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A survey of neural net applications to protective relaying and fault analysis

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This paper gives a survey of the Neural Net (NN) applications to protective relaying and fault analysis. The survey has concentrated on some recent NN applications reported in the literature up until early 1997. The main purpose of this survey was not to illustrate the variety of the NN approaches proposed so far but rather to indicate the most promising implementations as they related to the actual relaying and fault analysis problems that exist today and may benefit from the new approach.

Keywords: artificial neural network, neural net computing, power system protection, power system fault analysis

INTRODUCTION

The history of artificial neural networks is quite extensive and diverse to be mentioned in this focused article. The history of neural-net (NN) computing is not that long and can be traced to some recent origins [1]. A number of survey articles point to the early sixties as the period when some major fundamental concepts for NN computing such as the Perception Rule and LMS Algorithm were introduced [2]. Soon thereafter, a variety of new implementation ideas were proposed [3]. The computing with neural nets became a well established field by the late eighties [4].

The application of NN computing to power systems has a relatively short time span of less than 10 years [5]. In this time period a number of NN applications to power system monitoring, control and protection have been tried and some field implementations have been realized. However, the initial implementation activity was not equally strong in all parts of the world. Some regions, in particular Japan, were leading in the number and variety of implementations at that time [6].

As of now (summer 1997), the number of applications is quite impressive. However, the implementations are not equally spread over the power system applications. While the areas such as load forecasting and security assessment may have a number of practical solutions already implemented, other areas such as protective relaying and fault analysis are still at an exploratory stage [5].

This paper provides a survey of the application attempts in the protective relaying and fault analysis area. It should be recognized that this area has not seen practical applications as of yet, even though a formidable number of references have been published on the subject. In making a survey, this paper will not attempt to give an all-encompassing review of most of the published references. It will rather make an attempt to survey some promising directions and point to the references that can be used as a comprehensive description of these directions.

In order to accomplish its goals, this survey will start with a brief overview of the protective relaying applications and requirements that are the background of the survey. After that, a survey of the NN applications in transmission line relaying, other relaying, fault analysis, and applications related to protective relaying will be given in separate sections of the paper. The last section is devoted to the general issues and future directions.

Last, but not least, the time span covered by this survey should be noticed for the sake of further updates and future references. This survey will attempt to trace the origins of some of the applications and will cover various developments reported in the literature up until the early summer of 1997.

2. PROTECTIVE RELAYING APPLICATIONS AND REQUIREMENTS

It is obvious that any new technique applied to the field of protection relaying faces an extraordinary challenge to prove that its application can bring major cost/performance improvements. The application of the NN computing should not be an exception. However, the review of the references on this subject reveals that most of the authors did not feel obligated to stand up to the challenge. Hence most of the references are not making strong arguments and providing hard evidence of how the application benefits can be derived.

In order to bring some focus to the survey, this section points out some well recognized problems and issues associated with the existing practical approaches in the protective relaying and fault analysis areas. The focus is related to the application aspects that may require further improvements. Therefore, the improvements related to these applications may represent a good reference case for demonstrating the benefits of the NN approaches.

2.1 Transmission line protection

As it is well known, one of the most popular transmission line protection principles for the high voltage applications is the distance relaying. This principle has been used for over 50 years and demonstrated as quite reliable. However, some specific functionalities of this principle are still under investigation with a goal of finding better solutions in the future. Some examples of these functionalities with an indication of the potential problems are given in Table 1.

Table 1 Improvement targets for distance relaying

Target	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, and time varing fault impedance, CCVT "ringing" under a voltage collapse conditions
Autoreclosing	Discrimination between arcing vs. solid faults, accurate phase selection for single pole action, CT saturation.
Protection of Series Compensated Lines	Selection of the "appropiate" voltage and current under dynamic conditions of the MOV and gap operation
Estimation of System Frequency	Estimation of the distance using frequency based 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

2.2 Power transformer protection

Again, it is well known that power transformer operation creates some phenomena that are making the protection quite involved. Typical conditions are:

- Over excitation
- Inrush due to the transformer energizing
- CT saturation and mismatch

Under all of these conditions, the transformers may not be experiencing a fault, but the standard differential protection may be seeing a large differential current which in turn may result in the transformer protection operating. It is fortunate that most of the above phenomena can be distinguished based on some unique signal components such as high harmonic content or specific pre-fault conditions.

2.3 Busbar protection

One of the main problems with the busbar protection is the current transformer (CT) saturation. It occurs due to a high level of fault currents. At the moment of saturation, it becomes difficult to distinguish between a high loading and busbar faults. Since the tripping of a busbar may create a major black-out of a substation, further improvements are needed for making the busbar protection more selective.

2.4 Detection of high impedance faults

The high impedance fault detection (HIFD) in distribution systems may be associated with incipient events generating extensive arcing. Up until recently, a variety of different schemes for detection of the faults under arcing conditions were tested and very few have shown satisfactory performance. The methods that show definite ability to deal with the HIFD problems have been used today in extensive field trials[7]. It has been observed that these methods are able to detect high impedance fault conditions in most cases, while some difficult cases still remain undetectable. Therefore, an improved HIFD technique is still a continued goal of the future research.

2.5 Fault analysis

This application area is very broad and ranges from alarm analysis in the Supervisory Control and Data Acquisition (SCADA) systems, to the analysis of Digital Fault Recorder (DFR) and Sequence of Events Recorder (SER) files. In addition, the fault analysis may include definition of the restoration strategies. In some instances, analysis of incipient faults on power transformers and monitoring of circuit breaker operation may also be considered the tasks of the fault analysis.

Table 2 Description of common fault analysis problems

Application	Problem Description
SCADA	Lack of the temporal element, large volume of alarms, scanning instead of synchronized sampling of analog signals.
DFR	Large volume of data due to the high sampling rate, missing information due to incomplete connections in substations.
SER	Lack of reliable identification of the event that caused equipment operation, missing information about the change in analog signals.
Power Transformers Diagnostics	Slow evolving events, lack of empirical data, difficulty in correlating multiple events.
Circuit Breaker Diagnostics	Large volume of data, difficulty in having a reliable way of detecting CB state, difficulty in predicting failures

In any case, it has been well recognized that several common problems are found attempting to automate this function. A brief description of these problems is given in Table 2 for each of the fault analysis approaches.

2.6 Other related applications

Only a few additional applications will be mentioned to provide a reference to the related NN applications mentioned later on in this paper.

The load shedding application is quite interesting due to the wide area impact that it may have. It always has been a challenge to find a reliable technique that will be able to account for the varying rate of change of the system frequency.

The short circuit calculation under changing network topology and parameters is also a difficult problem. The existing techniques are not readily fit to deal with this problem.

Other interesting applications such as fault diagnosis in HVDC network, accurate fault location on transmission lines, and detection of animal caused distribution faults are also examples of applications that may benefit from improved techniques.

3. THE NN APPLICATIONS IN TRANSMISSION LINE RELAYING

Most of the reported applications are related to improvements in the distance relaying principle. Several references are also concentrating on some auxiliary functions such as autoreclosing, adaptive relaying and fault location. The survey of these references will first concentrate on the distance relaying, followed by other line protection and related applications.

3.1 Distance relaying improvements using NN

The largest number of published references dealing with the NN application in protective relaying is related to the improvements in distance relaying. Even though, some references are not mentioning the distance relaying functions as such, if they deal with some important implementation aspects of the distance relaying, they are classified in this group. A survey of the distance relaying related applications is given in Table 3.

Table 3 The NN applications related to distance relaying

Function	References	Improvements indicated by the authors
Fault Detection And Classification	[8]	Distinction between arcing and non arcing faults
	[9]	High speed fault detection and classification under changing system conditions
	[10]	Fault classification for the EMV lines with unified power flow controller
Directional Discrimination	[11]	Application to ultra-fast directional comparison scheme
	[12]	Accurate and reliable fault direction determination
Fault Characterization	[13], [14] [15], [16]	Improvements in determination of the distance and fault area estimation
Improvements in the Fault Distance Computation	[17]	Elimination of the influence of the DC offset
	[18]	Immunity to the CT saturation
	[19]	Applications suitable for series compensated lines
Adaptive Relaying Features	[20]	Applications to double-circuit lines
	[21]	Selection of appropriate operating characteristic
Autoreclosing and Related Functions	[8], [16], [22], [23], [24]	Improvements in the arcing fault detection and phase selection

3.2 Other line protection and related applications

A variety of other references have concentrated on some specific problems related to the protection functions other than distance relaying. In addition, several references have covered some applications that are not directly related to the protection but represent a major auxiliary application. A survey of these references is given in Table 4.

Table 4 Survey of other line protection and related applications

Function	References	Improvements indicated by the authors
Fault Location and Selection of the Faulted Line in a Network	[25]	Improved single-ended fault location
	[26]	Improved fault location for series compensated lines
	[27]	Improved fault location based on the ground wire current distribution
	[28]	Improved selection of the faulted line in a network
High Impedance Fault Detection	[29] [30]	Ability to differentiate between HIF and normal loading conditions
Distribution System Protection	[31]	Detection of animal-caused faults in distribution systems
Fault Disturbance Detection	[32], [33]	Detection and classification of different types of disturbances
Out of Step Protection	[34]	Advantage of initiating early tripping for unstable swings while avoiding tripping on stable swings

4. THE NN APPLICATION TO POWER TRANSFORMER PROTECTION AND FAULT ANALYSIS

The power transformer applications are next to the transmission line applications regarding the number of references published. Two major areas of study can be recognized for the NN applications. One area is related to the improvements in the power transformer protection. The second area is the fault diagnosis related to detection of incipient and slowly evolving faults.

4.1 Improvements in power transformer protection

All of the papers in this application category are concentrating on the improvements in the current differential relaying scheme, which is the fundamental scheme used in the transformer protection.

The references range from some very general considerations[35] to some very specific suggestions for the improvements. The first specific suggestion is given for the improvement in the ability to distinguish between magnetizing inrush and internal faults[36, 37]. The second specific suggestion is related to the improved relaying operation under a condition of the current transformer saturation[38]. A combined improvement for both problems is reported in a recent reference[39].

4.2 Power transformer fault diagnosis

As it is well known, power transformers are prone to incipient faults that may eventually result in catastrophic failures. In order to prevent such failures, it is very important to be able to detect the incipient faults at their early stage of development.

Two very common techniques for detection of incipient faults are the dissolved gas-in-oil analysis and estimation of partial discharge location. The neural nets have recently been applied to both problems. The dissolved gas-in-oil analysis can be enhanced by using NN to identify the relationship between the fault types and dissolved gases[40, 41]. The estimation of partial discharges can benefit from NN being applied to the ultrasonic signals to extract the fault location[42].

5. THE NN APPLICATIONS IN FAULT ANALYSIS

The fault analysis is an application area that has a variety of solutions depending on the type of the data acquisition equipment used as well physical location of the system implementation[43]. As a result, the application may cover alarm processing based on the data collected by the SCADA system situated in a centralized EMS location. Yet another approach may include the processing of the local substation data obtained through an enhanced Remote Terminal Unit (RTU) design. In addition, digital fault recorders (DFRs) and Sequence of Events Recorders (SERs) may be the source of data aimed at evaluating individual faults and related equipment operation. Finally, a hierarchial solution aimed at both the local substation as well as centralized EMS processing may be defined. In all of these cases, NN applications can be defined as a part of the fault analysis process. A survey of some typical examples of different NN application approaches is given in Table 5.

Table 5 Survey of fault analysis applications

Application	Reference	Improvements indicated by the authors
Alarm Processing (centralized)	[44], [45]	Faster and more selective extraction of the relevant fault information for the system
Alarm Processing (substation based)	[46], [47]	Faster and more selective extraction of the relevant fault information for the substation
Fault Analysis (DFR Based)	[48], [49]	Faster and more selective fault analysis for a given line
Alarm Processing (Hierarchical Solution)	[50], [51]	Faster and more selective fault analysis at both the local and centralized system levels

6. OTHER PROTECTIVE RELAYING AND FAULT ANALYSIS RELATED APPLICATIONS

The NN applications were also extended to a variety of other protective relaying and fault analysis problems. Even though, some of these applications may be quite unique, it may be useful to mention some of them in this survey to indicate some future directions.

An arbitrary selection of some promising NN applications that are related to the protective relaying and fault analysis area is given in Table 6.

Table 6 Some additional NN applications related to protective relaying and fault analysis

Function	References	Improvements Indicated by the Authors
Failure Diagnosis of Underground Oil Switches	[52]	Significantly better classification of the oil switch status than what is available with the current threshold classification method
Fault Diagnosis in HVDC Systems	[53]	Improvements in rapid and reliable detection of different types of equipment faults
Load Shedding	[54]	Intelligent decisions in selecting the load to be shed and avoiding unintentional operation
Short Circuit Calculations	[55]	Capabilty to perform fast and direct assessment of short circuit currents in the cases of changing network topology and parameters
Busbar Protection	[56]	Ability to cope with distorted current signal due to the CT saturation
Frequency and Harmonic Evaluation	[57]	High accuracy evaluation under supply-frequency drift and transient situations

7. OPEN ISSUES AND FUTURE DIRECTIONS

After reviewing the references mentioned in the survey, a number of open issues and possible future development directions can be noted. This section summarizes the findings related to the selection of NN applications, NN implementations, NN training and evaluation, software tools for implementation and testing, application benefits and field demonstrations.

7.1 Selection of NN applications

The review indicates that most of the development efforts were related to the most common relaying functions such as distance protection for transmission lines and transformer current differential protection. This is expected due to the importance, complexity and wide application of the mentioned protection principles. However, it is interesting to note that NN applications were mostly related to the fault detection and classification, which confirms the unique NN capability to act as a pattern classifier.

It is somewhat surprising that other applications such as overcurrent and busbar protection did not get more attention in evaluating suitability of the NN approach. In addition, the generator protection did not seem to attract much interest for NN applications as well. It is not clear why this is the case when all of the mentioned applications also seem to have a need for a reliable fault detector and classifier. Some future developments in this area are expected in the near future.

As per other non-relaying applications, it appears that fault analysis and detection of equipment incipient failure had created a lot of attention for NN applications. The ability of the NN architecture to process data in parallel and in a hierarchial fashion has been exploited in the fault analysis applications. The NN ability to learn from historical data was quite useful in the equipment diagnostic area. More developments are expected in both the fault analysis and equipment diagnostic areas in the future.

7.2 The NN implementations

The NN implementations are evaluated based on the NN architecture, transfer function and learning rule. It is quite amazing to note that almost all the papers are talking about the use of the feed forward multilayer perception (FFMLP) type of the architecture with the basic three layers being a typical choice. The transfer function selected almost uniformly throughout the papers was the sigmod nonlinear type. The back propogation learning rule was also selected in most of the references. Very few exceptions to the above mentioned choices were made in some references [22, 28, 33, 43, 47, 49, 55, 57].

Regarding the details of the NN architecture, most of the implementations were based on a three layer selection. The number of nodes is varying quite widely, since this is dependant on the application. The number of hidden layers is also different in some applications and varies from one in most applications to two in very few applications [17, 40, 54].

It is interesting to note that other types of NN architectures and related implementations have drawn very little attention even though they are widely used in some unrelated power system applications [4, 5]. Even for the FFMLP type of NN architecture, the variation in the details of implementation were rather minor from one application to the next. For the cases where the variations were noticeable, no clear evidence of the reasons for the choices was noticed. In general, for any of the decisions related to the choice of the NN architecture and other implementation details it was not made clear by the authors as why these particular decisions, and not some other ones, were made.

It is expected that the future approach will provide some answers to the above mentioned questions when the criteria for the particular implementation choices will be defined.

7.3 The NN training and evaluation

The NN training and evaluation are the most confusing issues that are treated in a far less comprehensive way than any other issue mentioned in the references. The choice of the types and number of training patterns, the methodology for the training sequence, and selection of the optimal training conditions are not elaborated on in enough detail in almost any of the references. Of course, a variety of details are provided in the references, but the information provided in most of the cases is impossible to use to perform an independent verification of the results by the reader.

Another observation is that most of the protective relaying applications were tried and tested using some form of the ElectroMagnetic Transient Program (EMTP). This is a well established tool for analysis of fault transients. However, very limited information on the selection of particular real-life systems and operating conditions is provided in most references. This fact is again restricting the reader from fully appreciating the difficulty and suitability of the selected EMTP based training and evaluation cases.

The fault analysis and equipment diagnostic applications are in particular difficult to evaluate since the information on practical data used for the training and evaluation is very limited and in some cases almost non-existent. The authors have only made the statements that the data may be realistic, but no further evidence is provided in many cases since most of the data is empirical and no simulation data is available.

As per the future trends and needs, it is definitely desirable for the authors to give special attention to the above mentioned issues. This is needed if any level of serious confidence is to be developed on the user's side for the future NN applications.

7.4 Software tools for implementation and testing

Most of the NN applications were implemented using custom software tools such as the 'C' or 'C++' programming language [11, 40, 50]. However, some of the references are relying on the use of standard NN toolboxes such as the one provided as a part of the MATLAB Signal Processing Package [36].

As per the software tools for testing of the NN implementations, the most commonly used tool is the EMTP. As mentioned earlier, this tool is widely used for the fault studies and recognized for its ability to produce very realistic transients as well as prefault and postfault steady state waveforms. It should be noted that the EMTP use may be limited in the cases of internal fault simulations, for power transformers and machines, for example. The EMTP use for evaluation of the NN implementations has to be verified through field test, which should be a standard practice in the future.

One important development that may facilitate future training of the NN based solutions is the new digital simulator technology [58]. The latest developments in this area allow for implementation of automated procedures for power system simulations and related NN training.

It is expected that future developments in this area will be facilitated through availability of more NN toolboxes as well as more versatile EMTP programs.

7.5 Application benefits and field demonstrations

Based on the published references, it is quite difficult to assess all of the benefits and results of the field demonstrations for several reasons. One reason is that some of the assessment results may be proprietary due to the advanced applications that may have some commercial advantage in the future and the information was not included in the papers. The other reason is the bias that most authors embrace, even unconsciously, to made the result look attractive. This is not a new approach or attitude developed just for the NN applications but is rather wide spread event when brand new techniques are evaluated. This is probably why there were no papers published so far that had a critical review of the NN applications including a comparative evaluation of the NN architectures and related implementation performance. A major problem is also the nature of the NN implementations where selection of the architecture and training cases is directly tied to the particular details of the application. Since most of the authors do not provide enough details about the evaluation models and simulations, it becomes quite difficult for a reader to repeat any of the study results to be able to make its own assessment of the benefits and field demonstration results.

However, after the review of all references is completed, the reader is left with some general impression about the benefits and related field demonstrations. The first impression is that the NN approach did not gain a wide application yet, based on a clear recognition of its benefits. There is as strong evidence that the NN use in some applications such as fault detection and classification as well as fault analysis and equipment diagnostics has a definite promise for achieving improved performance. On the other hand, there is not enough practical experience to assess the real significance of the improvements.

The future efforts in this area definitely have to include more comparative studies when the selected NN approach can be compared to the other NN approaches as well as existing techniques. The evaluation efforts should include very practical cases that should be well documented and readily described for any further analysis by the reader. The most important effort is to create as many as possible of the prototype NN applications that can be evaluated in the field through actual use. Unfortunately, very few references provide information on the field tests.

8. CONCLUSIONS

This paper gives an extensive survey of the published references for the last ten years on the subject of NN applications to protective relaying and fault analysis. A large number of references has been published so far but rather small variety of NN architectures and related implementation options has been offered. The references, almost as a rule, do not have comparative results to enable the reader to assess the practical value of the implementation approaches selected by the authors. Further research and development activity is needed to provide sufficient information of the practical benefits and advantages of the NN applications. The fault detection and classification as well as equipment fault analysis and diagnosis seem to be quite promising future applications.

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