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INTEGRATION OF A SYSTEM-WIDE PROTECTIVE RELAYING SCHEME IN A DISTRIBUTED PROCESSING ENERGY MANAGEMENT DESIGN

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ABSTRACT

This paper discusses some implementation issues related to a system-wide relaying scheme introduced earlier in an IEEE paper. A specific way of implementing this scheme is considered where an Integrated Control and Protection System is used as a substitute for a Remote Terminal Unit r[illegible] Supervisory Control and Data Acquisition System. [illegible].pproach brings protective relaying function into the Energy Management System design. Implications of this integration aspect are analyzed and specific issues of interfacing different control functions to the relaying scheme are outlined.

Keywords: Protective Relaying, Energy Management, Distributed Processing, Integrated Control and Protection.

1. INTRODUCTION

The fields of protective relaying and energy management control were always separated in the power system industry. This is reflected by different implementation approaches and equipment designs used for relaying and control. Furthermore, the operating practices such as testing, maintenance, and engineering design are quite independent in the two fields so that the personnel organization and responsibilities are also separated. The main reason for the mentioned separation comes from the two different concepts used to implement protection and control functions.

Protective relaying of electric power system is conventionally implemented as a decentralized function. The equipment used are protection relays located in the power system substations and switching stations, and their operation is primarily based on the local measurements. Each relay operates as an independent on-off automaton. The only coordination among different relays is performed through the relay setting coordination which is carried out at the planning stage. On the other hand, the energy management control functions are implemented in a centralized f[illegible] using a control center. In this case the power sys-t[illegible] .easurements are obtained at substations using Remote Terminal Units (RTU) and then this data is brought to the control center equipment using the extensive communication system. It should be noted that the protection relays and the RTU equipment in the substation are wired separately and they use different instrument transformers.

Some of the most recent developments in the fields of protective relaying and energy management control indicate a possibility for integration of the relaying and control functions. The first step in this direction is already achieved by development of Integrated Control and Protection Systems (ICPS) for substations [1]. This new approach enables not only the coordination of the local control and protection functions but also an integration of the ICPS equipment into the EMS design by using the ICPS in place of an RTU [2]. Yet another important development in this direction is a new system-wide relaying concept which is based on the overall power system measurements [3]. An analysis of the communication and processing requirements for the system-wide relaying points out that the scheme can be implemented using distributed processing in substations supported by a star communication network among substations [4]. The two mentioned developments suggest that the system-wide relaying can be implemented using ICPS equipment for logic processing and EMS communication system for the required data exchange.

This paper discusses a specific approach to relaying and control were both EMS hardware and software are shared by the control and protection functions. Furthermore, data bases and related processing are also shared and coordinated. This is achieved by implementing the system-wide relaying using the ICPS equipment. Since this equipment is proposed to be a part of the EMS design, it is possible to use the EMS communication system to perform required system-wide data exchange needed for the mentioned relaying scheme. On the other hand, the existance of the ICPS equipment also provides for some new possibilities for the EMS data base and processing organization. Some further analysis indicates that in this case control and protective relaying functions can be coordinated to provide some unique distributed processing EMS design features.

The first part of the paper gives a brief description of the system-wide relaying approach. Some characteristics of the ICPS concept are discussed next. Then, the integration of the system-wide relaying scheme in a distributed processing EMS design is analyzed. Special attention is given to the implementation of the primary and back-up protection. Coordination among protective relaying, local control and remote control functions is also outlined. Finally, some indication of the advantages and the further research activities is given in the conclusions.

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2. NEW APPROACH TO PROTECTIVE RELAYING

Discussion in this section is largely based on the previously published ideas about adaptive [5,6] and system-wide relaying [3,4]. However, the implementation issues discussed here represent new considerations.

2.1 Conventional Relaying Concept

As it is well known, the conventional relaying concept assumes decentralized protection of different power system apparatus and components. The system-wide coordination of the scheme is done through the relay setting coordination. This is performed based on short-circuit study for a given system and a given set of fault conditions. The overall fault analysis study is performed at the planning stage and no real-time adjustments are made on the settings during the power system operation.

The performance characteristics of the conventional relaying are quite well understood and the existing relaying systems are fairly reliable. However, the inherent disadvantage of the existing schemes is the lack of adaptivity to the change of power system operating conditions. Introduction of the microprocessor-based relays and relaying systems has provided an opportunity for some adaptive features and techniques to be implemented [5,6,7]. These techniques could only improve selectivity and/or dependability of the existing schemes, but they could not eliminate the inherent limitation of the existing schemes which is related to their decentralized measurement and decision-making concept. Typical example is the distance relaying scheme for transmission line relaying which has limited accuracy for several operating conditions such as series compensation and heavy fault current infeed from the other side(s) of the feeder(s).

Some of the adaptive relaying proposals have indicated possibility for a system-wide adaptive relaying [8,9]. However, the implementation issues in this case may be quite complex and limiting in achieving the performance improvements. The system-wide adaptivity is achieved by adapting individual relaying schemes in the entire system. Since the schemes are designed as decentralized automata, the need for system-wide coordination of the schemes remains as an inherent requirement which can not be eliminated. Other adaptive relaying proposals, related to on-line setting coordination, are possibly more appropriate [10], but the implementation problems are hard to resolve at this time.

As a conclusion, it is obvious that the new concepts of protective relaying is needed to take into account unexpected changes in the overall power system configuration and operating conditions.

2.2 System-wide Relaying

Another approach to protective relaying is to assume that the relaying scheme to be used takes into account the current conditions of the entire power system. This means that the criterion for relaying includes system-wide data which should be updated to reflect system conditions at the moment of the fault. In this case the scheme is inherently adaptive since it is derived based on the current system-wide measurements.

A scheme which is based on the system-wide criterion has been recently proposed [3,4]. This scheme uses the nested protection unit principle. This principle assumes that, at the moment of the fault, it is possible to determine at each circuit breaker whether the fault is located "inboard" or "outboard" with reference to the bus section to which specific breaker is connected. The next step assumes that a minimum cutset of circuit breakers which surrounds the fault and the smallest amount of sound equipment can be determined. This cutset is defined as the Current Minimal Protection Unit (CMPU) and the tripping action should trip all the breakers on this cutset.

Obviously, the above scheme satisfies inherent adaptivity since the CMPU criterion is determined based on the current status of the "inboard" and "outboard" conditions for each breaker. Besides being based on the system-wide data, this scheme is also quite powerful when the criteria for "inboard" and "outboard" determination is considered. The hypothesis testing approach is taken for this purpose and it is based on the comparison of the measured and the calculated values of the fault currents. It has been shown that fairly simple fault circuit modeling can be used to calculate the fault current [4]. The main advantages of this approach are the simplicity involved in determining the equivalent fault circuit "seen" from the breaker and the relaxation of the accuracy requirement for the fault current measurement.

2.3 Implementation Requirements

All of the new relaying approaches mentioned, namely the adaptive relaying and the system-wide relaying, do require computer-based equipment for their implementation as well as extensive communication facilities for data exchange among different equipment.

As it will be explained later, the adaptive relaying is considered here as an improvement to the conventional relaying scheme. However, it is believed that the adaptive relaying can only be effective if it is implemented at the substation level. Any other system-wide adaptive relaying approach is considered to be too complex and difficult to implement. Therefore, computational needs and communication requirements are in this case limited to the substation equipment. Table I provides specification of the major requirements for the adaptive relaying implementation.

The system-wide relaying implementation requires processing of data available at different parts of the power system. Therefore, specific location should be designated for the processing equipment, and an extensive communication system is needed to share the required data among different locations. The original proposal for the system-wide relaying scheme had included several communication patterns for the system-wide exchange of data [4]. The approach suggested here is a combination of the proposed communication patterns. It is assumed that the major processing steps are performed in the substation equipment. Communication with other parts of the power system could be performed using the EMS communication system. Present configuration of the EMS communication system is a star network. In this case the control center will only serve as a communication node and no processing would be done at that level. Some future trends in development of the utility communication system may introduce some new types of configurations [11]. This will not change the decentralized implementation concept but may affect the processing level at each of the substation systems. Table I also gives a summary of the requirements for the system-wide relaying implementation.

Table I: Implementation Requirements

Requirements	Adaptive Relaying	System-Wide Relaying
Sampling Sync.	Substation-Wide	Not Required
Communicat.	Substation-Wide	System-Wide
Field Signals	60Hz	60Hz+High. Freq.
Instrum. Transf.	Conventional	Unconventional
Needed Data	Substation-Based	System-Based
Time-Response	Fast	Slow
Interaction with Primary Protect.	Direct	No Interaction

3. INTEGRATED SUBSTATION CONCEPT

The Integrated Substation Concept was proposed in the late 70's through a design of an integrated control and protection system [12]. The main characteristic of the new concept was the use of a distributed multiprocessor system architecture based around a Local Area Network (LAN). In the mean time, the concept was further studied and a number of different ICPS designs were developed. The following sections provide analysis of some ICPS design issues which are essential when the distributed processing EMS application is to be consider.

3.1 ICPS Architecture and Functions

Typical ICPS architecture is given in Figure 1. As it may be observed, it is hierarchical with several levels of data base and processing resources [13]. One of the main design questions is how to allocate the substation functions to the distributed architecture of an ICPS [14].

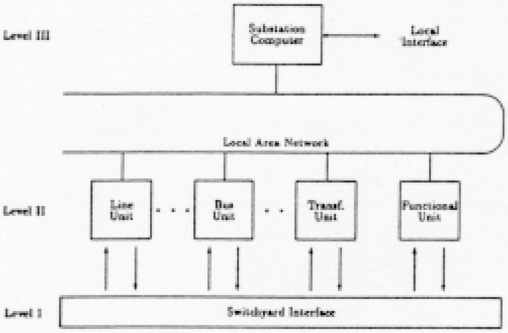

Figure 1. ICPS Architecture

The most common design direction so far was to try to preserve, as much as possible, the classical approach to function allocation. This translates into a requirement that the relaying functions are allocated to the processors at Level II shown in Figure 1. Also, it was assumed that the relaying functions have to have their dedicated field wiring for signal acquisition and tripping commands. The local substation control and monitoring functions are usually allocated at Level III shown in Figure 1. The reason for this allocation strategy was the need to provide these functions with access to the overall substation data base. The designs proposed in the past have incorporated very little deviations from the above mentioned approach and a strong contraversy still remains unresolved as to what level of coordination among data bases, digital algorithms and functions should be provided [15]. The following sections point out the possibilities and requirements for this coordination in the case that the ICPS design is used to implement some new relaying and control concepts.

3.2 ICPS Algorithms and Communications

In the case of the substation function implementations, the first step is related to the field signal processing algorithms. This step produces the required quantities for further processing. Therefore, the selection of algorithms for digital signal processing determines further use of the calculated quantities. In other words, each type of substation functions has a unique requirement regarding field signal processing. This situation lead to the most common ICPS implementation approach described earlier. This approach assumes that all of the algorithm steps for a particular function are executed in one processor cluster and local data bases are used primarily for that function. As a consequence, the communication requirement among different clusters are very limited since only limited data sharing among local data bases is needed. The only exception may be communication between the substation computer and the rest of the processing clusters. However, the LAN communication link may be quite active if some other approach to function allocation and algorithm utilization was undertaken.

3.3 ICPS Interfacing Requirements

This issue is related to coordination among protective relaying, local control and remote control functions. Physical interfaces for the substation protective relaying and control functions are located on the LAN communication system. For the remote control and the system-wide relaying functions an interface between the ICPS and the EMS communication system should also be available. The mentioned interfaces do require careful consideration of a number of different issues such as signal sampling, synchronization, data base management and data transfer time response [2].

Signal sampling is a function of number of consideration, but it can be concluded that any sharing of the field data samples through the ICPS data bases requires some kind of sample synchronization. This can be reflected by a requirment that the same number of samples in a power cycle is taken for different functions, or by a requirement that time synchronization of all sampling in a substation is performed. Since the sampling rate is directly related to the digital signal processing algorithms used, it is important that a methodology for algorithm synthesis is defined so that the same sampling rate can be used for algorithms that are uilized for different applications.

As far as the sampling synchronization is concerned, it is relatively easy to provide the synchronization for the entire substation system. However, the issue of the system-wide sampling synchronization still remains open since the suggested methods [9,16] may still require more analysis regarding complexity, security and the cost involved. Therefore, it can be concluded that only the substation-wide synchronization should be considered as a requirement which is relatively easy to implement.

Data base management is also an important issue since it is expected that several different users (functions) will use the same data base(s). Furthermore, the ICPS data base is distributed to the processing clusters (functional units). The data base updating and accessing has to be carefully coordinated so that the relevant data is provided within the required time-window of an algorithm. Particular attention should be given to the interfacing of the SCADA system data base to the ICPS data base.

Data transfer time response is related to the communication delays involved in transferring samples and calculated values from one data base to another. The most stringent time-response requirement are associated with the protective relaying functions. System-wide data exchange is dependent on the great distances and the large-scale communication network involved. This is the main obstacle for the system-wide relaying implementation. Therefore, a new strategy has to be defined where the system-wide relaying is used as a back-up relaying. As far as the substation-wide communication delays are concerned, it could be safely concluded that the existing LAN standards with 10Mb/s data rate can satisfy almost any time response requirements. This includes the worst case communication requirement where the signal samples have to be shared among different processing clusters within a time frame of several milliseconds (time between samples).

4. INTEGRATION OF THE SYSTEM-WIDE PROTECTIVE RELAYING INTO EMS DESIGN

As indicated earlier, it is assumed that an ICPS is available in all substations and it is used as a substitute for RTUs. The following discussion outlines how the protective relaying, local control and remote control could be implemented in the EMS distributed processing environment created by the use of the ICPS.

4.1 Protective Relaying

The main idea is to provide classical relaying schemes as the primary protection and the system-wide relaying as a back-up protection. Adaptive relaying is also proposed as an improvement of the classical relaying characteristics. However, the system-wide relaying does not appear as a conventional back-up protection but rather as a time-delayed primary protection. Obviously, a careful coordination between the classical and the system-wide relaying is needed in order to provide for an efficient and improved overall relaying strategy.

All of the relaying schemes do require measurements of the analog and the breaker status information. Therefore, algorithms needed for signal and status sample processing are common to all of the relaying functions. However, different calculated values are needed for different relaying schemes. For example, distance relaying used for primary protection may require calculation of parameters R and L or calculation of the phasor quantities. On the other hand, adaptive relaying may require additional sample processing to improve accuracy of the initial values. Finally, system-wide relaying requires current measurements at each breaker.

In order to provide consistent data bases to be shared by all of the relaying schemes, it is required that all of the signal sampling is the same and synchronized throughout the substation. It is also required that all the data bases in the system are updated for each new sample period. In that case, different relaying algorithms can be located at different hierarchical levels of the ICPS. For example, the primary protection algorithms could be located at the processing cluster level (Level II), given in Figure 1. In that case, all of the required data is available in the local data bases of the processing cluster. This level could also accommodate adaptive relaying features such as correction of the calculated line parameters due to the system frequency change [17]. Other adaptive relaying features such as the voltage restraint transformer protection [7] can also be accommodated at this level. However, in this case voltage samples from the line protection unit have to be transmitted, over the LAN communication system, to the transformer protection unit. Figure 2 and Table II give an example of the conditions which indicate feasibility of this approach since the minimum guaranteed access time for each processing unit is less than the time between successive samples.

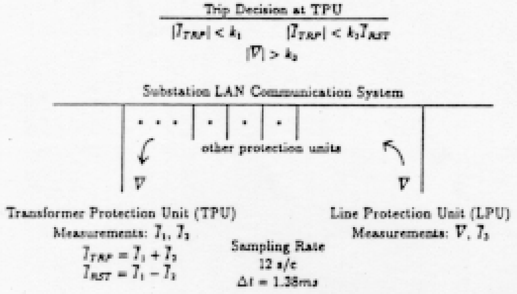

Figure 2. Adaptive Relaying Requirements

Table II: LAN Time-Response Requirements

- transmission protocol	:	token-passing	
- transmission speed	:	10 Mb/s	
- number of PU's	:	16	
- time allotment budget per station is	:	- transmission time for token	$10\mu s$
		- controller processing	$47\mu s$
		- information transmission	$13\mu s$
		Total	$70\mu s$
- minimum guaranteed access time for each PU	:	$70\mu s \times 16 = 1.12\,ms$	

The system-wide relaying algorithms should be located at Level III, i.e. at the substation computer. All of the measurements are performed at Level II but the required calculations of the currents using the theoretical model should be done at the substation computer since its data base contains overall information about the substation. In particular, switching status of the substation can be maintained at the substation computer data base. This data base should also contain information about the "inboard" and "outboard" parameters for each circuit breaker in the system. It means that this data base should have an image of the switching status for the entire power system. The additional information not available locally is brought from other substations through the EMS communication system. Connection of the EMS communication system to the ICPS LAN is shown in Figure 3.

Finally, it is possible to discuss a scenario for protective relaying implementation using EMS distributed design. In order to classify different actions, it is appropriate to consider different operational states of the power system namely normal, alert, emergency and restorative. In the normal state, all the samples are taken at each substation and data bases are updated accordingly. Protective relaying data validation [18] and confirmation of the substation switching typology [19] may also be performed at this time. An iteration of all the algorithms related to SCADA and other EMS functions is executed at this moment. Further discussion related to the normal operational state will be given in the following sections when local and remote function implementations are further analyzed.

As soon as the sampling algorithms detect a disturbance, system goes into the alert state. In this case all of the normal communications are suspended and the protective relaying algorithms are initiated. The primary protection and the back-up system-wide protection algorithms are initiated at the same time. In this case primary protection calculates the values of the fault parameters in order to verify the existence of the fault. Adaptive relaying features are also incorporated in this state. The system-wide relaying algorithms are executed at the substation level. Their execution includes directional measurement and calculation of the current for each of the breakers. The hypothesis testing for "inboard" and "outboard" decisions is also made at this time.

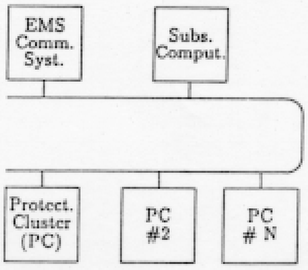

Figure 3. Interface between ICPS and EMS

In the case that the primary protection schemes determines existence of the fault, the emergency state is invoked. The primary protection tripping is then executed with all of the related switching sequences such as automatic reclosing. The system-wide protection algorithm is also executed to determine the Current Minimal Protection Unit (CMPU). In order to determine the CMPU breakers, each substation has to receive "inboard" and "outboard" information for all of the breakers outside that substation. For this purpose, extensive communications are performed through the EMS communication network.

As soon as the primary protection has been executed all of the new breaker status information is collected and verified in each of the substations. At that time status of the CMPU breakers is compared in each substation with the corresponding post-fault switching breaker status information. If a discrepancy occurs, the restorative state is initiated. Actions in this state are aimed to correction of the switching state needed to isolate the fault. Actions in this state would probably be initiated by the dispatcher and limited automatic action should take place.

4.2 Local Control

Once the ICPS becomes a part of the EMS design, a question needs to be asked as how the local control functions, available in the ICPS design, can be interfaced to the EMS remote control [20]. The most elaborate local control function is the automatic switching sequences, but the local control functions also include LTC control on power transformers, synchro-check and automatic synchronization of circuit breakers, and load shedding.

It is obvious that most of the local control functions are executed in the normal operational state and they are initiated by an operator. Therefore, the local control can only be considered as an extension of the remote control, i.e. an extension of the SCADA functions. However, availability of the ICPS system would require a change in the EMS SCADA function design since the related data bases, processing and communications would have to be quite different. The new design of the SCADA data base would assume that an extensive local data base is available in the substation and hence not all of the related measurements and status information would have to be sent to the control center. This approach would intensify processing at the ICPS level and would reduce communication requirements and the processing related to the control center SCADA functions.

The main advantage of the extensive local control functions may come from the reduced time-response and increased security. These functions are initiated by an operator but executed automatically. It is expected that their execution is faster and more secure since the operator is not involved in the execution steps. This feature is particularly important in the restorative state when rapid and secure execution of the switching sequences is needed in order to restore the healthy parts of the power system.

As far as the required data bases, communication and processing are concerned, the local control functions are primarily located at the substation computer level. It should be noted that these functions are mostly blocked during the alert and the emergency states and their main use is during the normal and the restorative states. One of the main implementations problems is how to interface these functions to the relaying and remote control functions. The interface with the relaying functions is mostly maintained through the use of the same data base where overall substation switching status is maintained. Interface with the SCADA requests, issued by an operator in the control center, have to be carefully designed to eliminate conflicts that may be generated by the simultaneous control requests issue by the local substation operator.

4.3 Remote Control

The remote control, in this case, is related to the classical EMS Control Center functions. Availability of the ICPS equipment enables a number of different strategies to EMS function implementation.

One approach is to increase the level of data preprocessing at the ICPS. A very extensive data base and processing capabilities of an ICPS could provide for a distributed SCADA data base. In that case operator at the control center will only be informed about major disturbances and/or actions by a very simple message. This message could be generated by an ICPS based on the full local knowledge about events. In the same way, the control center operator can issue short commands that could be interpreted and executed in the ICPS without direct interaction of the operator during different stages of the command execution. A major benefit in this case can be obtained from utilization of the local control functions.

Another approach is to distribute some of the control center algorithms to the substation level. This can be done by either defining distributed processing schemes for centralized algorithms or by substituting the centralized algorithms by decentralized algorithms. Typical example of the new approach for distributed processing of the centralized algorithms is the state estimation function and the transient stability control is an example of the decentralized algorithms.

Finally, yet another approach is to introduce some new monitoring functions at the substation level. One typical example is the fault diagnosis function. Presently, it is implemented at the control center and requires some quite elaborate expert system techniques [21]. However, the system-wide relaying provides quite accurate indication of the post-fault circuit breaker positions. Therefore, the fault diagnosis function can be implemented at the substation level by verifying the substation topology knowing what the CMPU breaker cutset should be. Another example is new maintenance function which could be introduced to take advantage of the hierarchical data base available in the ICPS. This concept can be applied to the entire substation or to the specific apparatus. An example of the latter is the power transformer monitoring function which can track transformer loading hot-spot temperature, generation of gases, gas content and other parameters. Based on these parameters, new maintenance strategies for power transformer could be implemented taking into account loss of life monitoring.

5. Conclusions

As a conclusion, the following advantages of the given approach and the future research activities can be outlined:

- System-wide relaying is inherently adaptive and therefore it is superior when compared to the classical relaying.
- Use of the ICPS design to implement system- wide relaying provides for distributed EMS environment which in turn enables implementation of the new EMS algorithm processing strategies.
- The main topic for further study of the protective relaying should be more detailed analysis of the coordination problems among primary, adaptive and system-wide relaying.
- New communication systems for distributed EMS design and system-wide relaying implementation should also be a topic of the future research.
- New algorithms and processing approaches for distributed EMS implementation using ICPS designs are other important topics for further analysis.

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RESUME

Ce rapport aborde quelques problèmes de réalisation, à l'échelle d'un réseau, d'un relayage présenté auparavant dans un rapport IEEE. On examine une façon spécifique de réaliser ce relayage là où l'on emploie un Système Intégré de Conduite et de Protection pour remplacer une Unité Terminale Eloignée (UTE) [RTU] d'un Système de Supervision, de Conduite et de Saisie de Données (SSCSD) [SCADA]. Cette approche fait entrer la fonction de relayage de protection dans la conception d'un Système de Gestion de l'Energie (SGE) [EMS]. On analyse les implications de cet aspect d'intégration et on expose les problèmes spécifiques liés à la façon de réaliser les interfaces de fonctions de conduite différentes avec ce relayage.

La première partie de ce rapport décrit une nouvelle approche du relayage de protection basée sur ce relayage à l'échelle d'un réseau. On traite les différences entre le relayage classique et cette nouvelle approche en faisant particulièrement référence aux caractéristiques adaptatives de ce relayage. L'attention est attirée sur le fait que cette nouvelle approche fournit un relayage fondamentalement adaptatif avec une sélectivité et/ou une fiabilité améliorées.

La partie suivante du rapport contient une analyse des caractéristiques du Système Intégré de Conduite et de Protection (SICP) [ICPS]. Cette partie traite, pour le SICP, de divers sujets tels que l'architecture, les fonctions, les algorithmes ainsi que les exigences relatives aux communications et aux interfaces.

Le reste du rapport traite de la réalisation de ce relayage à l'échelle du réseau à travers la conception d'un Système de Gestion de l'Energie à traitement réparti. La majeure part du traitement lié au relayage de protection est réalisée dans les équipements du SICP. La stratégie globale de la protection consiste à employer des relais classiques pour la protection primaire et le relayage à l'échelle du réseau comme protection de réserve. On emploie un relayage adaptatif, au niveau du poste, pour améliorer les performances de la protection primaire. Quelques considérations spécifiques concernent le problème de la coordination de relayages différents. Le reste de la discussion est consacré à des problèmes de réalisation liés aux fonctions de conduite en local et à distance. Il y a à considérer de nouvelles stratégies du fait que le SICP peut être utilisé pour effectuer un traitement local extensif. On propose ce nouveau concept pour la conception de SGE à traitement réparti là où le relayage et les fonctions de conduite en local et à distance sont totalement interconnectées et en même temps coordonnées en un seul système.