Fast System for Analysis of Protection Events

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[1]***Abstract* — The often unexpected load growth, failures of protection-related equipment and inadequate parameterization of protection functions make the analyses of protection events more complex and time-consuming. Besides, the amount of information that can be retrieved from modern digital relays is constantly increasing. In order to aid a quick decision-making and maintenance practices, this project aimed to implement a complete diagnosis system that is automatically activated whenever a protection-related event occurs. It covers the automation of the analysis system and the analysis system itself, which uses an expert system to process the data. It was important to observe that it is able to analyze different data sets in order to ensure the delivery of a report even when not all the expected input data is available. The system was successfully installed in a distribution substation of a Brazilian power distribution utility.**

***Index Terms* — expert systems, maintenance, power system reliability, power system protection.**

I. INTRODUCTION

It is of great importance to preserve high reliability levels of power electrical networks, while necessary maintenance services and quick actions are kept. To achieve this, it is necessary to know how to deal with unexpected events of the protection system, mainly due to unforeseen load increases, equipment failures and inadequate protection settings. In order to facilitate the processing of huge amounts of information that can currently be retrieved from modern digital relays and to provide a rapid diagnostic of protection events to help decision-making, an automatic system for analysis of the protection was developed.

References [1] and [2] provides an overview of an automated system, but focuses more on the calculation of faults. In [3] and [4], systems were developed taking into account full availability of the variables used. The current work focuses also on the aspect that not always there will be full availability of the variables either due to communication problems, lack of data in relays or due to any other reasons. One example is the fact that IEC61850 regulates the requirement of providing some data, but leaves other data optional [5].

An automated system implemented is described in this paper from data collecting to delivery of a report with the analysis of the protection event, with special focus on the analysis of protection, considering that the system was installed in a power distribution substation.

II. SYSTEM ARCHITECTURES

The protection analysis system was divided into four parts, as shown in the functional diagram in Figure 1, with the data flow.

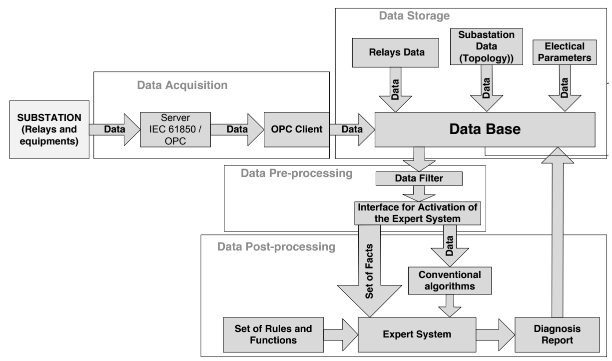

Fig. 1. Functional diagram and flow of the automation system data

It is to be pointed out that relays compatible with IEC61850 communication protocol were used, which are relays used in the substation where the system was installed and are basic items in new and upgraded substations. However, the use of an OPC server that enables communication with other protocol standards (for example, MODBUS, DNP3 IEC 60870-5-103) makes the application of this system possible in substations with other types of relays.

A. Data Acquisition

An IEC 61850/OPC server collects information of protective relays in the substation via Ethernet network. The IEC 61850 standard allows the generation of reports triggered by a change of state of some variables selected at IEDs (Intelligent Electronic Devices), without the need to send a request signal (polling). For this purpose, so-called Report Control Blocks (RCB) and groups of preconfigured data (called Data Sets) are used, which contain registered information. Then the OPC client works with asynchronous call with the OPC server. Thus, the server makes the Callback, responsible for reporting a change in value of some registered variable, causing the client to process this feedback.

B. Data Storage

The acquired data is saved in a relational database, which also contains information on the substation protection system,

[1] This work was developed thanks to the incentive to Research and Development of ANEEL, in project developed in partnership with CPFL.

such as the topology of the substation, the electrical network parameters and the settings of the protective functions in evaluation.

C. *Data Pre-Processing*

In addition to the data that come from the relays variables, it is possible to bring oscillographic data files when available. Such files contain digital states of some variables (e.g. trip) and analog values of the voltages and currents in all three phases. COMTRADE format files is used, which are generated when the protection actuates, recording data from a few moments before the event to a few moments after the event.

An application has been created to analyze the oscillographic data, obtaining data of the instants of circuit-breaker opening of each of its three poles, and perform a Fourier analysis of waveforms, determining the values of the magnitudes and angles before and after the trip.

D. *Data Processing*

The diagnosis is performed by an expert system based on production rules. The implementation was done in CLIPS software. This step is the main focus of this article and will be detailed in subsequent items.

E. *Results*

The result of the expert system processing is a text file (in XML format), which is made available for consultation in a Web interface, used for management of all substations by the utility company.

III. EXPERT SYSTEM

The expert system maps the knowledge on the operation of the protection functions, circuit breakers and short circuits in the form of patterns and using condition-action type chains, reproducing the reasoning of human experts. Such patterns are formed by production rules and facts. The facts contain input data (e.g. currents, voltages, digital variables, timestamps and information of item II-B of this paper) and intermediate results during processing. The rules are condition-action type ("if-then") in which, for an action to be performed, certain conditions must be met.

Expert systems represent greater efficiency in processing and facilitating maintenance services. There is no need to create a rule for each different combination of input facts, because the expert system is able to infer not explicit results from inference mechanisms [6] Furthermore, there is a great ease of adding/removing rules in the implementation when maintenance or upgrading of the algorithm is required.

A. *Knowledge basis*

Two methods of reasoning were used in order to provide more complete results and enable to provide results even without any input information.

1) Alarm Processing

This is responsible for simulating the most superficial reasoning in the diagnostic problem [7]. In this way, it consists in finding which relay has actuated; the state of the digital variable 'trip' and trip of the protection functions, digital variable 'open' of the circuit breaker and relay alarms; the magnitudes of the currents in the three phases; and messages on the status of alarms on the relay, when applicable, then providing a first set of result to identify the event occurred.

2) Model-Based Reasoning (MBR)

In MBR [8] a model is built with sufficient detail and complexity to describe the expected behavior of the relays and breakers which actuated in different fault conditions. With such information, a comparison is made with all the real behaviors, obtained via IEC 61850 and COMTRADE file. If the model results and actual results match, then the results are validated. If there is discrepancy, the causes and effects of this event will be analyzed.

Two methods were used to deal with the possibility of missing information. They are:

- Different rules for different input information: the objective that has to be sought to reach a conclusion about certain analysis (e.g. what type of short circuit) from different sets of input data;
- Different rules for the same final diagnosis: the objective is to find out which inputs are necessary for a conclusion to be true (e.g. what is necessary for a single-phase short-circuit has occurred).

B. *Diagnostic modules*

The system was divided into six modules. All modules use the alarm processing in a similar way as explained in item III-A-1 of this article. However, model-based reasoning differs greatly between the modules, as it is responsible for a deeper analysis of the event, depending on the particularities of each one. A detailing of the MBR is provided below.

1) Overcurrent Protection Analysis Module

This module provides the diagnosis of ANSI 50, 51, 50N, 51N and 51GS functions.

For the MBR, the model retrieves all values of parameter settings of the relays: pickup current; type of curve (e.g. IEC, IEEE); time x current characteristic of the curve; and settings of intentional time delays. With the values of short-circuit currents, it is possible to calculate the ideal performance time for neutral and each phase relays. The actual operation time is also calculated, i.e., the actual behavior of the relay in this regard. This is done by subtracting the trip and the pickup time label of digital variables.

Using the same reasoning, the values of the variable status are analyzed and their compatibility is verified. For example, if the trip is active but not the pickup, an undue operation is evidenced. In addition, the fault currents must be higher than the pickup current, the protection might not be blocked by some reason and one must deal with possible variations in the expected performance times, either by deliberate delays or errors allowed.

Figure 2 shows the overview of the model used for the prediction of the behavior of time overcurrent protection in phase A. In this case, the operation curve utilized is the IEC.

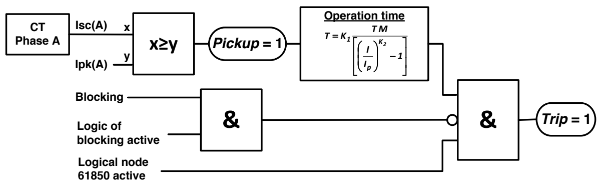

Fig. 2. MBR model of time overcurrent relay – phase A.

In all modules relating to protection functions there is a brief analysis of the status of the circuit breaker, establishing if the circuit breaker opened, failed or is in an invalid state, and if there has been the opening of the main circuit breaker or the backup circuit breaker. If the backup breaker has opened, there is evidence of possible failure of the main breaker, in the opening signal transmission of the main breaker, or wrong/outdated parameterization of primary protection relay. However, a separate circuit breaker module that contains a deeper analysis was also developed.

2) Transformer Differential Protection Analysis Module

For the differential protection model, the parameters of 87T protection for the Siemens 7UT6135 relay were considered. They are: slope 1 (Slope 1); slope 2 (Slope 2); base point 1 (BP 1); base point 2 (BP 2); and differential pickup currents for low and high restraint currents (respectively, Idif and Idiff in the operation curve in Figure 3).

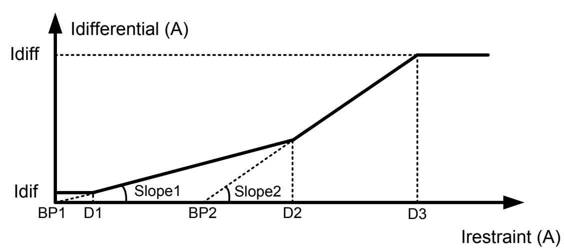

Fig. 3. Differential protection operation curve

Figure 4 shows the general MBR model of phase A differential protection. From currents measured in the primary and secondary CTs (which limit the differential protection area), the results are the restraint and differential currents, which are analyzed according to the operation curve in Figure 3. The blocking can be the result of the harmonic restraint mode, which aims to prevent undue trip caused by harmonics generated by reactors switching or overexcitation or transformer connection. In addition, cross-blocking may occur, which is also due to harmonic restraint, but to harmonics in other phases (B or C in the example), or blocking due to add-on stabilization mode, which aims to prevent undue trips caused by different saturations between the CTs in the event of faults outside the protection area. These blockings, however, will only be effective if there is no fast trip caused by high current in the differential protection zone. Finally, the opening signal is sent the circuit breaker through the 86T lockout relay.

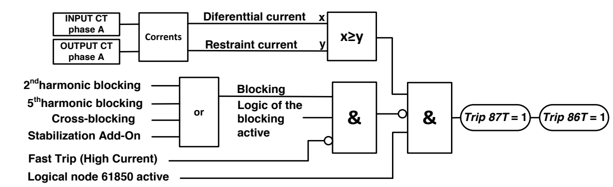

Fig. 4. MBR Model of differential protection – phase A

3) Reclosing Analysis Module

In addition to the analysis of the relays status, there are also analyzes of number and times of reclosing operations. If there is an IEC 61850 variable that provides information on which was the reclosing attempt, than the analysis becomes simpler and it just has to be checked if reclosing times are within an acceptable range relatively to settings. In the absence of such information, the expert system infers which was the more likely sequential attempt, given the informed reclosing times.

4) Transformer Lockout Auxiliary Relay Analysis Module

The 86T lockout auxiliary relay is used in conjunction with the transformer differential protection in order to perform the opening of circuit breakers without allowing these to be automatically closed by other commands. This module consists basically of the analysis the statuses that indicate its activation together with the statuses of the circuit breakers connected to the relay.

5) Circuit breakers analysis module

Figure 5 shows the general representation of MBR used for the circuit breaker. For the correct operation of the circuit breaker, the trip of a protection function must occur, the 43 Local/Remote switch must be in the Remote position and the IEC 61850 logic node of the object that commands the circuit breaker must be active [9]. If all these conditions are met, an opening signal is transmitted to the circuit breaker, which will receive value CB = 1 (Circuit Breaker) after a time delay due to the circuit breaker opening mechanism. A maximum time gap between the opening of the three poles of the circuit breaker is assumed. If this time gap is not respected, there is a situation of pole disagreement, which can also arise from the non-opening of one or more poles.

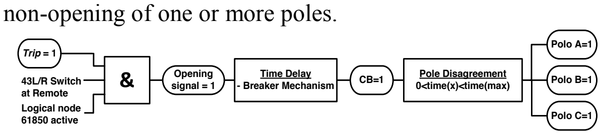

Fig. 5. MBR Model of breaker opening.

6) Short circuit analysis

The short circuit module uses the three-phase circuits theory [9] for diagnosing the type (three-phase, two-phase, two-phase-to-ground or single-phase-to-ground), which phases are involved and the intensities of the fault.

C. *Implementation of rules*

This item presents how rules are established from an MBR model. Some rules implemented for differential protection will be shown. The same reasoning is applied to pass any MBR model to an expert system rules. The following explanation refers to the model presented in Figure 4.

Rules 1 to 4 are built from block "&" to the right. Rule 1 indicates a correct operation of differential protection, being the assumptions composed by input and output facts, as shown in the model. The rules 2 to 4 indicate incorrect operation of protection, being composed by the output of the block "&" and the opposite of each of the inputs of the block.

Rule 1 uses four facts as assumptions. Facts 1 and 4 come directly from objects of IEC 61850. Facts 2 and 3, by their turn, come from other rules implemented in the expert system. Such facts must have been previously produced by these other rules so that rule 1 can be activated. Hence the name, expert system, based on production rules. Rules 5 to 7 produce the fact "there is no blocking of the 87T", which is later used by rule 1. These rules (5 to 7) use data directly from objects of the IEC 61850 and represent the denial of the result of the block "&" of the model. Rule 8 is the denial of block "or", whose conclusion fact is used under rule 5.

In addition, rules for the analysis of differential protection curves are implemented in the expert system and also to the opposite conclusions. For example, the block "or" should contain, in addition to rule 8, four more rules that lead to the conclusion "There is blocking", each of which will have as assumption one of the inputs of the block.

As a more general rule, block inputs "&" are used in the assumptions of a single rule. The inputs of blocks "or" are used in separate rules for each of the inputs. The denial of a block "&" is a block "or" with inputs and outputs denied. The denial of a block "or" is a block "&" with inputs and outputs denied.

Rule 1	**: Correct Operation of 87T**
Assumptions	1. 87T Trip; 2. Differential current and restraint current inside the Trip area of the curve; 3. There is no final blocking of 87T; 4. IEC 61850 logical node active.
Conclusions	Correct performance of differential protection 87T.

Rule 2	**: Incorrect Operation of 87T relatively to time-current curve**
Assumptions	1. Trip 87T; 2. Differential current and restraint current outside the Trip area of the curve;
Conclusions	Incorrect operation of differential protection 87T.

Rule 3	**: Incorrect Operation of 87T due to blocking**
Assumptions	1. Trip 87T; 2. There is final blocking of 87T;
Conclusions	Incorrect operation of differential protection 87T.

Rule 4	**: Incorrect Operation of 87T due to Inactive IEC 61850 logical node**
Assumptions	1. 87T Trip; 2. IEC 61850 logical node inactive.
Conclusions	Incorrect operation of differential protection 87T.

Rule 5	**: There is no final blocking of 87T**
Assumptions	1. There is no blocking
Conclusions	There is no final blocking of 87T

Rule 6	**: There is no final blocking of 87T**
Assumptions	2. Inactive blocking logic
Conclusions	There is no final blocking of 87T

Rule 7	**: There is no final blocking of 87T**
Assumptions	1. Fast trip (high current).
Conclusions	There is no blocking of 87T

Rule 8	**: There is no final blocking of 87T**
Assumptions	1. There is no 2nd-harmonic blocking; 2. There is no 5th-harmonic blocking; 3. There is no cross-block; 4. There is no add-on stabilization.
Conclusions	There is no blocking

IV. Cases Studied and Diagnostics

Results generated by the expert system, which was applied to a distribution substation with the topology shown in Figure 6, are presented in this section.

A. *Three-phase short circuit in Feeder 9*

A three-phase short circuit was applied in Feeder 9 of the substation. The reports generated by the analysis modules of overcurrent protection, of short circuit and of the circuit breaker can be viewed in Tables 1, 2 and 3. As shown, the relay correctly detected the fault but operated a little later than expected (in t = 0.338 s versus an expected time = 0.258 sec). Besides, the expert system correctly diagnosed the three-phase fault. Finally, the circuit breaker took longer to open (0.145 s versus 0.1 s expected), indicating the possibility of future faults, even though pole-disagreement did not occur.

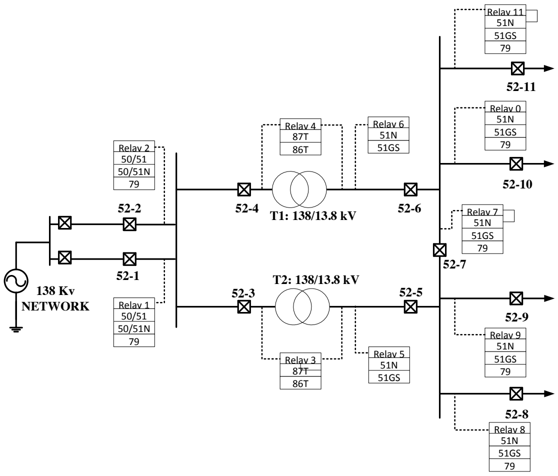

Fig. 6. Topology of the substation

TABLE 1
REPORT GENERATED BY THE ANALYSIS OF OVERCURRENT PROTECTION MODULE FOR THREE-PHASE SHORT CIRCUIT IN FEEDER 9.

Overcurrent protection module

- Relay responsible for actuating: Relay 9

Diagnosis of the time overcurrent relay function (ANSI 51)

- Pickup current adjustment = 240.0 [A]
  The time overcurrent relay (ANSI 51) performed in accordance to pickup adjustment.
- Phase A time overcurrent relay correctly detected a fault.
  Phase A current = 2764.0 [A]
- Phase B time overcurrent relay correctly detected a fault.
  Phase B current = 2764.0 [A]
- Phase C time overcurrent relay correctly detected a fault.
  Phase C current = 2764.0 [A]
- Relay operation under function 51 in = 0.338 seconds (s).
- Performance time not in accordance with IEC very inverse curve expected time, with Ip= 240.0 [A] and time multiplier = 0.2.
  Expected time = 0.258 seconds(s).

B. Single-phase short circuit in a transformer with differential protection

A single-phase short circuit was applied in phase C winding of transformer 1. The result of the analysis of differential protection can be viewed in Table 4. The expert system correctly detected a fault involving phase C, showing that the minimum value of differential current to restraint current was reached.

TABLE 2
REPORT GENERATED BY THE ANALYSIS OF SHORT CIRCUITS MODULE FOR THREE-PHASE SHORT CIRCUIT IN FEEDER 9.

Short circuits module

Diagnosis of short circuit

- A three-phase fault occurred.
- Affected phases: A, B and C.
- Phase A current:
  Module = 2764.0 [A]
  Phase = -70.2 degrees.
- Phase B current:
  Module = 2764.0 [A]
  Phase = 169.8 degrees.
- Phase C current:
  Module = 2764.0 [A]
  Phase = 49.8 degrees.

TABLE 3
REPORT GENERATED BY ANALYSIS OF CIRCUIT BREAKER MODULE FOR THREE-PHASE SHORT CIRCUIT IN FEEDER 9.

Circuit breaker module

Diagnosis of circuit breaker

- Circuit breaker: 52-9.
- There was the opening of the circuit breaker.
- The circuit breaker took longer than expected to open.
  Maximum expected time to opening = 0.1 second (s).
  Actual time to opening = 0.145 second (s).
- There was no pole disagreement.

TABLE 4
REPORT GENERATED BY ANALYSIS OF THE DIFFERENTIAL PROTECTION MODULE FOR SINGLE-PHASE SHORT CIRCUIT IN PHASE C WINDING OF TRANSFORMER 1.

Differential protection module

- Relay responsible for acting: Relay 4

Diagnosis of the transformer differential protection (ANSI 87T)

- The phase C 87T transformer differential relay detected a fault.
  Phase C restraint current = 20.543 [% of nominal current].
  Phase C differential current = 116.412 [% of nominal current].
  For phase C $I_{restraint}$ = 20.543 [% of nominal current] => $I_{differential,minimum}$ low set point = 9.022 [% of nominal current] so that phase C 87T relay can operate.

Finally, the system was tested in a computer with a processor Intel Core i3 working at 1.70 GHz and a RAM memory of 4GB. The full system delivered a response with the diagnostic report in less than one second, which is a very fast response for the purposes of this system, which aims to deliver quick reports in order to aid a decision-making after protection events.

V. CONCLUSIONS

The developed system is able to deliver in a matter of less than one second a report in the Web interface of the utility company. Such a system is currently installed in Companhia Paulista de Forca e Luz (CPFL) substation. Basic processing techniques of alarms and RBM along with inference techniques that deal with the absence of information have shown to be able to surround all cases studied. Full tests were conducted for short circuits (three-phase, two-phase, two-phase-to-ground or single-phase-to-ground) on all feeders, transformers and a substation bars, taking into account different states of the protection system (correct and incorrect actions). The system has shown to be fully effective, both in the case of full data availability or partial data availability, always describing the short circuit and analyzing the performance of protection. Thus, a much more efficient maintenance becomes possible for utilities, especially with regard to the prevention of faults in equipment, quick response to problems and need for reparameterization of the protection functions.

It is noteworthy that the use of an OPC server compatible also with other communication protocols (DNP3, Modbus, IEC60870-5-103, etc.) makes the compatibility of this system with digital relays using such protocols possible, just introducing a few adjustments of data addresses in the communication protocol used.

Suggestions for future developments include implementing a complete module for not only fault classification, but also for fault location. Another possibility is taking into account not only conventional information, but also any data that may be delivered through different relay manufactures. It was implemented several techniques in this system in order to provide diagnostics in every situation of availability of information, but when more data is available, more detailed reports can be delivered.

Finally, it is suggested that the IED manufacturers make the needed information available for complete diagnostics in the manufacturing series of their protection relays, or that changes in digital relays standards be introduced so that such information becomes mandatory, since even basic information like short circuit current may not be given by account of non obligation.

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