Automating the Diagnosis of Occurrences in Power Plants Using Data from DFR and Sequence of Events: An Expert System Based Methodology

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***Abstract*—This paper describes a novel methodology for automating the analysis of occurrences in power plants. The proposed scheme uses, as input features, oscillographic records from Digital Fault Recorders (DFR) and Sequence Of Events (SOE) from supervisory systems. The objective of the methodology is to help the engineer responsible for this kind of analysis by means of a pre-classification of the data. The analysts can then focus their attention to the most relevant occurrences. The tool described here is based on expert systems. It was developed and tested using data from real occurrences. The results show that the methodology is effective to automatically classify the most common situations in a power plant, thus helping the engineers deal with the large amount of data available today in the operation centers.**

***Index Terms*—Digital fault recorder, expert systems, phasor record, fault diagnosis, power systems, generators, power plants.**

I. INTRODUCTION

Nowadays the use of Digital Fault Recorders (DFR) is common practice in most power plants. These devices continuously monitor signals such as voltages and currents, aiming to record meaningful alterations in their values. In this way they play an important role in the maintenance of the quality and reliability of the power supply by monitoring power generators and also its protection system, providing valuable means to a deeper analysis of disturbances that commonly occur in power systems [1]. With the help of DFRs, the engineers can evaluate the performance of the protection system and, if necessary, make new adjustments in order to avoid undesirable generator trips. Using the data provided by the DFR, it is also possible to look for incipient faults in the generator and nearby equipment like circuit breakers and transducers.

The analysis of the DFR data is made by specialists dedicated to this task who should have a high level of knowledge about operation and the protection of the generators. In a generation utility, all the DFR data is usually concentrated at the central office where few people have the necessary skills to accomplish the task. As a result, these specialists are usually overloaded by the huge amount of DFR recorded data. In utilities with several power plants, this analysis has become a challenge to the specialized engineers, who have to prioritize some records because, in general, there is not enough time to examine all of them. This delays the analysis of more important events such as load rejection, faults, overload, etc. The following factors are responsible for the increasing amount of data to be analysed [2]:

- Number of channels: A single DFR may have dozens of analogical channels and usually when a DFR is triggered, it automatically triggers other DFRs installed in the same power plant, generating more data to be analyzed
- Low trigger levels: The threshold level that triggers the DFR is usually low, resulting in a lot of oscillography data that corresponds to normal situations
- Centralization: Data from several power plants is available at the utilities analysis center.

When the analysis of DFR data is performed, sequence of events recorded by the supervisory system may also be checked, in order to detect inconsistencies between these two sources of information. During this task, the specialist may also verify the performance of the protection system. In this way, a conclusion regarding the disturbance can be achieved and, if necessary, a report generated.

Several works have been published in technical journals and conferences proposing and testing schemes to automate the disturbance analysis task. However, they are designed mainly for transmission systems and do not take into account the characteristics of generation systems [3]. The majority of the schemes described in these papers for fault diagnosis and power quality analysis use computational intelligence (CI) techniques [4].

Davidson et al. [5] show the application of a multi-agent system to the automatic fault diagnosis of a real transmission system. Some agents, based on expert systems and model based reasoning, collect and use information from the supervisory system and from DFRs. Another recent paper proposed an expert system that makes use of data from DFRs and sequence of events of digital protection relays. It analyzes the disturbance and evaluates the protection performance [6]. With regards to power quality studies, Styvaktakis et al. [7] have employed a Kalman filter to separate the oscillography into pre-fault, fault and post-fault stages. The data from each segment is applied in an expert system that detects power quality events.

When applied in automated disturbance analysis of power systems, computational intelligence techniques are normally used in conjunction with techniques for feature extraction. The most common ones are the Fourier Transform [8], Kalman Filters [9] and the Wavelet Transform [10].

This paper focuses on the development of an automated scheme to examine DFR recordings, correlating this information with the sequence of events (SOE) provided by the supervisory system. The main motivation is the large amount of data that needs to be analyzed in the operation center of a generation utility. If the disturbance files are automatically classified, the engineer responsible for analyzing them would verify the most important ones first, taking the corrective actions when necessary. Consequently, records that do not need further analysis could be archived without human intervention.

The proposed methodology has been developed with collaboration of a power generation utility and a DFR manufacturer. The approach has been validated using data generated during real occurrences.

This paper begins with a brief explanation of the Data Management System (DMS) and the two types of data used by the proposed scheme (DFR and SOE) in Section II. In Section III a detailed description of the proposed methodology is discussed. A case study is presented in IV and practical results with more data are in Section V. Finally, the general conclusions are stated in Section VI.

II. DATA MANAGEMENT SYSTEM

The Data Management System is the platform where the proposed automated analysis module was implemented. The DMS provides the module with all the necessary information to reach a conclusion from the event that originated the disturbance sensed by the DFRs. Following sections will show that this information is the oscillographic records (from the DFRs) and the sequence of event records (from supervisory system). A simplified overview of the DMS implemented by the generation utility that supported this project is depicted in Figure 1.

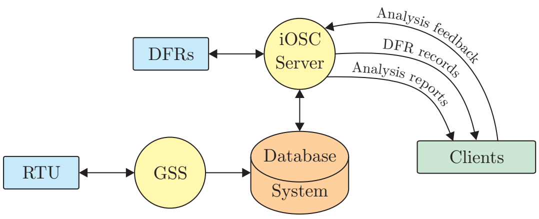

Fig. 1. Overview of the data management system.

The intelligent oscillographic server (iOSC) is the main component of the DMS. It executes the following functions:

- Collects the oscillographic records from the DFRs located at the power stations
- Stores the DFR records in a storage server
- Reads the Sequence Of Events (SOE) records from the utility database system where the Generation Supervisory System (GSS) stores them. The SOE comes from the remote terminal units (RTU) installed at the power stations
- Executes the automated analysis module for every new oscillography
- Stores the analysis report in the database system
- Provides user interactivity through a web server.

Within the iOSC the developer can install modules to automate or simplify the analysis of DFR data and SOE data. The scheme that is proposed in this paper is one of such possible modules. This module is already installed and working in the DMS.

The next two subsections will describe in detail the DFR and SOE records which are the two input data used by the proposed methodology.

A. *Digital Fault Recorders*

Digital fault recorders are responsible for generating oscillographic data files. An oscillography can be viewed as a series of snapshots taken from a set of measurements (like generator terminal voltages and currents) over a certain period of time. Usually these records are stored in COMTRADE format (IEEE standard C37.111-1999) [11], when the DFR is triggered by one of the following situations:

- The magnitude of a monitored signal reaches a previously defined threshold level
- The rate of change of a monitored signal exceeds its limit
- The magnitude of a calculated quantity (active, reactive and apparent power, harmonic components, frequency, RMS values of voltage and currents, etc.) reaches the threshold level
- The rate of change of a calculated quantity exceeds its preset limit
- The state of the DFR's digital inputs change.

In this way, DFRs are able to detect disturbances and when this occurs, all digital and analogical signals are stored in its memory, including the pre-fault, fault and post-fault intervals. Because the thresholds (also called triggers) are set aiming to detect every fault, DFRs may also be triggered during normal situations. For instance, energization and de-energization of the machine, or tests in protective relays while the generator is disconnected.

One of the main advantages of modern DFRs is their ability to synchronize their time stamp with the Global Position System (GPS) time base. Thus, in addition to synchronized waveforms, these devices are able to calculate and store a sequence of phasors of the electrical quantities before, during and after the disturbance. In general, one phasor is stored for each fundamental frequency cycle. Due to this lower sampling rate, a phasor recording, also called *long duration recording*, may contain several minutes of information, while the waveform recording, called *short duration recording*, only stores the data for a few seconds.

The long duration recording is the oscillographic data used in this paper. It should be noted that the proposed scheme is dedicated to power generators, the objective being to help the analysts by ranking the occurrences by severity. The main reason to use this kind of record is that in large generators the times associated with the transitory signals can be quite long (dozens of seconds or even minutes). Thus, the short duration records usually do not cover the entire occurrence. This is specially true in voltage signals, as can be seen in Figure 2 which shows the magnitude of the fundamental frequency phasor during a generator shutdown.

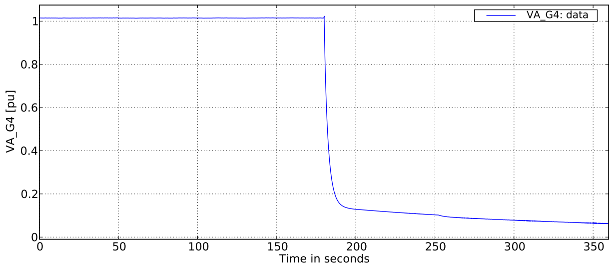

Fig. 2. A voltage profile sample during a generator shutdown.

As can be seen in this case, the transitory lasts for approximately 20 seconds in this case, which is far longer than the duration of a typical waveform record (usually 4 to 6 seconds).

A similar type of record was also used in power quality study, as shown in [12].

B. Generation Supervisory System

The Generation Supervisory System (GSS) is responsible, among other things, for register the sequence of events (SOE) in the utility's database system. The SOE is a series of messages that are recorded every time the state of a digital input monitored by a Remote Terminal Unit (RTU) changes. The states monitored by RTUs are, in general, auxiliary contacts of protective devices, circuit breakers (CB) and switches. For each record the following data are the main ones stored in a typical SOE report:

- The time stamp and date of the event, usually with a degree of accuracy within milliseconds and synchronized with GPS
- An indication of the substation or power plant where the event was recorded
- An indication of the circuit or equipment related to the event
- A unique tag associated to the digital input that originate the event
- A description of the event.

Using the GPS time base, the DFR and SOE data are synchronized and can be used in a complementary way to achieve a conclusion about the disturbance (if it was a disturbance) that triggered the DFR.

III. THE PROPOSED METHODOLOGY

A schematic of the functional blocks that forms the proposed automated analysis module is depicted in Figure 3. According to Figure 1, this scheme is implemented within the iOSC server.

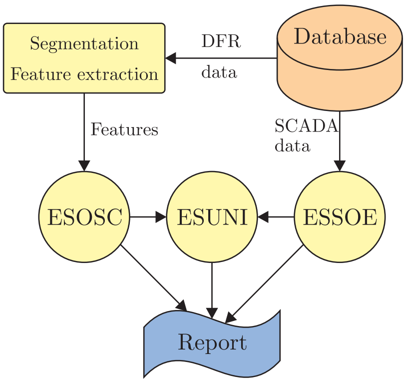

Fig. 3. Dataflow of the automated analysis module.

The necessary data are read from the DMS database. The DFR data, that is, the oscillographic records, are firstly pre-processed. This process consists in splitting the records into pre-disturbance and post-disturbance segments. For each segment some features are extracted.

The features extracted from the DFR data form the facts knowledge base of the Expert System for Oscillographic analysis (ESOSC).

According to the starting time and duration of the oscillographic record, the SOE within this period are read from the DMS database. These events, classified according to the functions that they represent, form the facts knowledge base of the Expert System for Sequence Of Events analysis (ESSOE).

The results of both expert systems are compared by another expert system (ES) called Expert System for generation Unit analysis (ESUNI). This ES is responsible for providing a final conclusion that correlates the analyses of ESOSC and ESSOE.

The analysis report contain the facts, fired rules and final results for each generation unit monitored by the DFR.

In the following subsections more details concerning the segmentation of DFR data and the knowledge base of the expert systems will be presented.

A. Data segmentation and feature extraction

Each channel of a phasorial record may have thousands of samples, which attest the necessity of a feature extraction. In order to accomplish this, the data from each channel has to be segmented. The purpose of the segmentation is to identify disturbances and split the signal into parts before and after each detected transient where the values do not change in time.

In [12], the event detection is performed through a detection index, di. In this work a similar procedure is applied, but the detection index is based on the standard deviation and is defined as follows:

$$di(n) = \sigma_{\Delta}(n) = \frac{1}{\Delta - 1} \sum_{i=n}^{n+\Delta} \left(u_{rms}(i) - \mu\right)^2 \qquad (1)$$

Where n is the sample index, u_{rms} is the absolute value of the phasor record, Δ is the length of the window, σ_{Δ} is the standard deviation calculated over this window and μ is the mean value of the data window. In this work, the chosen Δ was 480 samples (8 seconds), because of the slower dynamics of the considered perturbations.

When $di(n)$ exceeds a certain threshold δ, it is considered that the point n belongs to a disturbance segment. In this way, the first point where $\delta > 0$ indicates the beginning of a disturbance interval which ends after the last point where $\delta > 0$.

The feature extraction is done calculating the mean values of the samples where $di(n) < \delta$ before and after the detected disturbance interval. These values are stored in the ESOSC knowledge base along with the generator's three phase calculated power. All this information regarding analogical quantities is converted to per unit system (pu).

B. ESOSC

The ESOSC is responsible for classifying the oscillographic record according to the facts stored in its knowledge base. This is done by a set of rules defined with the support of a specialist and through intensive analysis of real long duration oscilography records. This rule set is divided into three subsets, called R0, R1 and R2.

The rules of the subset R0 are the first ones to be fired by the ESOSC inference engine after the data from the feature extractor is read. They are applied for each of the generator's current and voltage recorded data. These rules identify the kind of disturbance detected by the detection index (di). One example of such rule is:

- If the mean value of the signal before the disturbance is $< 0.1pu$ and after is $> 0.9pu$, then the event is classified as ENERGIZATION, which represents a change from zero to nominal

The conclusions obtained from the rules of subset R0 forms the conditions of the rules from subset R1. This set is used to achieve a more complete conclusion about the disturbance, correlating the events detected in each phase of voltages with the currents. The information about active power may also be used in some of these rules. One example is:

- If the voltage and current events are equal to DE-ENERGIZATION and the initial active power is higher than the minimum threshold ($0.1pu$) then for the this electrical phase the conclusion is FAULT, which means that the generator was disconnected while in operation;

The last subset, called R2, verifies if the diagnosis provided by subset R1 is the same for the three phases. If they are the same, the ESOSC execution ends, otherwise the result is a NO CONCLUSION code which indicates a single phase disturbance or a non foreseen situation.

A complete description of the rules subsets can be found on [2].

The possible results from the ESOSC cover the most common circumstances where the DFR may trigger. The following list describes these results. As stated earlier in this paper, most of the oscillographic records are due to normal operating situations that will fit in normal tripping, normal operation and null categories below.

- **Reverse power tripping**: This is a procedure used in thermal units to avoid potentially damaging over-speed operating conditions when disconnecting generators. It consists of a slow reduction of the steam applied to the turbine until the reverse power relay 32G (motoring condition) trips [13]. In this situation, normally the 32G relay triggers the DFR
- **Normal tripping**: Common procedure used to switch off a generator. Here the mechanical power is gradually reduced until the extinction of the load current allows the main circuit breaker to be safely opened. The DFR is triggered by undervoltage when the generator is de-energized
- **Isolated unit de-energization**: In this case, the generator is already disconnected from the system when the unit stop procedure is initiated. The DFR is also triggered due to undervoltage
- **Protection tests**: Maintenance tests of the protective devices while the generator is off also triggers the DFR, which is usually kept in operation
- **Normal operation**: The DFR may be triggered while the generator is under normal operating conditions, due to an external trigger, noise in the DFR inputs or a trigger maladjustment
- **Energization**: When the generator is being synchronized, the DFR may be triggered by the normalization of the lockout relay or during the transient period after the circuit breaker operation
- **Fault**: This includes short circuits, loss of synchronism and every kind of load rejection, which means the unit is disconnected from the system while power is being generated. The DFR is triggered normally by the protection system operation
- **Null**: These are the cases where the DFR triggers, possibly due to noise in its inputs when the generator is off-line
- **Inconclusive analysis**: This is the output when the scheme does not have enough information to achieve a conclusion about the disturbance.

C. ESSOE

The SOE that happened during the oscillography time lapse is analyzed by the ESSOE. The SOE read from the database are classified according to its type and function. The types are main protection relay trip; auxiliary relay trip and circuit breaker operation. Among these classes the events are classified according to its function, like overcurrent relay, lockout relay, main circuit breaker, manual opening of the circuit breaker and several other functions.

The classified events with the event status form the facts knowledge base of the ESSOE. With these facts and studying the protection system of the generator the rules to analyze the SOE can be written. An example of one of these rules is:

- If the event is the operation of a reverse power relay and it status changed to tripped and also the circuit breaker changed to open, then the result is REVERSE POWER TRIPPING.

From the rule above one can note that there is no way to distinguish between a manual and an automated reverse power tripping. The first is a common procedure to shutdown steam units and the latter is a fault. The analysis of the oscillographic record should be checked to distinguish both situations by means of the initial active power. If the power is near zero then the unit is being intentionally shutdown otherwise it is a hazardous situation.

The example above shows that the SOE analysis and oscillographic analysis should be correlated in order to obtain a final conclusion about the occurrence. This is the objective of the Expert System for generation Unit analysis.

D. ESUNI

The ESUNI consists of an expert system with a set of simple rules that correlate the results form ESOSC and ESSOE. An example of one of these rules is:

- If the result from ESOSC is de-energization with initial active power near zero and the result for ESSOE is reverse power tripping then the final conclusion is Unit De-energization by Reverse Power.

Several similar rules were defined in order to represent a set of pre-defined possible final results from the proposed scheme. For each generation unit these results are stated in the list below:

- Normal operation
- Out of service
- De-energization by reverse power
- Normal de-energization
- Energization
- Protection system tests
- Isolated unit operation
- Synchronism of the unit with the system
- Fault or forced shutdown
- No result.

It will be seen in the results that the majority of the occurrences fall into the generation unit normal operation or out of service classifications. When there is no result or the result is fault, the specialized engineer has to verify the analysis report and the data manually in order to figure out what really happened.

The most common causes of a no result conclusion are:

- Failures in the data collection system, like missing events in the SOE
- Wrong time synchronism between the oscillographic records and the SOE
- Spurious events in SOE due to noise at RTU inputs
- Wrong connections of current or voltage transformers with the DFR

IV. CASE STUDY

This section shows an application example of the proposed scheme in a real occurrence.

A. The power plant

The single line diagram of the electrical system where the automated analysis module was tested is shown in Figure 4. It is a simplified diagram without drawing the auxiliary circuits.

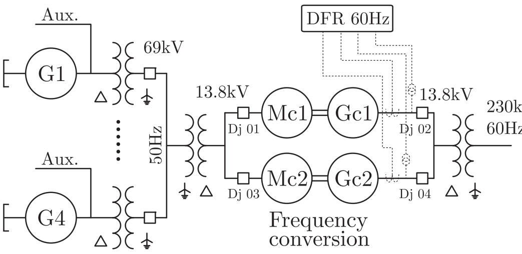

Fig. 4. Simplified single line diagram from the power plant.

The power plant has four 24MVA 50Hz coal-fired steam turbogenerators. These generators were installed in early times when the Brazilian power grid was not so much interconnected and there were several 50Hz isolated systems. As the system grew, two 35MVA electromechanical frequency conversion units had to be installed. Each of these units consists of a synchronous motor directly coupled to a synchronous generator with different number of poles. Both conversion units are connected to the main Brazilian 60Hz power grid.

The DFR reads the terminal voltages and load currents from both generators of the conversion units (Gc1 and Gc1). As they are synchronous generators and the terminal voltages and currents are available, the proposed scheme can also be applied to them, not only with turbogenerators.

B. Input data, features and ESOSC execution

Figure 5 shows the absolute value of the phasorial record of the disturbance. The drawing only shows the electrical phase A. Phases B and C have similar shapes.

It can be seen that the unit was operating under nominal values and after a sudden current increase the unit was tripped by the protection system. The painted gray region on Figure 5 represent the disturbance interval obtained by the detection index from (1). The features are calculated for the segments before the beginning of the disturbance interval and after the end of it. These calculated features can be seen in Table I.

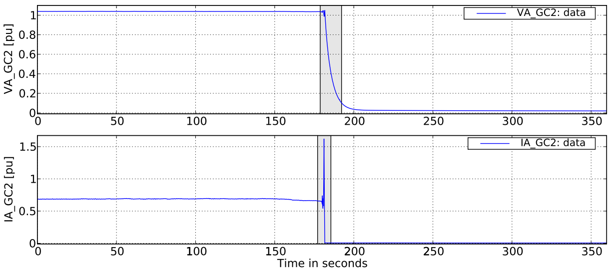

Fig. 5. Segmented voltage and current of the case study.

TABLE I
SEGMENTATION OUTPUT FOR THE CASE STUDY

Channels	Phases	Pre-disturbance mean value $[pu]$	Pos-disturbance mean value $[pu]$
VA_Gc2	A	1.038	0.025
VB_Gc2	B	1.048	0.024
VC_Gc2	C	1.032	0.030
IA_Gc2	A	0.687	0.006
IB_Gc2	B	0.681	0.006
IC_Gc2	C	0.696	0.008
P		0.252	0.002

In this case, the ESOSC obtain a conclusion of FAULT / FORCED SHUTDOWN. To achieve this, the rules of set R0 that represents a sudden drop down (or de-energization characteristic) are fired for each of the voltages and currents phases. Knowing that the active power was not zero before the disturbance, the rules from set R1 that relates sudden drop down on voltage with sudden drop down on current are fired. The same conclusion is obtained for the three phases, thus the FAULT/FORCED SHUTDOWN rule of R2 set is fired ending the ESOSC execution.

C. Sequence of events and ESSOE execution

The sequence of events recorded during this occurrence is summarized in Table II. This table shows SOE in a descriptive way with only the time stamp, the related component and a description of each event.

TABLE II
SEQUENCE OF EVENTS RECORDED DURING THE DISTURBANCE.

Time stamp	Comp.	Description
15:12:57.123	MC2	Phase sequence relay (47) tripped
15:12:57.132	MC2	Tripping relay (94M) tripped
15:12:57.199	MC2	Tripping relay (94M) changed to normal
15:12:57.219	DJ03	Motor CB changed (DJ 03) to opened
15:12:57.231	GC2	Unit synchronized signal changed to opened
15:12:57.372	DJ04	Generator CB (DJ04) changed to opened
15:13:03.613	MC2	Motor oil pressure relay tripped
15:13:03.632	MC2	Motor lockout relay (86M) tripped
15:13:05.308	MC2	Motor oil pressure relay changed to normal

With this SOE the ESSOE obtain the conclusion FORCED SHUTDOWN for the conversion unit 2. The events of a protective relay tripping (in this case, the 47), the operation of a tripping relay (94) and the opening of the the circuit breakers are the conditions used by the ESSOE to achieve this conclusion.

D. ESUNI execution

Using both the conclusions: FAULT / FORCED SHUTDOWN from the ESOSC and also FORCED SHUTDOWN from the ESSOE the ESUNI confirms that the results from both sources are coherent. A final result is then achieved and an analysis report is generated.

An indication flag in the web interface of the data iOSC informs the specialist engineer that a new automated analysis report is available. The engineer may then check the report and generate a new version of it, confirming or not the results provided by the automatic tool and adding comments and observations to it. All versions of the report are stored in the database system.

V. PRACTICAL RESULTS

The proposed scheme was also tested with a real set of data recorded during an one-month period in the same power plant from Figure 4. The records used to obtain these results are related to the turbogenerators, from the 50Hz portion of the power plant. Each one of them has the terminal voltages and load currents monitored by a single DFR.

Table III shows the results obtained for all four generation units. The total amount of analyses performed was 140.

TABLE III
TEST RESULTS.

Conclusion	Total	Correct result	No result
Normal operation	73	72	1
Out of service	53	53	0
Reverse power de-energization	5	3	2
Normal de-energization	1	1	0
Energization	2	1	1
Synchronism	3	3	0
Fault	3	1	2
Unforeseen cases	6		

From Table III it can be seen that the correct results obtained by the automated analysis represent more than 95% of the total. Among the 140 cases, only 3 can be classified as fault or forced shutdown cases. These results clearly show that the majority of the occurrences came from oscillographies recorded during normal situations or when the generators are out of service. Thus for most of the recorded data, the manual analysis by a human specialist is not necessary. The engineer should only check the fault cases and the cases where there is no result from the automated analysis module.

The inconclusive results in the fourth column of Table III indicate that the oscillography analysis and/or SOE analysis did not work. Considering the specific data set in Table III, these analyses could not be performed correctly because of missing key events in the SOE due to acquisition system failures. The table also shows that there are 6 unforeseen situations where the facts where correct but did not represent any situation considered in the rule set of ESOSC. All these cases should be analyzed by the specialist engineer.

VI. CONCLUSION

This paper discussed the importance of automating the analysis of operational data in power station. The amount of data recorded in a daily bases can be large enough to difficult its detailed analysis by professionals. The proposed scheme can significatively help the analysts by providing a previous classification of each occurrence that is easily accessible through the system's interface. This way the engineer may firstly analyze the most important cases like faults or forced shutdowns.

Both the oscillographic records and the SOE records are analyzed in the proposed scheme. The analyses of each one are made parallelly. This way, if one of the data sources fails, the result is not totally unreliable. The engineer can then verify the occurrence using the correct data source.

In order to obtain the knowledge base of the expert systems, extensive studies of the generators protection systems and operational procedures were realized. The ESSOE knowledge base should be reevaluated for each power plant, as their protection schemes can be different. The ESOSC do not need to be changed for a power plant to another.

The paper also shows that the phasorial records of the DFRs are more suitable than the waveform records to this kind of approach to help engineers in the analysis task.

The proposed scheme was applied for several real occurrences in a Brazilian coal-fired power plant. The results showed that the system is able to identify common situations when the oscillographic data may be automatically archived with a high percentage of success.

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