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PRACTICAL INTELLIGENT SYSTEM APPLICATION TO PROTECTION, AND SUBSTATION MONITORING AND CONTROL

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Summary - This paper reports on recent findings by the Task Force 34.03 established by the Study Committee 34 (Protection) to investigate practical intelligent system applications to protection, and substation monitoring and control. The intelligent system techniques of interest included expert systems, neural nets, and fuzzy logic while some other recent developments such as genetic algorithms are not investigated at this time. The Task Force has looked at two issues: status of the implementations today, and application areas where future implementations may bring major benefits. The review of the implementation status has revealed that most of the applications today are not in the protective relaying area but rather in the related areas of substation monitoring and control. The assessment of the future applications and benefits indicates that there are some promising improvements in the existing implementations of protective relaying functions and systems as well as in the new areas of system wide monitoring, relaying and control.

Keywords: Intelligent Systems-Protection-Monitoring-Control-Neural Nets-Expert Systems-Fuzzy Logic

1. INTRODUCTION

The intelligent system applications to the power systems area date back to the mid eighties [1-3]. As soon as the first implementations were completed and tested, the results have shown some potential advantages. This has initiated a number of studies and pilot projects to confirm practical aspects and benefits [4]. In some countries such as the USA, France, Portugal, and Japan, the initial developments and field applications were quite elaborate and field demonstrations span over a number of years [5]. The intelligent system applications generated considerable interest within CIGRÉ Study Committees as well. The Study Committee (SC) 38 (Power System Analysis and Techniques) has established an Advisory Group to review applications of intelligent systems to power systems. Initially a Task Force (TF) from SC 38, together with a Task Force from SC 39 (Power System Operations and Control) has examined major aspects of applications of expert systems [6]. After that, several SC 38 TF reports were generated covering applications of Artificial Intelligence in fault diagnosis [7], artificial neural networks for power systems [8], and experts systems to education [9]. Most recently a TF report on testing and maintenance of expert system solutions was also published [10].

The interest in intelligent system applications has also been initiated within the Study Committee 34 (Protection) by forming a working group "Configuration, Functional Integration, and Use of Expert systems" in 1993. As a result, a paper on the expert system applications has been published at the Helsinki Symposium in 1995 [11], and the Task Force 34.03 was formed in 1997. The final reports of the Working Group and Task Force are expected in 1998, with a summary of the Intelligent System Applications Section of the WG report to be published in Electra.

Finally, the other professional organizations such as the Institute of Electrical and Electronics Engineers (IEEE) have shown considerable interest in the subject. The Power Engineering Society (PES) of IEEE has at least three working groups in different committees and one subcommittee active in this area. The PES Power Systems Relaying Committee (an equivalent of the CIGRÉ SC 34) had formed a working group to survey application of expert systems to protective relaying, and the WG report was published in 1995 [12]. An extension

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of this Working Group activity was initiated in 1993 to survey the status of intelligent system applications in Protection Engineering. This WG report is expected to be released in 1998.

Based on the information contained in all of the mentioned reports and papers, the TF 34.03 has decided to make an assessment of two major issues: status of the implementations today, and application areas where future implementations may bring major benefits. The following sections contain initial results of this assessment.

2. APPLICATION AREAS OF INTEREST

Selection of areas of interest may be directly tied to a conclusion that the existing protection, control and monitoring applications may need further improvements, and hence the look at the benefits that the intelligent systems may bring to these areas. This notion that the improvements may be needed has created some skepticism within many industry segments since it is widely understood that the existing protective relaying techniques and approaches are quite cost effective and have been proven to be reliable for the last 50 years. Therefore, the assessment given below that indicates the needs for improvement in the existing protective relaying functions may be subject to interpretation, if not controversy.

It is far easier to talk about intelligent system applications in the new areas where the standard solutions are not available. In that case the intelligent system implementations are quite competitive since the criteria for acceptance is not biased by the performance of an existing solution, but is set based on a totally "fresh" view of the requirements. In this area it was easier to point out to some major potential benefits coming from using the intelligent techniques.

2.1 Improvement in the Existing Protective Relaying Solutions

To illustrate the areas of improvement in the existing protective relaying solutions, the following examples are selected: distance relaying, overcurrent relaying, transformer differential relaying, and bus-bar differential relaying. For each of these applications the improvements may be needed because of inaccurate data (as a result of complex nonlinear phenomena such as CT saturation, transformer inrush, arcing faults, high resistance faults); insufficient data (lack of measurements from the remote end for transmission line relaying, lack of voltage information for the differential relaying, lack of precise loading condition and switching state measurements for all the relaying functions); incomplete data (sequence values may not be accurate, detailed power apparatus models may not be available, only limited empirical field data is available).

Typical examples of the areas needing improvements in the distance relaying function are listed in Table I. For each of the areas, a description of the difficult conditions for the existing solution are listed [13].

The well known difficulties with the overcurrent protection are the ability to cope with drastic changes in the loading conditions, occurence of harmonics, and noise associated with arcing faults. The differential transformer relaying operation can seriously be affected by inadequate inrush current or overexcitation sensitivity as well as significant CT saturation or the ratio mismatch due to LTC operation. The bus bar protection still has the major difficulty in providing reliable operation for severe CT. saturation conditions or diverse bus bar switching schemes.

Table I. Areas in Distance Relaying That Need Improvement

Distance Relaying Function	Description of Difficult Conditions
Fault Detection and Classification	Faults during line energization, arcing faults, faults generating substantial DC offset and harmonics
Fault Location Estimation	A strong infeed from the other end, extensive mutual coupling, time varying fault impedance, CCVT "ringing" under a voltage collapse conditions, CT saturation
Autoreclosing	Discrimination between arcing vs. solid faults, accurate phase selection for single pole action, CT saturation
Protection of Series Compensated Lines	Selection of the "appropriate" voltage and current under dynamic conditions of the MOV and gap operation
Estimation of System Frequency	Estimation of the distance using frequency sensitive digital algorithms
Out of Step Conditions	Discrimination between "normal" power swings and "out of step" conditions
Protection of Parallel Lines	"Symphatetic trip", protection under power reversal conditions, over-reach and under-reach due to a fault on a parallel line

In almost all of the mentioned areas of improvement, the problems that need to be dealt with are further exaggerated by the changes in the utility industry where de-regulation and increased competition may bring new practices into system operation. Typical examples of the consequences are significant variation in the loading conditions, sustained operation at the point very close to the rating limits, excessive switching to accommodate selection among a variety of competing generation sources, increased de-emphasis on the trade-off between security and dependability with a tendency to require the schemes that are both secure and dependable. All of these consequences may require a major improvement in the various functionalities mentioned above.

2.2 Improvement in the Existing Protective Relaying – Related Functions

A variety of the related functions may also need further improvements. Most of the mentioned functions are related to the off-line applications such as maintenance (diagnostics, testing, change of settings) and planning (selection of settings, selection of the relaying schemes, anticipation of new protective relaying requirements). For those applications, the need for the improvements may directly be driven by the new requirements for reduced maintenance cost and improved reliability of system operation. A list of the possible areas for the improvements is given in Table II indicating the difficulties that are faced by the existing solutions.

Table II. Areas in Protective Relaying-Related Functions That Need Improvements

Relaying – Related Functions	**Description of Difficult Conditions**
Fault Location	Infeed from the other end, changes in source impedances, mutual coupling, fault resistance
Monitoring of Communication Channels for Relaying Schemes	Loss of carrier, spurious noise, "weak" signal, electromagnetic interface
Monitoring of Relay Operation (self checking)	Consistency of input/output channels, diagnostic of different failure modes
Setting Coordination	Dynamic changes in system conditions, changes in system parameters, selection of appropriate setting groups
Communication Between Relays and Operators	Complexity in the menu options, interpretation of the data measured by the relay, selection of operating characteristic options and relaying schemes
Calibration and Application Testing	Automation of testing procedures, generation of test reports, interpretation of test results

2.3 New Applications

As the power systems become overloaded for improved efficiency and retrofitted for more flexible control, a variety of new protective relaying and related functions may have to be specified. Even though, the generic terms for some of the relaying functions may be preserved, their functional requirements may be so different that a completely new implementation may be needed. Typical examples are the transmission line relaying functions for the lines whose load may be controlled by FACTS or nearby HVDC lines. For the lower voltage levels, the protection that needs to discriminate between faults and various power quality disturbances such as harmonics, voltage dips and switching transients may have to be developed.

A more complex solution may be required for the new relaying functions that may have to be implemented to preserve system-wide reliability of operation. Typical examples of these new functions are given in Table III. The tasks associated with each of the system-wide protection functions are also outlined.

Table III. New Applications for System-Wide Protection

New Function	**Tasks**
Wide-Area System Stabilizing Protection	Detection of the unstable conditions, tripping of the critical generators/loads
Wide-Area Overload Protection	Discrimination between an overload and a fault, implementation of an appropriate tripping action to alleviate overload
Wide-Area Protection Against Voltage Collapse	Detection of the voltage problems and implementation of an appropriate high speed local control action
Wide-Area Under/Over Frequency Protection	Detection of the complex changes in the frequency patterns, implementation of a selective load shedding and generator rejection schemes
Wide-Area Protection Against Sequence of Disturbances	Application of the special protection schemes for variety of sequences of disturbances

An additional area where new applications may be needed is the area of equipment monitoring and diagnostics. Even though this application area is not considered a part of the traditional protection engineering activity, it is expected that this area will draw considerable attention of the protection engineer in the future. As an example, a close monitoring of the power transformer incipient faults, slow evolving faults on the cables, and degradation of the circuit breaker performance may very well be new applications that will be considered an integral part of the protection systems in the future. Another example is an extensive on-line monitoring for the communication channels, protective relays, and controllers. This may also place an additional requirement on the design of the relaying systems in the future.

Finally, the area of continuing education for engineers and technicians may also be a challenging application area for the use of new techniques. It is well known that the industry restructuring and deregulation have created an unprecedented circulation of the technical staff. Under these circumstances the continuing education effort becomes quite important. The role of unconventional techniques in facilitating the transfer of knowledge will need to be investigated [9].

3. STATUS OF IMPLEMENTATIONS

Even though hundreds of papers were published on the subject in the last ten years, very few implementations have reached a maturity of being practical. The following survey is based on some examples where sufficient information is published to suggest that major improvements have been achieved. The survey is grouped into the following categories: protective relaying, related control functions, fault analysis, and setting coordination.

3.1 Protective Relaying Applications

Three protective relaying applications have seen major improvements from the use of intelligent techniques. These relaying applications are listed in Table IV providing the outline of the benefits and associated published references where these benefits are further elaborated on.

Table IV. Implementations in Protective Relaying

Relaying Function	The Technique and Related Improvements	References
High Impedance Fault Detection	Expert system and advanced signal processing techniques used to improve selectivity of HIF Detection	[15]
Distance Relaying	Neural net applications bring improved fault detection, classification, directional discrimination, parallel line protection, series compensated line protection, and autoreclosing	[13]
Transformer Current Differential Relaying	Fuzzy logic applications bring improvement in transformer differential protection by providing a multi-criteria approach	[16] [17]

One of the main obstacles for wider use of the intelligent techniques in the protective relaying area is the stringent time response requirement for the relaying functions. Computation of an intelligent technique-based relaying is typically more time consuming than what is acceptable. Hence only a function with a relatively slow time response (high impedance fault detection), or a fragment of a function (parts of the distance relaying function) could easily be implemented so far.

3.2 Related Control Functions

The relaying functions may not be considered as directly involved in the system control actions today. However, the relaying is performing an on/off control action in itself, and may also call for some operator-initiated or event initiated control actions. Hence, it is quite appropriate to consider some of the related control function implementations as the part of the protective relaying applications.

There are very few examples of a successful implementation of the intelligent techniques for some control functions related to the protective relaying action. One is development of a new voltage control equipment using Fuzzy Interference [18]. The other one is the use of expert systems in providing advanced operation guidance for a 500 kv substation [19]. Several attempts at improving the autoreclosing function were also made using neural net techniques as mentioned in the earlier discussions related to the improvement in distance relaying [13].

3.3 Fault Analysis

The fault analysis is a term widely used to designate a variety of functions associated with analyzing fault events. Most of the intelligent system applications to this area are related to the use of expert systems and neural nets to automatically analyze alarms and other switching events using SCADA systems [6,7]. For the purpose of our discussion, we are only concentrating on the implementations related to the analysis of the data provided by the equipment typically used by the protection engineers. Table V lists some of the recent implementations indicating the intelligent techniques used and referencing the published sources.

Table V. Implementation in Fault Analysis

Equipment/ Function	The Technique and Related Improvements	Reference
Digital Fault Recorders	Expert system and neural net based automated data analysis	[20] [21]
Sequence of Event Recorders	Expert system and model based automated data analysis	[22] [23]
Digital Relays/Fault Locators	Use of expert systems for relay failure diagnosis; Use of neural nets for fault location improvement	[24]* [13]

* The technique described in ref. [24] is used for relay failure diagnosis application.

3.4 Relay Setting Coordination

The problem of the relay setting coordination requires two important steps that need to be implemented in order to accomplish this function. The first step is calculation of short circuit currents while the next step is coordination of settings. For both of these steps, intelligent system techniques were recently used.

The use of neural nets in improving the short circuit computations was reported in [25]. The improvement was related to an ability to perform fast and direct assessment of short circuit currents in the cases of changing network topology and parameters.

The use of expert systems in improving the setting coordination has been reported by several authors [26-27]. The main improvements that are claimed by the developers were the benefits of consistent decision making, fast proof of the concept, and easy verification of the setting constraints [26].

4. FUTURE EXPECTATIONS

To pave the way for further evaluation and assessment of intelligent system applications, it is important to recognize that a variety of issues have yet to be resolved. After these issues are resolved, future intelligent system applications may be more likely to produce expected benefits. The following discussion is centered around definition of the issues to be resolved as well as the applications expected to be implemented in the near future.

4.1 Issues to be Resolved

One of the main issues to be resolved is the specification of the areas of improvement in the protective relaying field. Even though, most of the experts would agree that some improvements are needed, there is no clear definition of the required improvements. The difficulty in developing the improvement requirements may be driven by the lack of the definition of the difficult applications where some of the existing solutions may fail, or the existing solutions can not meet the requirements and new solutions are needed.

This problem of the lack of the agreed upon field applications, that may be used to specify the new requirements and evaluate new solutions, directly leads to the issue of the availability of adequate assessment tools and methodologies. As it is well known, development of digital simulators for relay testing has opened a wide area of possibilities in specifying realistic test conditions and evaluating new relays and relaying implementation techniques [28]. With this in mind, it is critical that the new tools are used to specify a methodology for evaluating the existing and new solutions for some difficult application cases [29]. It appears essential at this time that a set of power system configurations and operating conditions be clearly specified for evaluation of the existing and new solutions. Having defined the improvement targets, the developers of new intelligent system applications can have a clear indication of what are the expected performance requirements to be achieved with the new techniques.

Another important issue is definition of the new applications that may be needed in the future due to de-regulation and increased competition. Again, a clear specification of the requirements may be needed to initiate development of some practical application using new techniques. An issue directly associated with the new applications is the criterion for cost/performance assessment of the new applications. It is obvious that the criteria set for the existing applications may not be acceptable for the new applications. This consideration is extremely important since some of the new techniques may require totally different engineering, maintenance and educational tools to deal with every day task of designing, developing, implementing and supporting the new solutions. Not only that the tools may be different, but the required skills may be different as well. Altogether, the initial cost to bring these changes into the practice may be quite high. A very simple question that may require a complex consideration to obtain an answer may be asked: even though the final performance benefits may be quite attractive, is it really desirable to bring the intelligent systems into the practice at an increased overall cost.

At this stage it is probably unrealistic to expect a simple answer to the above question. It is more realistic to wait for the cost/performance criteria of de-regulated environment to establish itself together with related specifications of the required solutions. In this effort, it is important that the community of protection engineers gives its contribution by keeping an open mind towards intelligent techniques and its potential benefits.

4.2 Future Applications

This section points to a variety of future applications that have shown some promise through initial developments recently reported. The examples of such applications are: substation wide disturbance detection and classification, substation wide equipment status monitoring, adaptive relaying and automated control, system-wide disturbance monitoring and related stability control. A summary of expected benefits is given in Table VI.

The new applications are definitely dependent upon an ability to automatically search through a variety of operating constraints and conditions, which is very well handled by the expert system technology. The ability to deal with a variety of unfolding nonlinear problem solving tasks in parallel and at a high speed will also be desirable, which is very well handled by the neural net technology. Finally, many situations where the decisions need to be made using imprecise data will also have to be handled, and the fuzzy logic technology is quite suitable for these tasks.

One final observation is that most of the new applications may require the use of variety of the new technologies combined in a hybrid solution. It is, therefore, expected that future investigations will be centered on the advancements in the applications of the individual technologies as well as the new approaches of combining various technologies.

Table VI. New Intelligent System Applications and Expected Benefits

Application	Expected Benefits
Substation Wide Disturbance Detection, Classification and Analysis	Ability to utilize data from digital relays, digital fault recorders, sequence of event recorders and other IEDs in analyzing the events automatically.
Substation Wide Equipment Status Monitoring	Ability to utilize local measurement from new sensors and classical monitoring equipment in predicting the maintenance needs
Inherently Adaptive Local Relaying and Automated Local Control	Ability of the relaying to operate under any prevailing operating conditions maintaining high selectivity and dependability; ability to isolate and/or restore the faulted equipment automatically
System-wide Disturbance Monitoring and Related Stability Control	Ability to use protective relaying and other specialized controllers as a system-wide structural control system aimed at maintaining system stability under wide area disturbances

5. CONCLUSIONS

The following conclusions can be formulated as the TF recommendations:

- The existing applications of the new technologies that have produced clear benefits are rare and are mostly related to the local monitoring and control functions.
- The relaying applications that have shown some benefits from using the intelligent techniques are very limited and include some selected distance relaying functions, power transformer differential protection, as well as some improvements in the overcurrent protection and high impedance fault detection.
- In order for the new technologies to be thoroughly evaluated for the benefits that they may produce, a clear definition of improvement targets for the existing solutions have to be developed, which is not available today.
- A major expectation of the new technologies is in new developments related to further automation of the local actions as well as in the system-wide coordination of the relaying and control.
- The CIGRÉ SC 34 needs to extend its work to define a set of criteria and applications that can be used to evaluate the improvements in the existing implementations and benefits of the new solutions that can be developed using the intelligent techniques.

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