

# Adaptive Strategies in Power Systems Protection using Artificial Intelligence Techniques

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**Abstract** – The present generation of digital protection devices allows the implementation of adaptive strategies for power system protection. This paper presents an overview of the use of Artificial Intelligence (AI) techniques to improve some aspects of power systems protection, especially adaptive protection. Each technique is briefly described and in the sequence some applications of this technique to the problem being discussed are presented. The study focuses on the following techniques: Multi-agent Systems, Artificial Neural Networks, Genetic Algorithms, Expert Systems and Fuzzy Logic. This review shows that with the technology available today, some old unsolved issues of power system protection can now be solved and well-known protection philosophies can become more effective and reliable.

**Index Terms** – Power System Protection, Artificial Intelligence, Adaptive Protection.

## I. INTRODUCTION

In the last decades, Electrical Power Systems (EPS) have enlarged to meet a growing demand for electrical power. They also become more interconnected and difficult to operate, especially after deregulation, which reduced the cooperation and increased the competition among agents. Thus, the tasks of operating, planning and protecting these systems can no longer be held in the traditional form.

The protection of EPS should take into account that the topology and the loading of these networks are constantly changing, requiring adaptive techniques to improve its effectiveness. Otherwise, the protection of the system may become useless for certain fault situations.

The concept of adaptive protection is presented as a philosophy that adjusts the protection devices to suit the varying conditions of the electrical system [1]. The use of adaptive protection is feasible when digital relays are applied, considering their ability to change their setting on-line and processing speed. However, some aspects may be improved with the use of Artificial Intelligence (AI) techniques in conjunction with such devices.

Several AI techniques have been proposed to solve problems related to the area of protection of electrical

systems. Numerous works can be found in the literature with promising results [2]. Some AI techniques are more applicable than other as far as adaptive protection is concerned. This paper will firstly present some AI techniques that are currently being used to implement adaptive strategies to protect EPS. In the sequence other AI techniques are discussed in order to highlight features in certain applications of power system protection.

## II. AI TECHNIQUES AND THEIR APPLICATIONS FOR IMPROVING POWER SYSTEM PROTECTION

Some microprocessed protection devices allow the configuration of groups of protection settings. Artificial intelligence techniques can be used to optimize these settings and the logic that defines which group should be active during the online operation of the protection system. Another factor that benefits the adaptive strategy is the use of dedicated computer networks in electric energy utilities, increasing the reliability of communication means. In the next items some AI techniques applied to improve power system protection (adaptive or not) are discussed.

### A. Multi-agent Systems (MS)

In order to understand the use of a MS for adaptive protection, a definition of "agent" is necessary. Several authors define "agent" in a way that is more suited to the application they have in mind. In [3] several definitions are presented. This paper presents Pattie Maes' definition: "*Autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed.*"

MS are classified as Distributed Artificial Intelligence and to perform their tasks a reliable communication system is essential. Through this communication network the agents can interact with each other and with the environment where they inhabit. When applied to power system monitoring and protection, the agents collect data from a network of intelligent devices (IED-Intelligent Electronic Device) and based on these data they execute their tasks.

Electric energy utilities have been adapting their dedicated computer networks (intranet) to respect the requirements necessary to the application of IEC 61850. These improvements provide the features necessary to implement

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MS in protection systems [4, 5]. Some of these features are listed below:

- High capacity of data transmission.
- Management of Information: better integration among the devices responsible for the system protection.
- Operating System: possibility of remote monitoring and control.

Considering the restructuring of communication systems, several authors proposed applications of multi-agent systems to solve various problems in the area of power systems. This paper discusses some of these applications in the area of adaptive protection of EPS.

### B. Applications of MS to Power Systems Protection.

The protection of electrical power systems has the characteristic of being distributed, usually a protection device protects only one piece of equipment (transformer, busbar, transmission line, etc.). This feature facilitates the application of MS. Agents can be responsible for detecting considerable changes in the power system and then modify the settings of digital relays to improve their response in this new situation.

In [6] the authors present MAWAPS (Multi-Agents and WAN based Adaptive Protection System), which aims to adapt the settings of digital relays to the conditions of the operation of an electric power system. The main agents in this system are defined as shown in the table below:

Table 1. Architecture of MAWAPS [6].

Agent	Task
Dispatching	Detects a change of a switch state.
Communication control	Controls messages according to their priorities and ensure that they arrive at destinations in time.
Network topology analysis	Reviews and updates the network topology when the state of changes.
Impedance matrix computation	With the new topology data calculates the impedance matrix.
Adaptive setting calculation	Calculate the adjustments according to the impedance matrix, calculates of the short-circuit current.
Relay	Runs the algorithm to decide whether the protection should work or not.
Mobile management	Manages the mobile agents system
Network monitoring	Monitors the communication network and assesses its capacity.

When the *Dispatching Agent* detects a switching event within the power system, the *Adaptive setting calculation Agent* is informed that it should calculate new settings, and the *Relay Agents* are advised not to use the current settings and wait for the new adjustments. *Network topology analysis Agent* updates the system configuration, and the *Impedance Matrix Computation Agent* is enabled. With this information, the *Adaptive setting calculation Agent* calculates the short-circuit currents through the WAN (Wide Area Network), and the new settings are sent to all *Relay Agents*.

In [7] the authors suggest a distributed and multi-layered architecture for adaptive protection of substations. There are

three layers in their multi-agent approach, which are: equipment layer, substation layer and system layer. Within each layer, several types of agents are defined, as shown in the table 2:

Table 2. Architecture of MS [7].

Layer	Agent	Task
Equipment	Measurement	Collects measurements and states of equipment.
	Protector	Identifies the fault and isolates the faulty area.
	Performer	Sends trip signal and isolates fault area.
Substation	Region	Gathers information and sends to the management agent.
	Management	Calculates the new settings of the relays and sends it to the protector agent.
System	System	Collect new system data and sends to the evaluation agent.
	Evaluation	Evaluates the new settings of the protection system.

Another kind of agent found in all layers, the Mobile Agent, moves among software agents and protection devices, looking for information to be applied in different functions and different devices.

Apostolov [4] emphasizes the relation between IEC 61850 and the dissemination of Multi-agent applications to solve the adaptive protection problem. In the same paper an application of adaptive control for Load-Shedding, using a MS to optimize the search for the feeder in which the load should be reduced is proposed. The input data are the condition of the feeder and the loads that are part of the load-shedding scheme. Other information used are the changes in frequency, rate-of-change of frequency and average rate-of-change of frequency. The load-shedding algorithm is executed continuously by *System Agent*, aiming to determine which circuit breaker should receive a trip signal, to optimize the load-shedding.

In [8] the authors propose an adaptive strategy for adjustment of distance relays for multi-terminal lines using the MS technique. The multi-agent structure used is composed of three kinds of agents: The *Operation Agents* are local, responsible for monitoring the operational condition of each terminal; the *Breaker Status Agents* are also local and responsible for monitoring the changes in the network topology through the circuit breaker status; the *Coordination Agents* collect information from other agents, defining actions and transferring knowledge to other coordination agents. These agents determine the best relay settings.

Protection systems are naturally distributed, but communication networks interconnecting substations and protection relays make the use of Multi-agent Systems viable.

### C. Artificial Neural Networks (ANNs)

The Artificial Neural Network (ANN) is a multilayered parallel structure, resembling the brain in two aspects:

- Knowledge is acquired by the network from its environment through a process of "learning";
- Forces of connection between neurons, known as synaptic weights, are used to store the knowledge acquired.

Some other characteristics of ANNs [27]:

- Non-Linearity: Usually the physical mechanism responsible for generating the input signals is inherently non-linear;
- Generalization: produces output suitable for entries that have not been presented during the training ("learning") phase;
- Mapping of Input-Output: classification of patterns (maps the existing input-output relationship in a more precise way);
- Adaptability: it can be retrained to deal with minor modifications. It can be designed to modify its weights in real time;
- Response to Evidence: it can provide information about the confidence or belief in the decision provide at its output;
- Fault tolerance: even with the loss of neurons, it supplies consistent responses at its output.

The characteristics outlined above have led several authors to choose this AI technique for the development of tools with the objective of improving the protection of EPS.

On the other hand, one difficulty frequently found when implementing ANNs is the necessity of a considerable amount of historical or simulated cases to use in their learning and evaluation phases.

#### D. Applications of ANNs to Power Systems Protection

Most applications of ANNs in the area of power system protection are for the protection of transmission lines. Their use provides advances in the performance of distance relays. Distance relays operate by calculating a quantity (impedance, reactance, etc.) that, in the presence of faults, is proportional to the distance from the transmission line terminal to the point of the short circuit. The authors in [9] propose a Multi-layered Perceptron (MLP) network, trained using known cases and the Back-Propagation algorithm. The choice for ANNs is due to four factors that directly influence the function of distance protection:

- There are adverse effects of uncontrollable variables such as the fault resistance, reactance and location.
- The X/R ratio of the source.
- Pre-fault load flow also affects the apparent impedance seen by the relay.
- Infeed from the line terminals

According to the above factors, it is evident that this is a problem of pattern recognition and the use of ANN is indicated. The results obtained by the researchers show a significant improvement in the selectivity of distance relays.

Another important area where many applications of ANN are found is equipment diagnosis.

In [10] the authors present a hybrid tool for the dissolved gas analysis of power transformers. Its inputs are the concentration and the increase rate of combustible gases. The approach combines the results provided by well accepted methods published in standards with the ones provided by an ANN trained with real cases. A fuzzy system is used to reach a final conclusion.

In [11] the authors present a similar approach, but they apply a Kohonen network, because the problem can be reduced to a binary problem. These networks make use of unsupervised learning.

Analyzing the applications of ANN previously cited we observe that authors have chosen this technique mainly due to its capacity of pattern recognition and generalization. These characteristics would also be important for the purpose of adaptive protection.

#### E. Genetic Algorithm (GAs)

Genetic Algorithms (GAs) is one of the main algorithms in the set of Evolutionary Computation. They can be defined as robust search mechanisms based on the principle of population genetics, in other words, natural selection and evolution. They perform a search in a space of possible solutions in a given domain [12].

The interest for GAs has been increasing quickly, and they provide powerful adaptive search mechanisms. Another fact that attracts researchers to this technique is its excellent results in optimization. Traditional optimization methods require a starting point for their search, which sometimes may lead to a local optimum. On the other side, several initial points (population) are used in an GA and their values are selected through a random process, increasing the chances of finding the global optimum.

#### F. Applications of GAs to Power Systems Protection

GAs are used in Protection Systems as an optimization means. In [13] the authors present a method for the coordination of over-current relays. Similarly, in [14] the technique is used to determine the coordination among over-current relays and also their coordination with the zones of distance relays. In both applications the populations are formed by a series of bits (strings - representing the chromosomes). These strings are processed by the genetic operators of selection, reproduction and mutation [16].

Each string in a population represents a possible solution of the problem to be optimized. In [13] and [14] the solution was the best setting of each protective relay, aiming to achieve the best coordination. The value of each bit or group of bits represents variables to be adjusted (thresholds of time and or current) in the relay. Each solution is evaluated by a fitness function, which plays an important role in the process.

In the applications described in these papers, the populations analyzed by Genetic Algorithms represent possible solutions to the problem. The reproduction process can create more capable individuals and optimize the solution.

## G. Expert Systems (ES)

Expert systems (ES) are part of a subdivision of Artificial Intelligence, the symbolic branch. This symbolic technique makes extensive use of knowledge obtained from human specialists [15].

The architecture of an ES generally consists of three modules: rule base, working memory and inference engine. The knowledge about the domain is represented by the rules in the rule base and the facts in its working memory, forming the knowledge base. The inference engine performs the control and evaluation of the system by applying the rules according to the information of working memory.

The success of the implementation of an ES depends on the quality and organization of the information stored in the knowledge base. Some aspects can be evaluated to decide the use of an ES:

Expert systems are particularly useful to deal with problems usually solved by human experts. Developments using this technique focus on tools to support decision making on post-failure analysis, equipment diagnosis and protection coordination. The knowledge necessary to build these systems can be achieved from manuals and other technical literature, but usually the availability of a specialist is essential.

## H. Applications of ES in Protection Systems of EPS

In protection systems, expert systems are usually applied to support operators and protection engineers in decision making processes, with the objective of supplying reliable decisions in a faster way.

Some off-line applications are post-failure analysis and diagnosis of defects in power equipment. In general, the solution of these problems demand high experienced specialists, who spend long periods of time in these tasks due to the large amount of data involved.

In [17] the authors propose an ES that designs protection systems. This ES deals with a vast database that is divided into data about relays (specifications, names and settings) and the equipment being protected (transmission lines, transformers, busbars). The inference mechanism examines and evaluates some functions using the rules and search strategies during the reasoning process. It is able to work in the presence of uncertainties and to explain its conclusions. A graphical interface allows the interaction with the user. Through the interface, the user can enter the necessary information for running the software. The outputs / responses from the SE are reports and specifications of the devices necessary to achieve a comprehensive protection of the system in question.

As previously mentioned, one of the major problems that protection engineers have to deal with is the analysis of a large amount of data generated by sophisticated supervisory systems. In [18] the authors describe an ES developed to evaluate the performance of the protection system. This ES analyses a large amount of data registered during disturbances in the electrical system. The sources of this data are digital fault recorders and digital relays. The Decision

Support System (DSS) is based on the comparison between the expected behaviors of protection devices with the events recorded by the monitoring systems. Some rules predict the expected actions of the protection system, and their conclusions are compared with its actual behavior. If any inconsistency between the two patterns is observed, it is recorded and the expert system indicates incorrect operation of protection system.

In [19] the authors propose an ES to achieve the selection, location and coordination of protective devices in a distribution system. The ES implemented is formed primarily by the knowledge base and the inference engine. The rules in the knowledge base are divided into three categories: Coordination Rules; Placement Rules and Selection Rules. The data is stored in a relational database. There are separated rule processors for each group of rules but these three processes are mutually dependent.

The use of SE is indicated when a problem cannot be modeled mathematically and is usually solved by a human expert.

## I. Fuzzy Logic

The major problem of Boolean logic is that we live in an analog, not in a discrete world, and usually our problems do not have only two states.

The theory of fuzzy logic was first proposed by Zadeh [20]. Unlike the Boolean logic that assumes only the states "zero-false" or "one-true", fuzzy logic can take values between "zero" and "one". When fuzzy sets are considered, elements can partially belong to these sets, so each element is associated to a pertinence value, which indicates how much it belongs to the set. Consequently, one can infer rules and obtain conclusions about a problem by combining the pertinence values of the facts in the rule conditions. In order to do so, usually a transformation from analog quantities to fuzzy sets, i.e. *fuzzyfication*, has to be done to allow the appropriate analysis of the problem (process of inference). Afterwards, in the end the output suffers a *defuzzyfication* process [15].

There are two factors in the fuzzy logic that stand out. The first factor is the usage of linguistic variables, so that variables can be defined according to human's natural language (high, low, possible, etc.). The second factor is that fuzzy rules are also structured as "if-then". These features make fuzzy logic tolerant to inaccuracies and uncertainties.

## J. Applications of Fuzzy Logic in Protection Systems of EPS

The main reasons for the use of fuzzy logic in power systems are listed below [21].

- Constant changes in the network topology, due to switching maneuvers and insertion or disconnection of pieces of equipment, such as capacitor banks;
- Uncertainties of the monitored signals, due to communication channels and / or measurement devices;
- Several types of faults;

- Uncertainties due to the deregulation of the energy market;
- Human errors during the planning phase or in the operation of electric systems.

The use of digital relays facilitates the application of this technique.

It should be pointed out that the main function of a transformer protection system is the differential (87). This function compares the primary current to the secondary current, and when this value surpasses a threshold previously set, the protection device detects an internal fault.

However, for an appropriate comparison between the currents entering and leaving the transformer, some factors must be taken into account: the ratio between the currents in the primary and secondary windings, the phase displacement of the currents (depending on the type of connection - delta or wye) and the inrush current. When the transformer has tap changers, the variation it causes in the transformer ratio has to be considered. Current transformers (CTs) should be specified appropriately, avoiding their saturation during faults.

Even when these aspects are taken into account, protection devices may fail in some cases, for instance [22]:

- Short-circuit between turns generates a differential current below the threshold, thus the relay does not operate although it should
- External faults may saturate the CTs, resulting in an inappropriate relay operation;
- Situations of overexcitation may be confused with internal faults;
- Uncertainties and / or inaccuracies in the various measurements.

Solutions to these problems usually make use of signal processing algorithms, such as the Fourier transform [23] and the Kalman filter [24]. However, doubtful cases may still occur.

Fuzzy logic can be applied to improve the reliability of the transformer protection. A fuzzy multi-criteria approach is presented in [22]. In this methodology the uncertainties of the measured signals and the system configuration are modeled and the decision of sending a trip signal is taken considering various criteria, each one with a corresponding weight.

Fuzzy logic has also been applied to evaluate the performance of protection systems. Monsef et al [25] present a fuzzy expert system with this objective. The expert system analyses protection alarms and circuit breakers status to generate several hypotheses with different ranks. Breaker and relay failures/missed signals are reported in each hypothesis.

An application for diagnosing faults in a transmission system is presented in [26]. The authors use information on circuit breaker status, the operational response of relays and the topology obtained from the Supervisory Control and Data Acquisition (SCADA) system and IEDs. Based on this information, the expert system identifies the faulted component. Its inference engine is able to deal with the uncertainties inherent to the task of protecting transmission

equipment. An explanation module justifies how a conclusion was reached.

This technique stands out from other techniques because it is the only one that can deal with imprecise information. The decisions taken by protective equipment are often based on inaccurate data. Thus, fuzzy logic is indicated for interpret these data and to transform them in useful information.

### III. CONCLUSION

This study aimed to introduce the use of artificial intelligence techniques to power system protection, mainly to the adaptive protection problem. Several AI applications to this problem were found in the literature and some of them have been briefly described in this paper.

Each technique has particular features that may be advantageous or hot when applied to solve a specific problem.

This review has shown that the techniques more frequently used to implement adaptive protection strategies are multi-agent systems and artificial neural networks. However, the choice of an AI technique for solving a problem depends on several factors, including:

- Type and quantity of data available;
- Data distributed or centrally located;
- The relation between inputs and outputs is well-known or not (model);
- The procedures usually applied to solve the problem;
- Necessity or not of a real time solution;
- Existence or not of a specialist willing to help in the development of a computational tool.

It should be pointed out that the use of artificial intelligence facilitates the implementation of the adaptive protection philosophy in digital relays, which represents a major advance in the protection of electrical systems. In the past, the protection engineer was constrained by the software provided by the relay manufacturer, but now he has the freedom to create new protection functions, which may be more complex and specific to each case.

The utilities benefit from the increase in its system reliability, due to the reduction in the number of cases of inappropriate protection behavior.

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