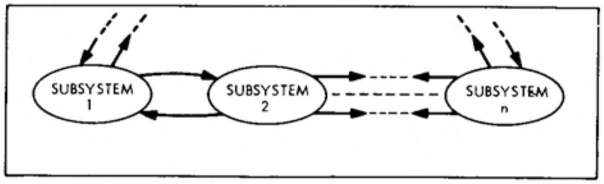


Fig. 5. Interconnected system.

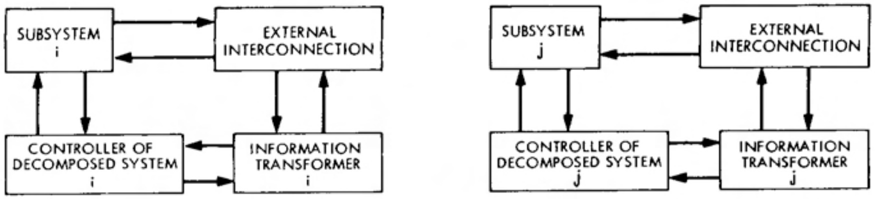


Fig. 6. Controllers of level decomposed subsystems.

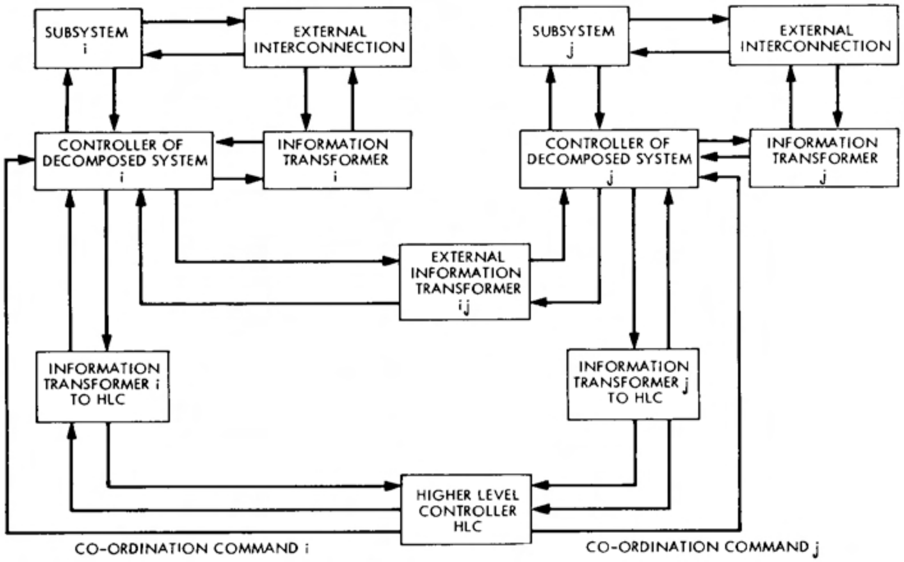


Fig. 7. Coordination.

4.2 *Measures of coordination*

Coordination can be measured on a scale of zero to full coordination. Consider the situation of Fig. 6. Assume that the information transfer ratio is zero (*i.e.* open circuit) and the external information transformer ratios are all zero in Fig. 7. This corresponds to *zero coordination.* The two subsystems are being controlled in a completely decentralized manner. Zero coordination is in general unattainable (unless the two levels physically separate) since by observing one subsystem we necessarily obtain some information on the external interconnection. Assume that the system has not been decomposed and is being controlled optimally relative to a single goal. We shall refer to this as the *fully integrated control system.* A *fully coordinated* system is a decomposed system whose subsystems are being controlled and the subsystem controllers coordinated in such a manner as to achieve a performance equal to that of the fully integrated control system.

From the point of view of reliability, complexity, etc., it is desirable to have a fully coordinated control system as opposed to a fully integrated control system (see also discussion in §6).

We should also point out the relationship between coordination as discussed here and information structure coordination. These are different concepts as

(1) a fully coordinated control system has a completely coordinated information structure, but

(2) a system with a completely coordinated information structure is not necessarily fully coordinated (if, for example, the individual subsystems do not have a common goal).

In the case of mode decomposition full coordination corresponds to a sequence of control actions whereby the system is brought back from the emergency mode to the normal mode in minimum time and zero coordination corresponds to the situation where the system operates in the various modes in an independent fashion and no coordinating action is taken.

4.3 An example: dynamic economic dispatching problem

To illustrate the concept of coordination we consider the dynamic economic dispatching problem for an interconnected system. The general problem may be posed as follows. Given the predicted uncertain dynamic load demands on two individual systems (of Fig. 1), schedule the dynamic generation patterns of each individual system and the power interchange program (including the pricing) such that the over-all demand is met at minimum cost (the cost function being an integral over one day) subject to the network and other dynamic constraints being satisfied. Thus the general economic dispatching problem is a dynamic optimization problem.

The steps in the solution of the problem by decomposition and coordination will now be indicated. We first apply *level decomposition* to decompose the over-all problem into two decentralized dynamic economic dispatching problems (one for each individual system) by fixing the interchange of power and the price mechanism.

Assuming the dynamic decentralized economic dispatching problems can be solved for a given level of interchange and given price mechanism, the *coordination problem* is to find the optimal price mechanism so that the system is guided towards the over-all optimum. The coordination in this case can be made either by information transfer between the two controllers or by means of a "superior" controller (at Level 3 of Fig. 1).

The dynamic decentralized economic dispatching problem is then further decomposed by applying time decomposition. The solution is divided into four parts:

Control function	*Time scale*
Unit commitment	hours
Economic dispatching problems	minutes
Load-frequency control	seconds
Governor action	fewer seconds

The basic coordination problem here is:

(1) to make sure that the unit commitment leads to feasible economic dispatching solutions;

(2) to update the unit commitment so that an improved solution to the dynamic dispatching problem can be obtained; and

(3) load-frequency control and governor action should attempt to maintain the optimal plant loading and also to maintain tie-line schedule and system frequency.

Finally, with regard to mode decomposition, in the emergency mode economics is sacrificed and one tries to obtain the maximum load solution subject to the system constraints being met. The coordination problem is to bring the system back to the normal mode using a dynamic restoration procedure in minimum time without violating constraints.

5. DATA FLOW

A decomposed system usually involves extensive data flow between the individual subsystems. This data flow can consist of direct commands, goals, constraints, direct measurements, estimated values, structural models, equivalents, etc. We will now briefly consider two aspects of this data flow question: (1) routing, and (2) coding.

To illustrate the routing problem, assume information is to be transferred between the individual systems of Level 2 of Fig. 1 so that they can make independent decisions. Two extreme methods of routing this information are:

(1) Pair-wise information exchange: the individual systems exchange information directly and independently with each other;

(2) Information exchange center: all information is channelled into and out of a central facility.

These two extremes are illustrated in Figs. 8(a) and (b). The information exchange center can perform a variety of tasks, such as:

(1) provide buffer storage as needed,

(2) assign message priorities,

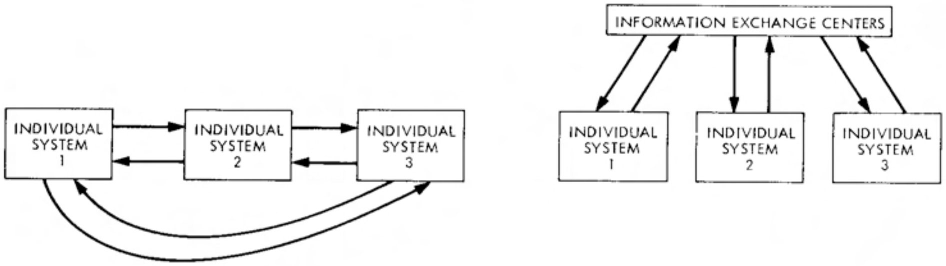
(3) adjust data format to be compatible with individual systems' computers,

(4) maintain updated data files which can be accessed by individual systems, and

(5) convert the data in the data file into a form requested (needed) by an individual system (*e.g.* computed network equivalents).

Such tasks can be very important from a practical implementation point of view. However, by assumption in this discussion, the resulting information structure (uncertainty and degree of coordination) is the same for both Fig. 8(a) and Fig. 8(b) so data routing does not affect information structure.

In Fig. 8(b) the information exchange center can be viewed as a Level 3 (interconnected system) in Fig. 1. However, in this example it is being assumed that the individual systems are making independent decisions so, in Fig. 8(b), the infor-



(a) PAIRWISE INFORMATION EXCHANGE

(b) INFORMATION EXCHANGE CENTER

Fig. 8. Two methods of routing data flow between individual systems.

mation exchange center (at Level 3) is improving the degree of information structure coordination; it is not involved in decision making. From a conceptual point of view, it is important to emphasize the difference between higher level decision making and a higher level information exchange center which is simply one way of routing the data flow.

The preceding routing discussion points out the important point that a system may be decomposed one way relative to decision making and a different way relative to data flow.

The data flowing between, for example, the individual systems as in Fig. 8 can be "coded" in various ways. For example, instead of exchanging complete short-range load forecasts for every hour of a 24-hour day, the forecasted curve can be coded (parameterized) by a few parameters (such as Fourier coefficients). In this example, as in almost all cases, coding is simply a way of reducing the amount of data to be exchanged without appreciably affecting the information structure. In many cases there is no difference between the concept of equivalents and the concept of coding the information to simplify the data flow. In fact one of the main reasons for the discussion of the coding concept is to point out its close correspondence with the concept of equivalents.

The discussions on routing and coding of data flow have used level decomposition to illustrate the ideas. However, the ideas also apply to time and mode decomposition.

Since routing and coding problems do not affect the information structure or the actual decision-making process, data flow is not a "basic" aspect of hierarchical system theory. The main reason we have discussed it is because the choice of a data routing procedure and methods of coding can have a strong influence on the costs and reliability of the over-all system.

6. TRADE-OFFS IN DESIGN OF HIERARCHICAL SYSTEMS

Thus far we have discussed decomposition, coordination, information structure and data flow. The various possible combinations of these ideas lead to an almost infinite range of possible hierarchical systems. Since the "optimum" hierarchical

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system is strongly dependent on the nature, needs and existing structure of the particular power system of interest, we concentrate only on the nature of the many trade-offs which must be considered.

The amount and type of level and time decomposition strongly influence the trade-off problem. However, we will assume these decompositions to be already fixed. For simplicity we will restrict discussion to level decomposition.

The discussion will consider only coordination and information structure trade-offs. Data flow problems are important in terms of cost and reliability but can, to some extent at least, be decoupled from coordination and information structure considerations.

One way to view the over-all trade-off problem is in terms of

(1) amount of coordination,
(2) amount of information in the information structure, and
(3) degree of information structure coordination.

All other things being equal, an increase in any of these three factors results in improved system performance. However, such increases cost money and the area which yields the most return per dollar spent depends heavily on the particular problem under consideration.

The reliability issue must also be considered. An increase in coordination or degree of information structure coordination is often obtained by some sort of centralization of facilities (such as a higher level controller or a regional information exchange center). Such centralization may increase performance but decrease reliability in the sense that the over-all system becomes vulnerable to the loss of the centralized facilities. An increase in coordination or degree of information structure coordination also usually implies an increase in complexity (computers talking to computers, etc.). A basic rule is that "complexity causes trouble" so as much simplicity as possible is desired.

A combination of cost and reliability arguments leads to the one general rule of hierarchical system design that we are willing to state.

> Minimize the amount of coordination and information structure coordination subject to the constraint that system performance is satisfactory.

Admittedly this rule is not quantitative. It is just a statement of a goal of good engineering design.

Another type of trade-off is between communication and computation costs. For example, it is possible to concentrate most of the computing capabilities at the highest level (the interconnected system). This requires extensive communication but prevents unnecessary duplication of computing facilities at the lower levels (say the individual systems). Another example is the difference between inherent available information and usable information as discussed in §3.4. The amount of information in the information structure can be increased by communication between levels or by increasing computation to convert more inherent information into usable information.

As an example of the complexities of these trade-offs, consider the problem of trying to use turbine valve openings and/or excitors to damp small amplitude, low frequency (2–10 second period) but long lasting system oscillations. For simplicity of discussion, we will naively assume there is only one individual system at Level 2 in Fig. 1 and concentrate on the interaction between the one Level 2 decision maker and the many individual power plants at Level 1. Three of many possible approaches to this problem are as follows.

(1) Central Direct Control: Level 2 receives all information available from Level 1. Level 2 sends direct commands to the individual turbine valves and excitors. Level 1 makes no decisions. This is a fully integrated control system with no decomposition.

(2) Central Supervisory Control: Level 2 receives some of the information available from Level 1. Level 2 identifies (estimates) the nature of the oscillation and then adjusts the Level 1 controller (governors, voltage regulators) by specifying the gains, time constants, etc. to be used. The Level 1 controller remains in direct control.

(3) Adaptive Local Control: Level 2 plays no role. There is no data flow between the individual Level 1 controllers. Each individual power plant at Level 1 adapts its own control laws (gains, time constants, etc.) depending on an identification of the nature of the oscillations made by direct measurements available at the power plant.

Central Direct Control is very expensive and complex to implement and is unreliable in that it is very vulnerable to the loss of the Level 2 controller. Note that, even when in operation, Central Direct Control is not guaranteed to work because the amount of information (structure and parameter-variable values) on what is actually causing the oscillations may be relatively small (large uncertainty). Adaptive Local Control involves no data flow between subsystems but still has some degree of coordination and information structure coordination because of the identification (estimation) done at the individual power plants. Adaptive Local Control is most reliable in that it involves no central facility. Both Adaptive Local Control and Central Supervisory Control involve adjusting the gain, time constants, etc. of the governors and voltage regulators; they simply use different information structures. The cost trade-offs between Central Supervisory and Local Adaptive Control are not obvious as Adaptive Local Control requires many individual small computer systems while Central Supervisory Control requires a communication system and one relatively large computer. The choice between these three approaches (and there are many other reasonable approaches) is not clear. However, using the general rule of minimizing coordination as much as possible, Adaptive Local Control is most desirable *if* it proves to be effective. If Adaptive Local Control cannot do the job, Central Supervisory Control is the next most desirable. Central Direct Control should be attempted only as a last resort. A final possibility, not yet mentioned, is to design the system (including voltage regulator and governor gains, time constants, etc.) so that oscillations are never important. This is the ultimate as far as minimizing control costs and maximizing reliability but the best way of doing this that we know is to increase the capability of the transmission system. This is very expensive.

7. SUMMARY AND CONCLUSIONS

In this paper we have discussed various concepts of hierarchical multilevel system theory and illustrated these concepts by considering the real-time control of bulk power systems for economic and reliable operation. We have shown how decomposition according to level, time and mode is a natural way to decompose the complex task of controlling an interconnected power system. We have then discussed the concepts of information and information structure. The concept of coordination was introduced and we discussed a scale of measurement for coordination. The relationship that necessarily exists between information structure and coordination (a concept different from that of information) was investigated. We then discussed data flow within the decomposed system. The final section was devoted to various trade-off considerations.

The goal of this paper has been to provide a general understanding of hierarchical system theory (as we view it) and its relationship to selected aspects of the real-time control of bulk electric power systems. The most important single point of the paper is that there are a huge number of possible trade-offs which must be considered before choosing a final design.

Hierarchical system theory is in its infancy. We hope that the concepts discussed in this paper and illustrated with reference to the real-time control of an interconnected power system will be useful in the future development of the theory.

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Discussion

H. Glavitsch (*Brown, Boveri & Co. Ltd., Baden, Switzerland*)

I was a little bit surprised that the authors attached a measure of quality to the centralized computer as far as reliability goes. In the paper a comparison was made with the conclusion that the reliability is improved when the local adaptive system is used. If we look at this in the framework of hierarchical systems, neither one of the two extreme cases is really hierarchical. In one case we have direct digital control and in the other we have a completely decentralized control with a lot of observation capability. Would you please comment on this because it seems to me a contradiction.

F. C. Schweppe and S. K. Mitter

The term reliability was used in a general sense to emphasize the potential vulnerability of a highly centralized control system to the loss of the highest level controller, and to emphasize the authors' opinion that the best answer is the simplest answer that works. The term was not meant to correspond directly to "power system reliability" as this expression is usually used, although there is obviously a relationship between the reliability of the hierarchical control structure and that of the power system itself.

In the example, three types of configurations were discussed:

(1) Central Direct Control,
(2) Central Supervisory Control, and
(3) Adaptive Local Control.

Central Direct Control is, indeed, direct rather than hierarchical control and was included only to reference the extreme case. However, the question of whether Adaptive Local Control is a hierarchical system is a matter of viewpoint. We consider it to be hierarchical because of the information coordination which results from processing observations from a common system. From our point of view, Adaptive Local Control is not completely decentralized, even though there is no external data flow between the controllers.

C. J. EAGLEN (*Brown, Boveri & Co. Ltd., Baden, Switzerland*)

How do the ideas of multilevel control cater for batch and continuous systems?

Decomposition and allocation of control functions is to my mind necessary to realize real-time solution to an optimal control problem. How do the authors propose that the local optimization and decomposition can be structured to realize this?

What dissimilarity may exist between the processes at a level? If only a small dissimilarity may exist we may have too many levels.

F. C. SCHWEPPE AND S. K. MITTER

It is not possible to answer the questions raised by Dr. Eaglen adequately within the scope of this discussion. However, the following points can be made:

(i) There is no general theory of hierarchical systems, and we tried to stress this in our paper. Each case has to be looked at individually, although there are classes of problems in mathematical programming where some theory exists. Dr. Eaglen is trying to pose questions which are too general and, as such, ill-posed —at least in the present state of development of the theory.

(ii) The ideas of multilevel control are applicable to both batch (discrete-time) and continuous systems.

(iii) Dr. Eaglen is quite correct in stating that decomposition and allocation of control function is necessary to realize real-time solution to an optimal control problem. However, it should be pointed out that multilevel hierarchical system theory is not just a tool for solving optimal control problems. In fact, it is the authors' belief that far too much emphasis has been placed on optimality. In complex systems problems there usually does not exist a *single* optimality criterion.