A SYSTEM APPROACH TO THE DESIGN OF AN INTEGRATED MICROPROCESSOR BASED SUBSTATION CONTROL AND PROTECTION SYSTEM

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Abstract. This paper is concerned with a system design of an Integrated Substation Control and Protection System. An analysis of functional requirements is performed first. The multilevel, hierarchical system representation concept is used as an analysis tool. As a result of the analysis, system architecture and algorithm requirements are specified next. Then, an allocation of system functions is performed. System interfaces and data flow are also discussed. Finally, a microprocessor-based configuration is proposed.

Keywords. Integrated control and protection; computer relaying; power system control; system analysis; hierarchical systems; computer applications; computer architecture; microprocessors; multiprocessing systems.

INTRODUCTION

The research area of Integrated Substation Control and Protection Systems is in an early development stage. Even though Integrated Systems were proposed in the mid seventies, so far there is only one such a system built and tested (Tanaka and others, 1980). However, several proposals were published recently (Hope, Malik, 1980; Ibrahim and others, 1979), which introduced quite complex functional and architectural system requirements. A need for an efficient design approach is emerging when one is concerned with a detailed design of an Integrated Control and Protection System (Deliyannides, Kezunovic, Schwalenstocker, 1980; Kezunovic, 1980).

This paper is concerned with a system approach to the design of an Integrated Substation Control and Protection System. The substation system is analysed using basic concepts of the Theory of Hierarchical, Multilevel Systems (Mesarovic and others, 1970; Schweppe, Mitter, 1972). These concepts are applied to perform classification of system functional requirements. As a result of the performed analysis, some inherent characteristics of system architecture and algorithms can be identified. A distributed processing, microprocessor-based system architecture is proposed.

SYSTEM FUNCTIONAL REQUIREMENTS

An analysis of system functional requirements is performed using theoretical concept of hierarchical levels that can be found in a multilevel control system (Mesarovic and others, 1970; Schweppe, Mitter, 1972). An assumption is made that such a concept can be applied to the Substation Control and Protection System and the following level decomposition is performed:

- levels of description or abstraction,
- levels of decision complexity,
- levels of organization complexity,
- levels of information exchange.

An anlysis of these hierarchical levels has revealed some important relations between various functional requirements.

Levels of Description or Abstraction

Functional relations within the Integrated Substation System are quite complex and it is appropriate to identify levels of detail that can be used in describing system relations. It is belived that a top-down approach can be favorable in this case. The following levels in a top-down approach seem quite convinient: block representation of the overall system, representation of functional relations within the system, representation of actual system architecture, definition of processing levels within the system, software modules, description of algorithms contained within each of the modules. It should be noted that the above levels are listed in the order of the description detail level starting with the overall system block diagram as being the top level (the lest detailed level).

Levels of Decision Complexity

Decision complexity levels are, in the case of a Substation Control and Protection System, related to the following control types:

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- direct control,
- optimizing control,
- adaptive control.

Direct control. A summary of direct control functions is given in Table 1. It should be noted that all of these functions are automatically executed after a particular change is observed in the monitoring variable. Obviously, operator is not directly involved in execution of these functions. However, operator indirectly affects performance of automatic functions becouse the control settings are specified and maintained by the operator.

Optimizing control. It is interesting to note that there are very few optimizing control functions within an Integrated System. These are primarely Voltage and Var Control as well as some dynamic Restoration Switching Sequences. However, local Voltage and Var Control as well as Switching Sequences have to be supervised by a centralized control system. This enables coordination between the optimizing goals of the overall system and the goals of a substation system.

Adaptive control. Most of the adaptive control functions are referred as operator-related functions. These include monitoring and data acquisition functions as well as some post fault analysis and manually initiated functions. A list of adaptive control functions is given in Table 2.

TABLE 1 Direct Control Functions

Direct Control Funct.	Time required for execution						Operat. state			
	ms		s		min		N	A	E	R
Apparatus protection:										
- Transmission Line	x								x	
- Transformer	x								x	
- Bus	x								x	
- Breaker	x								x	
- Reactor	x								x	
Back-up protection		x							x	
Out-of-step protect.		x	x						x	
Tie tripping			x	x					x	
Transfer tripping		x							x	
Fault detection	x							x		
Fault classification	x							x		
Reclosing		x								x
Synchronism checking		x					x			x
Synchronizer closing		x					x			x
Circuit rearrangement		x							x	
Circuit restoration			x							x
Load shedding				x				x		
Generator dropping				x				x		
LTC control			x					x		
Computer system:										
- Failover switching	x								x	
- Automatic restart		x	x						x	
- Self-checking	x	x						x		
- Program initial.		x	x				x	x	x	x
- Power fail. recov.			x							x

TABLE 2 Adaptive Control Functions

Adaptive Control Funct.	Time required for execution			Oper sta	
	ms	s	min	N	A
Application functions:					
- Fault location		x			
- Fault analysis		x	x		
- Monitoring functions		x	x	x	x
- Conventional data acquisition funct.	x	x	x	x	x
- Circuit switching		x		x	x
- Manual operation of breakers, switches, reactors, capacitors		x		x	x
- Contingency evaluat.		x			x
Computer system:					
- Change of settings		x		x	
- Man-machine equipmt. operation		x		x	x
- Maintenance switch.		x	x		
- Testing and diagnst.		x	x		x
- Programs initial.	x	x	x	x	x
- Syinchronization	x	x		x	

It is interesting to note the following c racteristics of the levels of decision co plexity:

- time required for execution,
- operational states.

These characteristics given for the vario control functions are sumarized in Table and Table 2. The two columns designated f each time unit (milliseconds, seconds, an minutes) designate several units if it is left column, and several hundred of units it is a right column. Columns for the ope tional state refer to the Normal State (N Alert State (A), Emergency State (E), and Restorative State (R).

Levels of Organization Complexity

There are at least two organization level within our control system:

- local control level,
- centralized control level.

Local control level. It accomodates numbe control functions which actually perform dependetly. This level is the substation control level as related to the control c substation switchyard equipment. In the c of the computer system, the local control vel is represented by each of the system ssors, including the supporting chips.

The bay control level accomodates a numbe direct control functions which control ci breakers of a particular bay. In some cas local bay direct control functions could tiate an action in some other bays, but t action is independent of the control goal of the other bays. This is the case when a protection function initiates tripping of breakers in the local bay as well as in some adjacent or remote bays. The bay control level also accomodates a number of data acquisition functions as well as a number of monitoring functions. However, some of the bay level functions can be implemented at the centralized level, which depends on the organization strategy of the control system.

Centralized control level. It includes functions that relay on the information about the overall system. In the case of the substation switchyard control, centralized level is responsable for control actions that affect the overall substation. Similarly, for the computer system, centralized level is responsable for supervising all of the processors within the system. In general, centralized control level is also responsable for interfacing of the substation control strategy and the computer system control actions to the outside world.

The substation centralized control level mostly relates to the overall data acquisition and monitoring functions. It also accomodates substation switching actions aimed toward substation sectionalizing, rearrangement, and restoration. Optimizing control functions also belong to the centralized control level. Most of the external interface functions are also located at this level. This is particularly true for the Man-Machine Interface and the Energy Control Center interface. In the case of the computer system, most of the maintenance, testing and switching functions are performed by the centralized control level. A common data base,that is created and used by data acquisition and monitoring functions is also mainteined at the centralized level. Control of the computer system peripheral devices is also performed by this level.

Levels of Information Exchange

The following discussion gives an analysis of levels of information exchange as related to the Substation Control and Protection System. The criteria for classification includes (Schweppe, Mitter, 1972):

- types of information,
- sources of information,
- methods of information transferring.

Types of information. Included are, in general, variables in the form of status, analog, and accumulated values as well as parameters. When these types are converted into digital form, they are either bits, bytes or words. A classification of information can be based on content, which in our case, can be either data or control information content. However, the most interesting content types are based on the kind of processing that is used to generate a particular information item. An example of the data acquisition processing operations is given in Fig. 1.

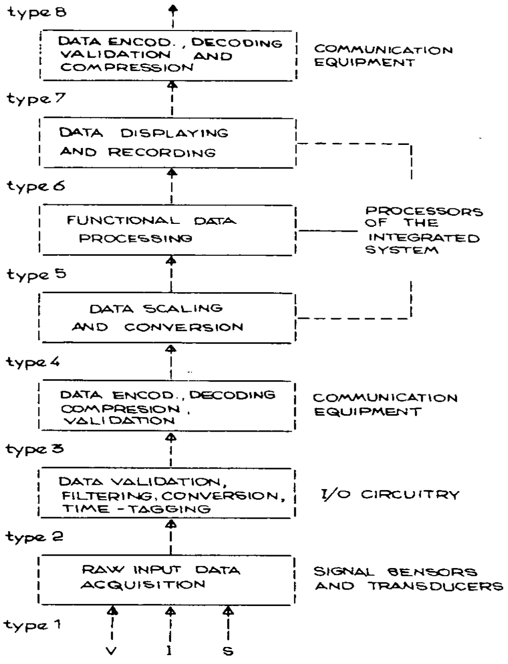

Fig. 1. Data acquisition processing

Sources of information. These sources can be classified into two major groups: internal and external sources. This classification is made in reference to the substation computer-based equipment. Internal information sources are various algorithms that are being executed, and events sensed by the system processors. The group of external sources includes the substation apparatus and equipment as well as the Man-Machine and system communication interfaces.

Methods of information transferring. These methods are in general concerned with information routing and information coding. It is interesting to note that both pair-wise and the centralized information routing is needed in the Integrated System. The most obvious information paths implemented using the pair-wise routing are the ones that connect control subsystems that are located at the local control level. Centralized information routing is used to provide interfaces to the computer system from the outside world. Information coding is dependent on the information path characteristics. If the path includes a transmission chanell, then some form of information coding is required. However, if the path connects two locally based processors, then the coding might not be necessary. In this case the information can be transmitted directly over a local bus. Particular solutions depend on the computer system architecture.

SYSTEM ARCHITECTURE AND ALGORITHMS

Finally, our discussion has reached the point where particular design specifications for an Integrated Microprocessor-Based Substation Control and Protection System can be outlined. The discussion topics are presented in the following order:

- system configuration,
- allocation of system functions,
- system interfaces,
- system algorithms and data flow.

System Configuration

In general, system configuration selection depends on functional requirements. The analysis of functional requirements given in the previous section can be used to decide which type of computer configuration is the most suitable. An introduction of the proposed configuration is given in two steps:

- configuration functional requirements,
- configuration physical layout.

Configuration functional requirements. A hierarchically structured functional organization is envisoned, which is configurated as it is shown in Fig. 2. Concentrating and local functional units satisfy two basic organization levels discussed in the previous section. Local functional units are intended to accomodate direct control functions. Concentrating ctional units are suitable for optimal a adaptive control functions. Coordinating implies a need to coordinate local contr ctions. Connecting functional units prov appropriate information routing between two basic organization levels. It is o that both coordinating and connecting le are needed in order to provide required terface between the two basic organizati vels. This interface provides an ability each level to perform as a separate enti and at the same time they can coordinate activity.

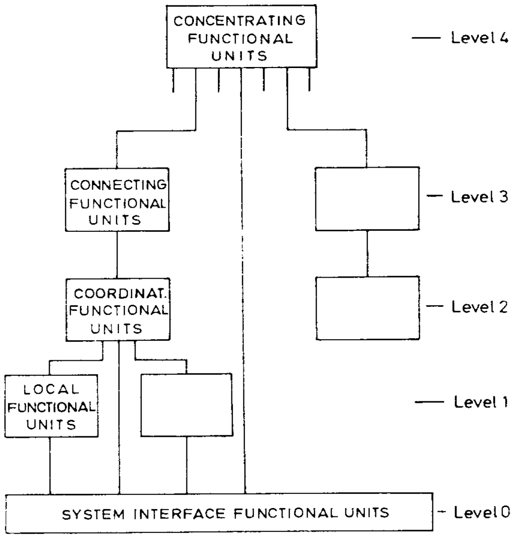

Fig. 2. Hierarchically structured functional organization of the Integrated System

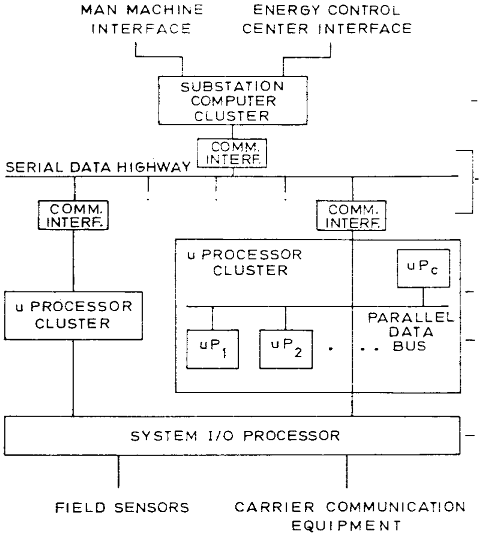

Fig. 3. Microprocessor-based configuration for the Integrated System

Configuration physical layout. It should selected so that it can accomodate confi tion functional requirements. Selected c guration with the basic elements is outl in Fig. 3..As it can be observed, the pr sed configuration is hierarchically stru having processing elements at each of th viously defined levels. Processing elem are grouped in the microprocessor-based ters. Each of the clusters can be used t form specific local control function. Su tion computer cluster serves as data con trator for the overall system. It is con to interfaces which require overall syst Each of the local control clusters is co ted to the field sensors and the carrier mmunication equipment. These interfaces de necessary communications with the sub tion switchyard equipment. The switchyar pment can be located in a substation o some remote site.

Allocation of System Functions

There are many ways of allocating system functions to the configuration given in Fig. 3.. The following discussion relates control functions given in Table 1 and Table 2 to the processors given in Fig. 3..

Level 0. These processors are mainly assigned to perform several data acquisition and communication functions given in Fig. 1.. Input signals to this level are the new input data going up to the computer system, and the commands going down to the substation switchyard equipment. Output of this level are the preprocessed data going to the microprocessor-based clusters, and the control signals going to the switchyard equipment. Therefore, functions of this level manipulate the data stream going upward to create data types 1 through 4 indicated in Fig. 1.. Data stream going downward is manipulated performing the basic communication functions.

Level 1. This level accomodates most of the direct control functions. Each of the apparatus protection functions is allocated to at least one microprocessor. Protection-related functions can be also allocated to a processor at level 1. Some of these functions are not time critical and can be allocated to level 4.

Level 2. Processors at this level perform basic function of cluster coordination. Some of the data acquisition functions as well as some of the monitoring functions can be also assigned to processors at this level. These processors also perform local data concentration which enables more efficient transmission of data to processors at the upper levels.Control commands and data comming from the upper levels are classified and routed by the level 2 processors to the appropriate processors at levels 1 and 0.

Functions allocated to the processors at level 1 and level 2 can be grouped and allocated as a group to a particular microprocessor-based cluster in several ways. One possible way is to group them by the switchyard components, namely lines, buses and transformers. This grouping is belived to be convinient as far as the software implementation is concerned.

Level 3. Basic functions needed to interface lower level clusters to each other as well as to the substation computer cluster , are executed at this level. Therefore, these processors are primarely carrying out the information routing and information coding.

Level 4. Processors at level 4 accomodate most of the adaptive control functions. Some of the direct control functions, that are not time critical, are also allocated to this level. These processors also perform data concentration needed by the Man-Machine and the Energy Control Center interfaces. Data base management functions are allocated at this level.

System Interfaces

System interfaces can be classified in two major groups: internal and external. There are several types of internal interfaces that can be found in an Integrated Sytem. One type are system buses which connect system processors and suporting components. Included are private buses that connect each processor to its private memory and the I/O chips. Also, included are multiprocessor parallel buses which tie together processors within a cluster. Finally, there is a system bus, namely the serial data highway that is used to connect system clusters. External interfaces include communication interfaces to the switchyard located data acquisition equipment, interfaces to the carrier equipment as well as the communication interface to the Energy Control Center. The Man-Machine equipment interfaces also belong to the external interfaces.

System Algorithms and Data Flow

The following discussion gives an overview of the overall system functioning.Algorithms and data flow are grouped by the levels given in Fig. 3.. Computational activity at each level as well as the interaction between the levels are analyzed for each of the four operational states The two basic algorithm and data flow groupings considered separately are:

- application oriented,
- computer system oriented.

Application oriented algorithms and data flow. They are related to the Integrated System action needed to perform the basic application task, namely protection and control of a transmission substation.

In the Normal state, system receives new data from the field transducers. I/O subsystem performs basic preprocessing of input data as it is described in Fig. 1.. Then, the preprocessed data is used by the algorithms located in processors at levels 1 and 2. Most of the analog data that is sent from each of the clusters is now in the form of averaged values rather than in the form of samples. Therefore, the amount of data that is supplied to the substation computer cluster is reduced compared to the original amount supplied by the field transducers. The amount of data that is flowing from the substation cluster to the lower levels is very small and restricted to some manually initiated switching operations.

The Alert state of operation is pretty much the same as the Normal state as far as algotihms and data flow are concerned. However, some additional algorithms are initiated to account for some of the Alert state activity. Nevertherless, system data flow is very little affected by the activity of the additional algorithms.

The Emergency state places extremely severe computational burdens on processors at levels 1 and 2. Most of the protection algorithms are initiated, which creates additional data within these processors. Also, a large amount of oscillography data needed by some restorative algorithms has to be transmitted to level 4. There is also emergency status data that has to be transmitted as soon as possible. This data originates at level 1, and has to be immediately transmitted either to the field equipment or to some other clusters. This places particular burden on level 0 processors as well as level 1 processors. Some priority data transfer scheme has to be developed which would perform the emergency data transmission immediately, suspending the regular data flow.

Finally, the Restorative state has a reduced number of algorithms compared to the Emergency state. However, there are still more algorithms involved in this state than in the Normal state of operation. Data flow from the field to the upper levels is pretty much the same as in the Normal state. The exception is additional data flow activity neede to clear data accumulated at levels 1 and 2, as a result of the suspended data flow required by the Emergency state. Data flow from level 4 to lower levels is more involved than in the Normal state since some of the adaptive algorithms at level 4 create switching signals to be sent to the field equipment.

Computer system oriented algorithms and data flow. As it can be observed from Table 1 and Table 2, algorithms related to computer system operation in the Normal state are spread around the system and are basically aimed toward moving the data within the system. Data flow that is critical is initiated by the system synchronization algorithm. Some of the Man-Machine interface activities are also time critical.

The Alert state introduces some additional computer based algorithms which are executed only during this state. They can be located at any level within the system and produce some statistical data which must be moved to level 4. Some of the algorithms in this state produce significant amount of data, but this is not time critical data. This can be accomodated by the regular data flow which is quite similar to the data flow present in the Normal state. However, some of the algorithms of the Alert state can initiate some Emergency state algorithms, in which case this initiation data has to be transmitted as soon as possible.

The Emergency state initiates algorithms that require quite involved data flow. Some critical data may be generated, which then must be quickly transmitted between processors located anywhere in the system. In the most critical case when the failure of the I/O subsystem is detected, a requirement to transmit large amounts of data from one cluster to another has to be satisfied. This data flow requirement is also time critical.

Finally, the Restorative state might req
special algorithms to be executed and sp
data flow to be carried out. This activi
be quite involved which depends on the d
philosophy applied to protect the comput
system from reaching the other states, o
the other states are reached to efficien
recover.

As a conclusion to this section, it can
observed that there are quite different
rithm and data flow requirements present
each of the operational states. It shoul
noted that the application oriented and
computer system oriented operational sta
requirements given above are analyzed se
rately, but can occur simultaneosly in t
real operational enviroment. Therefore,
system has to be properly designed to ac
modate the worst case situation.

CONCLUSIONS

The discussion given in this paper outli
a system approach that can be used to de
an Integrated Microprocessor-Based Subst
Control and Protection System. It is obv
that a more detailed design procedure is
if one is to design and implement an Int
ted System. However, the approach propos
this paper is considered appropriate an
neficial as a first step in designing th
tem. It is belived that the analysis pro
performed using the system approach enab
better understanding of some fundamental
racteristics of the system, which can si
ficantly affect the detailed design proc

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Discussion to Paper 95.4

Y. Tamura (Japan): Would you make clearer the relationship between the (convergent) solution to be obtained from the state transition diagram and the number of CB's to be opened in case of faults, which is larger than the minimum number of CB's to be necessary to get rid of the faults? The statistical parameters used in the state transition diagram have to be very accurate in order to get a solution of reasonable accuracy. The size of statistical set should be large enough to estimate the precise values of those parameters? Could you please comment on the above points?

J. L. Boussin (France): figure 3 is the model for only one circuit breaker. The substation is reliable if all the control-line systems are in states different from state (F). The substation is safe (deteriorated safety) if, for example, only one substation is in a faulty state. The defect is eliminated with a correct time. The defect is not propagated in other substations. For a large number of statistical parameters it is possible to take the same value for two control-systems in an EHV substation. We check for a variation in those parameters, and there is no change in the comparison between the two control-systems. For some statistical parameters (P_D, P_C, ρ, P_{DD}), the best control system depends on the value of the parameters; in that case we know that: (a) we have found an important parameter (this is not evident before modelling), (b) we have to check the real value of those parameters with prototypes, and that is what we are doing now. With studies on sensitivity to parameters, we were able to reduce the size of the model of a substation (50-70 states).

M. Kezunovic (Yugoslavia): Why are you using four microprocessors for the distance protection function when it is possible to use just one microprocessor?

J. L. Boussin (France): We want to be able to detect a fault in less than 16 ms, in all the cases, even if there is a change in the direction of the defect, the nature of the defect. In 1979 the Motorola 68,000 microprocessor was not available, but the 8086 of INTEL was ready to use with all the circuits needed (boards, multi-microcomputer structure, software, etc). It is possible to implement the algorithm on other hardware structures. This is what we are now doing.

Discussion to Paper 95.5

M. Kezunovic (Yugoslavia): It is interesting to note that there are different approaches to the design of an integrated system. One example is the AEP Corporation system which combines the conventional allocation of functions with conventional wiring. Another example is the Westinghouse/EPRJ Project which has unconventional allocation of functions and unconventional wiring. The examples that are in between the two mentioned systems are the Mitsubishi/Kansai Electric System and the Laborelec Alpes System. Those systems have the allocation of functions and wiring organized by the speed of the data sampling required. The method for analysis presented in our paper helps to distinguish between the various functional and system requirements that affect the final design. The integrated system discussed in this paper enables a whole new set of functions that can be part of an energy control center. On the one hand, it is possible to perform the preprocessing of the data which goes to an energy center. This reduces the computational load at the computer system in a centralized point where an energy control center function is allocated. On the other hand, it is possible to perform decentralization of the energy control functions by assigning some of those functions to an integrated system. An example could be the state estimation function. Finally, it is possible to include the protective relaying functions, through an appropriate interface of an integrated system, in the functional set of an energy control center. This opens totally new application possibilities, and some new functions for the energy control center can be defined.