

THE ICPS APPLICATION IN A NEW DISTRIBUTED APPROACH TO EMS IMPLEMENTATION

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Abstract. This paper introduces a possible distributed processing implementation of EMS functions. The approach discussed is based on two major developments. One is the development of Integrated Control and Protection Systems (ICPS) for substation applications. The other development is related to the distributed algorithms for power system data acquisition, control and protection. Both developments are utilized to define a new implementation approach where the ICPS equipment is used in place of the conventional remote terminal units. The paper illustrates this approach by providing examples of protective relaying, state estimation, and stabilizing control functions.

Keywords. Power system control; substation control and protection system; adaptive relaying; state estimation; decentralized control.

INTRODUCTION

Two major developments in the process of computerization of power industry are coming from two different ends. One is the Integrated Control and Protection System (ICPS) for substations (EPRI, 1981), and the other is the Energy Management System (EMS) for control centers using decision and control (Zaborsky, Prasad and Whang, 1980).

The integrated control and protection approach for substations was introduced as a technological improvement in the late 70's. The major benefits were expected in the area of reduced substation wiring, improved equipment monitoring and enlarged data base. Integrated system also provides substantial processing, communication, and man-machine interface improvements not found in the existing substation control and protection equipment. The present situation, with several of integrated control and protection systems being field tested and offered as commercial products, poses a number of questions regarding utilization of these systems (Kezunovic and Perunicic, 1987; Nilsson, 1985). New control and protection concepts, that utilize the mentioned characteristics to generate some new benefits, are still needed.

On the other hand, the control center for EMS applications using decision and control, have become an expanding business. So far, the EMS control has been designed as a centralized coordinator which gathers all the required global data and information from RTUs through communication network. The necessary computation is carried out at the control center to monitor and to control the system.

As a consequence of the mentioned developments, a natural question arises: Is it possible to distribute some of the computing load to the local computers placed at substations, and at the same time to maintain the required processing coordination for EMS and relaying functions?

Advanced computer system and communication architectures and technologies can be implemented both at the substation and at the control center level to facilitate distributed processing approach (EPRI, 1987; Horton and Gross, 1987). Distributed sensors, computing power, data base, and controls are available for EMS to use. There are several potential benefits of this approach. First, distributed processing would relieve some of the computing load at the control center and thus more involved functions can be added to further utilize the control center. Second, the distributed computing can increase the reliability of the implemented functions. The failure at one local computing facility will not jeopardize the overall operation.

Third, the distributed data base is updated and checked easily at a local level, and thus more reliable data base for the system can be maintained. Fourth, the ICPS interface to the EMS architecture allows for implementation of the new relaying approaches. Finally, the distributed environment can increase the overall utilization of the computational and communication resources.

This paper discusses the distributed approach by giving examples of some of the EMS function implementations using the ICPS designs in place of RTUs.

ICPS CHARACTERISTICS AND POTENTIAL USE

This section points out some characteristics of the ICPS designs that are utilized to implement the distributed processing concept. The discussion concentrates on the following ICPS issues that are common to almost all of the ICPS designs: system architecture and allocation of function; distributed data base and EMS interfacing.

System Architecture and Allocation of Functions

An analysis of the substation control and protection functions reveals that there are at least three hierarchical levels of functional organization (Kezunovic, 1982). The first level is interface to the switchyard where measurement and actuator subsystems are allocated. The next level is associated with the direct control functions that require a fast time response, such as protective relaying functions. The functions that are related to the overall substation control and protection represent the third level. Examples of the substation functions are: operator measurements, automatic switching sequences, and breaker failure initiate.

The choices for computer and communication system architecture to support the mentioned functional levels are numerous. Several criteria for function allocation can be defined (Kezunovic, 1984). If the criterion is that the ICPS resembles the conventional system design, then each individual substation control and protection function can be allocated to different processors at level II. In that case a separate wiring is used to connect these processors to the switchyard equipment, by using the level I signal conversion interface. The substation computer is used only to gather the related measurements and indications, and in this case no function coordination is done at the substation level. Yet another criterion might be optimization of the switchyard signal wiring. Fig. 1 indicates the switchyard equipment that corresponds to different bays and/or related functions.

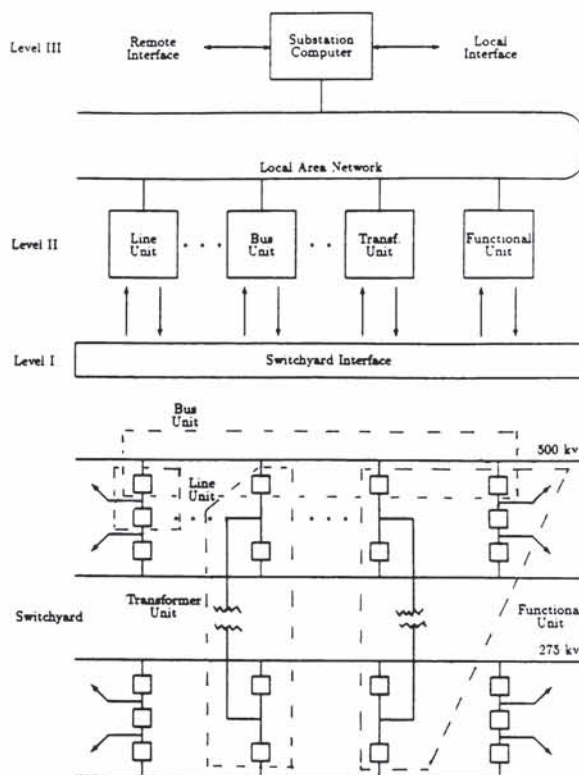


Fig. 1. Typical ICPS Hierarchical Organization for the Related Switchyard Equipment

For the given ICPS architecture and the substation layout, it can be observed that the equipment and/or function zones overlap which means that the associated signal connections are redundant. This signal wiring redundancy can be eliminated by sharing each individual substation connection among several users (functions). This concept is known as "data sharing" and can be implemented using different LAN communication arrangements. The implementation choice will affect the design of level I interfaces. The data exchange among level II functions will also be affected by the data sharing implementation. As a consequence, functional allocation at all levels can be different from the classical one allowing for function coordination in the ICPS multiprocessor environment. This facilitates implementation of the EMS distributed functions since the system architecture and allocation of functions can be selected to optimize the requirement of the overall substation function coordination and data exchange needed for the EMS applications.

Distributed Data Base and EMS Interfacing

One specific application of the ICPS is as a substitute for Remote Terminal Units in the EMS design (Kezunovic and Perunicic, 1987). This situation places some special ICPS implementation requirements.

As mentioned earlier, the main requirement in this case is that substation functions allocated at levels I and II are in close coordination with functions at level III. This means that the ICPS data base is implemented in a distributed manner with an extensive data exchange performed over the LAN communication system. Signal sampling and processing as well as data base maintaining and updating have to be synchronized throughout the ICPS. The sampling synchronization might not be required in the classical ICPS application, but the EMS-related application is dependent on this feature.

The other important issue is the data base content and related signal processing. Classical EMS interface requires data that is

mostly related to the normal operational state of a power system. Substation protection and most of the automatic control functions are traditionally based on the data that corresponds to the signals generated during power system faults. Therefore, in the case of the ICPS application for the EMS distributed function implementation, it is required that flexible signal processing algorithms are defined to provide for straightforward implementation of different processing requirements. This design feature would enable "tuning" of the digital algorithms to the desired accuracy levels required by different applications such as protective relaying, SCADA measurements, local and remote decision and control of substations. Details of such an algorithm synthesis approach are given by Perunicic and colleagues (1988).

PROTECTIVE RELAYING AND RELATED CONTROL FUNCTIONS

This section illustrates some new design approaches for protective relaying and related control functions using an ICPS implemented as a part of the EMS configuration. Several differences between the new approach and the existing practice are outlined and major benefits obtained by the new approach are emphasized (Kezunovic, 1989).

Classical Solution to Relaying and Control Functions

As it is well known, the classical protective relaying functions are "on-off" type direct control automata that are distributed throughout the power system. Their decision is made based on the specified set of measurements and the settings. A system-wide fault study is performed in order to calculate the short-circuit quantities related to the selected number of fault situations. These quantities are used to carry out the relay setting coordination study that is done off-line. Therefore, the protection philosophy of the entire power system represents a combination of the individual relay logic set to respond in accordance with the previously studied worst case fault conditions.

The main problem with the above approach is an inherent limitation of some of the individual logic schemes to make precise determination of the fault quantities based on the local measurements only. Another disadvantage is associated with inability of the existing protective relaying scheme to adapt to major changes in the power system operating conditions. In particular, if some unexpected normal and/or abnormal power system conditions do occur it is very likely that the protective relaying scheme will not operate as expected. This, in turn, can cause reduced selectivity of the protection scheme which may lead to major blackout.

The main question to be asked is as follows: Are there any new approaches to protection that can be used to improve the existing schemes? A number of positive answers to this question were given in the past in a form of new proposals for adaptive and system-wide protective relaying (Kezunovic, 1989). However, one of the main obstacles to the implementation was unavailability of the adequate technology base. The problem was further complicated by the pressing requirement, coming from the present practice, that the protection functions must be implemented as stand alone system with no interaction with any other data acquisition and/or control system.

Development of the substation based ICPS provides both the technology base and the required experience to consider its interface to the EMS design for further developments of the adaptive and system-wide protective relaying concept.

Another set of functions, the control functions for apparatus switching, are closely related to protective relaying. Classical implementation of the existing systems, to perform substation interlocking and switching, are hard-wired systems. These systems are quite difficult to implement and to change. They only give status indication and there is no incorporated processing capability to provide an operator with diagnosis of any sequency malfunction and/or interruption. All automatic switching sequences are initiated by the protection relay actions. Other switching actions, associated with operator requests, are quite often executed on a step-by-step basis with no automation

applied to the overall sequence execution. Most of the post-fault switching requires diagnosis of the faults as well as accurate validation of the final topology of the system. These actions are, as a rule, performed at the control center based on the status and alarm information obtained through a SCADA system. The restoration sequences are also determined at the control center and their execution is carried out using SCADA system.

A number of techniques to automate some of the mentioned analysis and execution steps associated with the switching sequences have been proposed in the past. However, the implementation approaches were not taking into account a close coordination among substation and control center actions. More precisely, there was no sharing of the common data base proposed. Furthermore, no capabilities for extensive analysis of the switching events and the fault diagnosis were assumed to be available at the substation level. Also, substation automation was not considered as a part of the overall SCADA control philosophy.

The use of the ICPS in place of the RTU provides new opportunities for the system switching function implementation and analysis due to the distributed data base and processing capabilities.

New Approaches to Protective Relaying

This section is not aimed toward explaining the new relaying schemes introduced so far for adaptive and system-wide relaying, since these schemes are well documented (DOE, 1989; Zaborsky, Ilic, and Huang, 1987). It is related to the implementation issues of the mentioned schemes. The role of the ICPS is explained in this context.

The first important conclusion is that both adaptive relaying and system-wide relaying are "better" approaches than the conventional protection. The adaptive relaying assumes that a coordination among relays is required to improve the performance of the classical relaying schemes. The system-wide relaying is inherently adaptive since it derives the specific protection logic based on the given system conditions. However, both adaptive and system-wide relaying require extensive communication facilities to coordinate relaying functions. At the same time the question of reliability and/or time response of the new protective relaying approaches arises. An efficient protective relaying scheme should take advantage of both approaches by providing a careful coordination of the related measurements and relaying actions.

One approach suggested here for implementation is to use the substation-wide adaptive relaying for primary protection and system-wide relaying for back-up protection (Kezunovic, 1989). By using this approach, it would be possible to utilize the advantages of both concepts. The adaptive relaying would be implemented locally at the substation, and it will improve the performance of the classical protection. This is done by utilizing the local measurements to adapt the relay schemes to the change of the system operational conditions, and yet the required fast response time would be maintained. The system-wide relaying is inherently adaptive, which assures it improved selectivity. However, it requires some communications to perform the required system-wide exchange of data, and this determines its delayed action as a back-up protection.

The system-wide relaying can be implemented in a distributed way (Zaborsky, Ilic, and Huang, 1987) to provide for the required coordination between the primary and the back-up protection. The ICPS interface to the EMS facilitates the required system-wide exchange of data. The additional information from other substations can be routed via SCADA communication interface. The same signal measurements are used for both the primary and the back-up protection. The logic for the primary protection is executed at the protection units while the logic for the substation-wide relaying is performed at the substation computer. Tripping decisions are first made by the primary protection. In the meantime the system-wide protection gains some time required for the system-wide coordination of each of the substation processing results. The tripping decision of the back-up system-wide relaying is checked against the primary protection decision.

Any discrepancy requires further coordination by the means of corrective switching to satisfy the system-wide decision. A close analysis of the circuit breaker operational availability, indicated by the successful tripping caused by the primary protection, should be used to select appropriate sequences of the corrective switching.

New Strategies for Switching Function Analysis

The substation based processing coupled with the new relaying provides potentially much more efficient technique for the analysis of the relaying-related switching actions, than the new schemes proposed for the control center (Wollenberger and Sakaguchi, 1987). The new relaying approach has an important benefit that all of the fault diagnosis and fault location techniques can be derived as a direct outcome of the substation-based protection processing (Jeyasurya and colleagues, 1989). This comes from the fact that all of the relaying measurements and final breaker status information are available in the ICPS data base. In that case some extensive data validation techniques can be applied to assure the correct representation of the relay measurements (Gonzalez-Urdaneta, 1977). Also, some systematic substation switching logic confirmation schemes can be used to verify the substation topology (Brand and colleagues, 1986). Finally, a combination of the analog and status information, available at the substation data base, can be used to diagnose and locate the fault (Girgis and Johns, 1988). The main advantage in this case comes from the distributed processing approach obtained by utilizing the ICPS data base and processing capabilities. The results of all of the mentioned steps, obtained at each substation and communicated to the control center, provide to the system operator full and explicit information about the operational condition of the power system.

Another advantage of the ICPS-based automation concerns the operator-initiated switching actions. All of these actions can be processed at the ICPS in order to verify their validity. If the validity is confirmed, then the switching actions can be automatically executed by the ICPS. This facilitates confirmation of each switching step and enables a full verification of the final switching state. If some problems occur during the sequence execution, the operator is promptly informed about the problem with clear indication of the causes.

DISTRIBUTED STATE ESTIMATION

Power system state estimation is generally formulated as a weighted least squares minimization problem. The resulting nonlinear equations are linearized around an initial guess and the solution is obtained iteratively solving the linear equations of the form:

$$[G(X^k)] [\Delta X^k] = [\Delta t(X^k)] \quad (1)$$

where: $G(X^k)$ is the information matrix evaluated at iteration k ,

ΔX^k is the correction in state vector X ,

$\Delta t(X^k)$ is the weighted measurement mismatch vector.

Eq. (1) is solved repeatedly until $|\Delta X^k| < \text{tolerance}$. Typically the information matrix does not change significantly. Using the P-Q decoupling assumptions, G can be decomposed into two decoupled submatrices which are evaluated once at the initial guess and maintained constant.

It is possible to exploit the sparsity of G and apply the parallel solution scheme (Abur, 1988) to eq (1). The solution of eq. (1) involves two steps: triangular factorization and forward/back substitutions. While the former is done once, the latter step is repeated at each iteration. The second step can be described by the following two equations:

$$L D y = \Delta t \quad (2)$$

$$L^T \Delta X = y \quad (3)$$

where: L, D, L^T are the triangular/diagonal factors of G ,
 y is the intermediate forward solution vector.

In (Abur, 1988) it was shown that by proper ordering of G , the normally full right hand side vector Δt can be broken down into several very sparse vectors Δt^i whose sum remains equal to Δt . Each of these very sparse Δt^i 's as well as their corresponding forward solutions y^i 's defined by:

$$L D y^i = \Delta t^i \quad (4)$$

can be computed independently and in parallel. Once y^i 's are computed, they must be summed up to obtain y of eq (2). This completes the forward substitution step. The back substitutions (eq (3)) can be similarly parallelized, this time breaking down ΔX according to the same pattern used for Δt (Abur, 1988). At the completion of this step, subsets of the entries of ΔX will be obtained concurrently by processors assigned to each cluster i .

Implementation of this idea will be possible by utilizing the ICPS in substations. For a given measurement configuration, the clusters of nodes can be designated and each cluster can be assigned to a substation. This way, each substation ICPS will receive measurements only from those nodes in its cluster and will carry out the computations associated with Δt^i and Δy^i concurrently with other substations. The only synchronization in this scheme is required before the summation of y^i 's at each state estimation iteration. Assuming that a central computer is coordinating the process, this summation and the synchronization can be taken care of centrally. The steps of the proposed distributed scheme, as well as the communication and processing requirements are outlined in Table 1.

The above described distributed computation scheme has been simulated in a serial machine assuming that 10 parallel processors are available, and one processor is assigned as a central computer and the remaining 9 are used as local computers. The IEEE 118 bus test system with 10 injection, 358 line flow and 118 voltage magnitude measurements is used for this simulation. Different parts of the scheme are timed separately. For comparison purposes, the same parts are run using the conventional state estimation scheme. Table 2 shows the comparative timings for both cases. The ratio indicates the overall computational gain through the use of the distributed scheme.

The ratio in Table 2 is somewhat optimistic since the communications delays are not taken into account. However, considering the fact that communications are needed only twice per iteration and only for a small portion of the overall system states (the ones in the trunk of the factorization path graph) it is expected that the performance of the scheme will not be significantly degraded by it.

Recent installments of ICPS for various power systems makes it possible to actually implement the proposed scheme and test its effectiveness in real-time power system environment.

Table 1: Distributed State Estimation Steps

Step	Task	Processing Computer	Processing Type
1	Forming G	Central	Sequential
2	Factorizing G	Central	Sequential
3	Compute t^i 's	Local	Parallel
4	Forward Substitutions	Local	Parallel
5	Transmit y^i 's to the central computer		
6	Summation	Central	Pairwise Parallel
7	Transmit y^i 's back to local computers		
8	Backward Substitutions	Local	Parallel
9	Check Convergence	Local	Parallel
10	Transmit Convergence Flags to the central computer		
11	If converged, stop; else go to step 3.		

Table 2: Simulation Results, IEEE 118 Bus Test System

Task	Time (sec.)
Forward Sol.	.9325
Summation	.0109
Backward Sol.	.9625
Total Parallel Solution	1.9059
Total Sequential Solution	17.125
Ratio	8.98

DECENTRALIZED STABILIZING CONTROLS

As explained earlier, the ICPS is equipped with new data base and digital algorithms capability. In particular, new data on voltage, currents and power will be continuously available during the emergency and fault clearing periods. Algorithms can be designed to extract the transient power components out for each line (Perunicic and colleagues, 1989). Based on this information, observation decoupled target can be computed and the control can be decided to stabilize the system. Three control hierarchies are proposed (Zaborsky and Huang, 1984). Due to space limitation, only the cluster feedback stabilization and its ICPS implementation is presented here. The configuration is illustrated in Fig. 2.

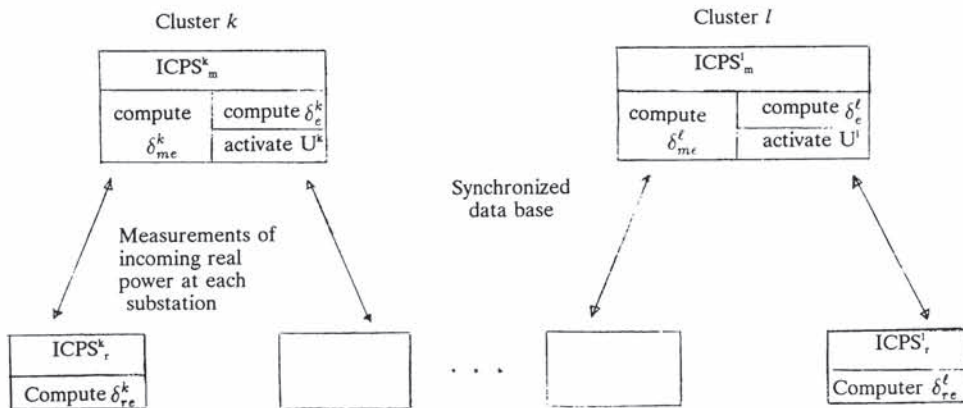


Fig. 2. ICPS communication configuration to implement stabilizing controls.

Computation of Observation Decoupled Reference

At each bus, we have $P_i - P_{Li}$ (the net power injection) and $\frac{E_i E_j}{x_{ij}} \sin(\delta_i - \delta_j - \theta_{ij})$, the real power across the lines from the measurements at the sampling rate of 10^3 sec. Here $x_{ij} \angle \frac{\pi}{2} - \theta_{ij}$ represents the transmission line impedance. E_i, E_j are the voltage magnitudes at buses i and j , respectively. Some processing may be needed to get rid of the subtransient components to obtain the desired components. Then the target phasor and angle δ_{ie} can be computed through the following equations

$$P_i - P_{Li} = \sum_{\substack{j \neq i \\ \text{over the} \\ \text{connected} \\ \text{neighboring} \\ \text{buses}}} \frac{E_i E_j}{x_{ij}} \sin(\delta_{ie} - (\delta_j - \delta_i) - \theta_{ij}), \quad (5)$$

where: $|\delta_{ie}| < \pi/2$.

The computation can be carried out by expanding $\sin(\delta_{ie} - (\delta_j - \delta_i) - \theta_{ij})$ into components of the measured values of real power across bus i and bus j , $\frac{E_i E_j}{x_{ij}} \sin(\delta_i - \delta_j - \theta_{ij})$, and the computed value $\cos(\delta_i - \delta_j - \theta_{ij})$.

Decoupled Clusterized Stabilizing Controls

Braking resistors and SMES are expensive control devices. When only a few such devices are available, the control law needs to be designed in such a way that it incorporates the needed information across the system to effectively stabilize the system. But at the same time, such information gathering should be simple enough to be implemented reliably. One idea is based on the clusters of machines which have a tendency to swing together. In this case, the cluster and optimal control locations can be found through the clustering scheme (Huang and Antonio, 1986). The cluster information can either be stored in the control center, or in the ICPS substation where the braking resistors are located. Such a control law is defined as follows:

1. Compute δ_{ie} as in previous subsection. Measure the rotor velocity $\dot{\delta}_i$.
2. At EMS, or the ICPS substations where the braking resistors are located, compute the following cluster angle target and cluster velocity, and estimate $\dot{\delta}_e^k$ numerically.

$$\begin{cases} \delta_e^k = \frac{\sum J_i \delta_{ie}}{\sum J_i}, \\ \dot{\delta}_e^k = \frac{\sum J_i \dot{\delta}_i}{\sum J_i}, \end{cases} \quad (6)$$

where $i \in \text{cluster } k$.

3. Find the required control amount in cluster k by

$$v^k = \begin{cases} \frac{J^k}{\delta_e^k} (\delta_e^k - \dot{\delta}_e^k) + P^k + k_{1k} + \frac{J^k}{\delta_e^k} k_1 & \text{if } \dot{\delta}_e^k > \varepsilon, \\ \frac{J^k}{\delta_e^k} (\delta_e^k - \dot{\delta}_e^k) + P^k - k_{2k} + \frac{J^k}{\delta_e^k} k_1 & \text{if } \dot{\delta}_e^k < -\varepsilon, \end{cases} \quad (7)$$

where ε is a preset value, say .5 cycle/sec.

J^k is the total inertia at cluster k , i.e.,

$$\begin{aligned} J^k &= \sum_{i \in \text{cluster } k} J_i \\ k_{2k} &= \frac{1}{J^k} \sum C_{mr}^{kl} \frac{E_m' E_r'}{x_{mr}^{kl}}. \end{aligned} \quad (8)$$

where:

$$C_{mr}^{kl} = \begin{cases} 1 & \text{if there is a transmission} \\ & \text{line from } m\text{th machine in} \\ & \text{cluster } k \text{ to } r\text{th machine} \\ & \text{in cluster } \ell, \\ 0 & \text{otherwise.} \end{cases}$$

$$k_{1k} = \frac{D[\pi |\dot{\delta}_e^k|_{\max}]}{N - 1 - D}.$$

D is the number of states in cluster k such that $|\dot{\delta}_e^k| \leq \varepsilon$ at time t .

4. Set

$$\begin{aligned} U^k &> V^k \text{ if } \dot{\delta}_e^k > \varepsilon, \\ U^k &< V^k \text{ if } \dot{\delta}_e^k < -\varepsilon. \end{aligned} \quad (9)$$

Communicate the values to the substations where the controls are located and initiate the control at the substations.

Many simulations have been carried out. One of the runs is given as follows in Fig. 3 and Fig. 4. The simulation is carried out on a modified IEEE 118 bus system. The modification is made so that there are three clusters in the system. A detailed description of the data is available in a DOE report (Zaborsky and Huang, 1983). A fault is created by a 3-phase short circuit on line 17-38 with a fault duration of 12 cycles. Line 17-38 and 200 MW of load at bus 17 is lost at clearing of the fault. Then cluster 1 is separated from the rest of the system. Some bus angle trajectories from three separate clusters are given in Fig. 3. Three discrete braking resistors located at buses 12, 46, and 80 are initiated at the end of the fault. In Fig. 4, the sample angle trajectories are clearly stabilized and in Fig. 5 the corresponding control amplitudes are given. It can be seen the system is settling down to the new steady state since the control amplitudes and durations are decreased gradually.

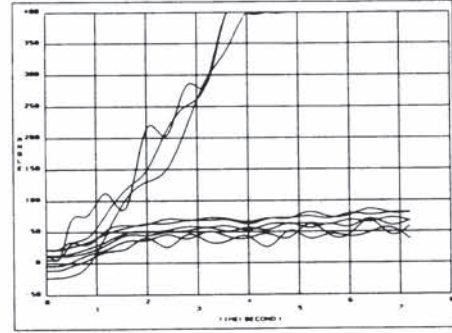


Fig. 3. Angle trajectories after fault without control actions.

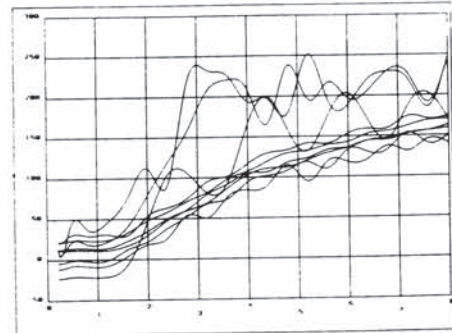


Fig. 4. Angle trajectories with clustered feedback control law initiated at buses 12, 69 and 80.

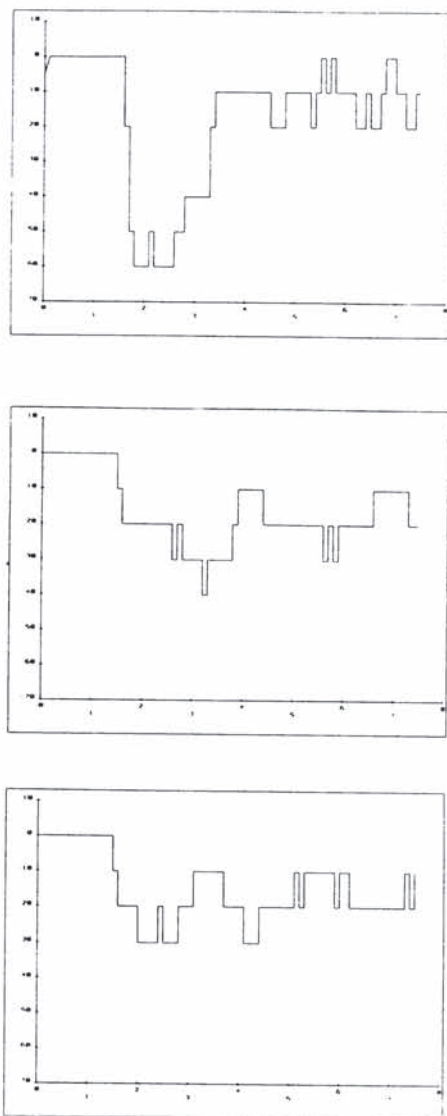


Fig. 5. Discrete control actions at buses 12, 46 and 80. The controls are assumed with steps of 10 MW with maximal 60 MW. The controls are taken at the closest discrete value to the computed setting values.

CONCLUSIONS

The discussion of the paper indicates a new approach obtained by combining the two new developments, namely the ICPS and the decentralized control and decision. The benefits of this approach are illustrated by providing examples on protective relaying, state estimation, and stabilizing control functions. However, the distributed processing implementation requires further investigation of the following problems:

- EMS and protective relaying function coordination in the distributed EMS architecture.
- Synchronization of data sampling and data base maintenance for the distributed EMS data base.
- Communication system requirements for the distributed EMS implementation.

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