Enhancement of an Expert System Philosophy for Automatic Fault Analysis

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Abstract: The authors wish to share some of their ideas for automatic fault analysis systems based on oscillographic fault recorders. The authors hope to elicit discussion that will enlighten critical aspects around automatic fault analysis systems. Systems like these may have many purposes, such as for instance to recognise and categorise the faults. Other purposes are to determine fault locations and to record data about fault level and fault resistance. A particular purpose that has not developed to the desire of most utilities is to accurately evaluate the correctness of protection operations for a fault. This may be due to the diversity of protection devices available and the enormous amount of permutations of binary indications possible. It may also be due to suppliers' desire to maintain secrecy of their programming code in fear of losing their intellectual property. By means of an openly coded Expert system with a robust evolutionary rule-base and algorithm-base, it may be possible for suppliers to retain secrecy of some algorithms and heuristics while still allowing a utility to optimise the Expert system for accurate analysis. The envisaged system is intended to provide System Operator control personnel with information in a near-real-time frame so as to help them with operational decision making. This paper aims to explain the meaning of the term 'Robust Evolutionary Expert System', and then to show how inclusion of this concept into an automatic fault analysis system elevates the probability of realizing a successful and effective system. Some other finer points of automatic fault analysis systems are also explored, and risk analyses are performed on aspects that may lead to failures or problems.

Subtitle / keywords: Automatic Fault Analysis: Robust Evolutionary Expert System

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1. Introduction

It is the aspiration of every electric utility to maintain network integrity and stability throughout, and to continue power supply to customers without interruption. To support this aspiration, many attempts are made to enhance automatic protective relaying systems, to implement wide area protection systems (sometimes called special protection systems) and to improve the quality of information available to human operators (let us call them "controllers") in network control centres. It is on this last option that this paper and the work behind it are focusing. By improving the speed, validity, completeness and accuracy of information provided to controllers, much may be achieved to alleviate serious network disturbances. This may be done by using data which is made available through the SCADA system, such as the Expert Systems described by Huang (2002), Sidhu, Huff and Cruder (1997), Minakawa et al. (1995), Bernard and Durocher (1994), or Yongli et al. (1994), the last of which proposed using only circuit breaker alarms.

However, in the work presented here, it is hoped to improve the completeness and accuracy of the analysis of the protection operations and their correctness, by adding data available from Digital Fault Recorders (DFRs) that include oscillographic recordings of voltages and currents, as well as binary signals from protection relays. Phadke and Thorp (1996) correctly highlighted that while most protection systems are designed to discriminate accurately and operate only for the particular conditions for they are set to trip, unfortunately, protection relays that are designed to prevent excess damage to equipment may often contribute to network instability or loss of network integrity.

To enable proper analysis of protection relay operations in the larger context of power system events, an automatic fault analysis system is required that is able to identify faults (location, time, type), distinguish them from other power system phenomena (power swings, voltage instability etc.) and determine accurately which protection relays operated correctly or not. Hossack et al. (2002) describe a system that performs almost all of these functions, by employing separate Intelligent Agents for different functions, such as Incident/Event Identification (IEI), Fault Record Retrieval (FRR), Fault Record Interpretation (FRI) and Protection Validation & Diagnosis (PVD). None of the necessary answers for protection operation assessment can truly be accurately resolved without the availability of oscillographic voltage and current traces. Without accurate fault information (type, resistance, location), or without comparison of fault inception times with relay operating times, it is also not possible to make a truly accurate assessment of the protection operation.

This paper describes motivations, some requirements and some possible solutions for an Automatic Fault Analysis System that is to be installed at the National Control centre of Eskom in South Africa. For brevity it shall be called the "*AFA System*" from hereon forward. It is important to note that this is not the first attempt at realising an automatic fault analysis system based on oscillographic fault records from DFRs in South Africa, and readers are referred to the proposal by Stokes-Waller (2000). Please refer also to the more recent proposal by Keller, Henze and Zivanovic (2005), in which they demonstrate how SVMs can be used in a Fault Classifier. The ambition to obtain an automatic fault analysis system is not unique to Eskom or South Africa. In fact, Sevcik et al (2000) demonstrated how that a similar system was configured and tested for Reliant Energy HL&P in the USA. One of the main drivers for this aspiration is highlighted by Kezunovic and Philippot (2003), namely the conflict between intensifying requirements for performance assessment versus an ever increasing shortage of relevantly skilled man-power.

2. Technologies Used for Automatic Fault Analysis Systems

Yuehai et al. (2004) demonstrate a method for fault type identification, using threshold pickups for several variables, combined in a logic table that determines the type of fault identified. This requires a great deal of predetermined values based on human expertise. The most important variables are the relative angle between zero sequence and negative sequence currents and voltages, the relative change in current magnitude (each phase) and the relative change in voltage magnitude (all phases and phase-phase).

Whereabouts of the fault location is important when the evaluation of protection relay performance is evaluated, as well as for primary information to power system personnel who need to inspect the equipment condition. Yuehai et al. (2004) goes on to show that double-ended fault location is much more accurate that single-ended fault location. For this however to be successfully executed, the fault records from all recorders need to be synchronised, clustered and categorised in terms of relevance to a particular fault.

To this end the exact fault inception time and fault duration must be resolved. In this respect, Ukil and Zivanovic (2005A) demonstrate the application of abrupt change detection by using a wavelet transform. They go on to demonstrate how this can be used to synchronise disjointed records of the same fault from different recorders, and further how relay operating time and auto-re-close time delays can be determined with this method (Ukil and Zivanovic, 2005B). In a paper by Barros, Perez and Pigazo (2003), the authors claim that the Short Time Fourier Transform (STFT) is often more suitable for analysis of power quality disturbances than wavelet analysis and use Kalman filters to identify the onset of power quality disturbances (PQDs).

Bollen et al. (2007) compare abilities of Expert Systems (ES) and Support Vector Machines (SVM) to classify PQDs. They also compare two segmentation methods, namely a Kalman filter and a derivative-based method applied to RMS sequences. They conclude that SVMs require many learning instances, and that instances compiled of synthetic data fail to teach SVMs appropriately. They also conclude that it is significantly easier to incorporate power system knowledge into an ES than into a SVM, although this could probably be solved by adding ES features to an SVM. A survey by Ibrahim and Morcos (2002) reveal that a wide variety of "Artificial Intelligence" methods have been experimented with to analyse PQDs, among others Fuzzy Logic, Expert Systems, Artificial Neural Networks (ANN), Genetic Algorithms (GAs) and Adaptive Fuzzy Logic, which is understood to incorporate some ANN or GA abilities to learn or optimise. A method was developed by Kezunovic, Luo (Shanshan) and Sevcik (2002) to perform fault location in conditions of sparse field recording availability, using Genetic Algorithms (GAs).

While power quality disturbance diagnosis is a different subject in its own right, many of the same requirements apply to automatic fault analysis. For instance, Sun, Jiang and Wang (1998) shows how Artificial Neural Networks (ANNs) can be used to analyse and report on the correctness of protection relay operations, provided that different ANNs are designed and taught for different time-spaces on the fault event sequence. In order to cluster (group) relevant recordings, the fault voltage waveform profiles (or other relevant features of the fault) from various recordings have to be compared. Fukuyama and Ueki (1991) showed that ANNs can be successfully used to perform waveform recognition and fault identification; as long as they are verified by means of a rule based Expert System (ES). The use of Neural Networks Fault Detection (NNFD) and classification is also proposed by Zhang and Kezunovic (2004), combined with Synchronised Sampling Fault Location (SSFL). However, two years later the same authors (Zhang and Kezunovic, 2006) seem to prefer rigorous mathematical solutions for detection, classification and location by comparing modal components of currents against thresholds, leaning heavily on synchronised sampling. In essence, these mathematical solutions perform various current differential calculations on sequence component transforms of discrete time domain samples of the phase currents and voltages, hence the significance of synchronised sampling with GPS synchronisation. In a proposal for using records and reports directly from relays, Luo (Xu) and Kezunovic (2005) demonstrate how the CLIPS expert system shell can be used to apply what they call Forward and Backward Chaining Logic Reasoning to evaluate protection relay operations. It appears to be a practical application of Event Tree Analysis as discussed earlier by Zhang and Kezunovic (2004). Unfortunately traditional attitudes are very negative towards the concept of direct access to information from protection relays, at least in South Africa, that is. This is mainly due to fears of sabotage and mismanagement. For that reason, although we would very much like to include relay records, and we can certainly prepare the *AFA System* for incorporating that, we must for the time being be satisfied with fault recorder reports only.

3. Description of the Automatic Fault Analysis System

The *AFA System* shall be a Server system that shall be prompted by the creation of fault record or report files on its entry folders by Fault Recorder Master Station Stations. These Master Stations shall operate independently of the *AFA System*, and shall access fault recorders of various types directly, by the various protocols appropriate to the relevant types of fault recorders to be accessed.

Once a Fault Recorder Master Station Station has obtained a new Fault Record, it shall export that record with suitable identification to the appropriate *AFA System's* entry folder, in Ascii Comtrade format, Binary Comtrade format, Text Record format or Text Report format with various sequences of analogue and digital channel configuration. Every time a new fault record is detected by the *AFA System* in one of its entry folders, it shall be imported by the *AFA System* and processed.

The *AFA System* shall perform all analyses on the newly imported record by means of signal decomposition, Fault Classification, Binary Analysis and Expert System Rules, including identification of related records and combination of data and analyses of related records. The *AFA System* shall store all data and results of analyses.

The *AFA System* shall then perform any configured automatic alerts, and publish or export all configured automatic reports or fault record files to the relevant destinations. The *AFA System* shall allow the configuration, export and viewing of data, reports, fault records, impedance plots and trends by Visitors through Web Browsers, according to certain security requirements. The *AFA System* shall also allow Users and Experts to amend data, and Experts to amend the analysis formulas and outputs, according to specific access requirements.

Figure 1 below gives a conceptual diagram of the different components of the *AFA System*, first shown by Keller, Henze and Zivanovic (2005). It is also instructive to study the diverse conceptual diagrams provided by Yongli et al. (1994), Sevcik et al. (2000) and Bollen et al. (2007), each illustrating their structure with a different paradigm.

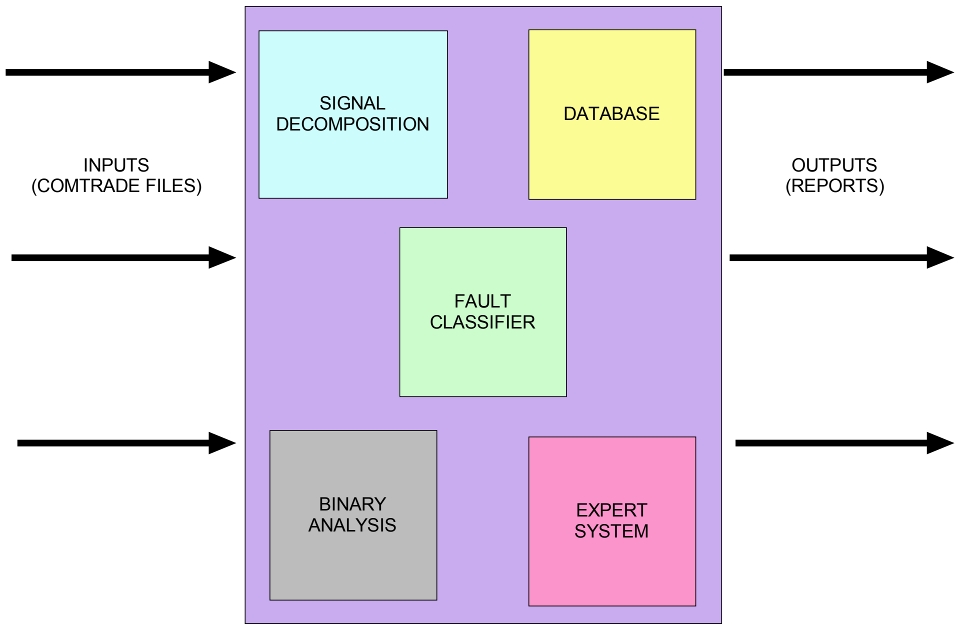

Figure 1: Conceptual Diagram of the *AFA System*

Further on in this work we will concentrate on the requirements and possible solutions for Binary Analysis and the Expert System, assuming that Data Collection, Signal Decomposition and Fault Classification have been taken care of. For a more detailed description of Signal Decomposition and what is expected of a Fault Classifier, refer to Keller, Henze and Zivanovic (2005).

4. Automatic Analysis Versus Human Analysis

4.1 Trends in Substation Automation

Post-mortem investigations can always be carried out over many weeks, and all the data can be fine combed at leisure. However, during operational time frames, Crossley and Hor (2005A) contend that the amount of substation data generated by microprocessor-based IEDs is rapidly becoming too much for humans to interpret. They go on to demonstrate principles for weeding out unnecessary or erroneous data, and to generate decision rules by means of Rough Sets. In subsequent proposals, they provide an alternative by focusing on unsupervised classification based on rough sets within a substation (Crossley and Hor, 2005B), and they show how training of a classifier is done by providing a set of training data, and then testing its performance on a set of test data (Crossley and Hor, 2005C). Together with Watson, Crossley and Hor (2007) continue to pursue Rough Set theory to achieve automatic decision making for the purpose of event analysis.

As can be seen from the above, apart from the analysis itself, several other factors have to be taken into account. Ackermann (2002) already alerted us to the fact that the evolving substation and protection IED technology is increasing the amount of information available dramatically. While this additional information can be beneficial to applications such as State Estimators and Automatic Fault Analysis Systems, it will be necessary to implement carefully designed methods to collect, transmit, process and store the relevant data.

Dongyuan, Xinghua and Xianzhong (2003) demonstrate how that "Local Management Computers in Substations" can be used to facilitate communication between relays, fault recorders and central data processing and analysis components. In order to facilitate integration of data, a uniform DFR file format is required, as shown by Kezunovic and Popovic (2002), who proposes the use of the COMTRADE standard format. The use of new IEC standards (IEC61850 and IEC61970) for data integration is recommended by Kezunovic, Djokic and Kostic (2005), but they caution that further changes may be necessary to adapt to evolving functions, some examples of which they demonstrate. Similarly, Apostolov (2004) refers to an ASEAS (Automatic Substation Event Analysis System), and show what requirements are necessary for it to be implemented by means of the IEC61850 protocol, in order to facilitate data transfer and information extraction. Apostolov (2006) also promotes monitoring of circuit breakers and instrument transformers, and subsequent user notification for predictive maintenance. This is included in requirements by Kezunovic and Latisko (2005), in a proposal for an Automated Analysis Substation System (AASS), in which they added to the list: DFR and relay record analysis, power quality analysis, fault location, verification of switching sequences and "Two Stage"state estimation.

4.2 South African Background

Since 1992 Eskom Transmission has introduced DFRs on all Transmission feeders (220kV and above). The present setup comprises of a diversity of oscillographic and travelling wave fault recorders installed at diverse substations throughout the country, connected to a telecommunications network that spans the entire transmission network. In the present setup, all recorders are accessed via a X.25 protocol, to make the process simple and uniform for the sake of the human engineers. In addition, due to legacy devices, the communication speed is limited to 19200 Baud (Bits per second), which slows down potentially faster communication with more modern devices. The analysis of the data coming from these recorders can provide valuable information to controllers with respect to the operating of the power system. Due to this Eskom Transmission embarked on a process to analyse these faults as soon as possible and to provide the controllers at the National Control Centre with near real time information. This process involves engineers/technician to be on standby 24 hours a day. These standby personnel are contacted as soon as a fault occurs on the network, and they then perform the following manual procedures:

1. They write down detail of the incident provide by the controller. This step often takes about one minute, taking into account common telephonic courtesy between people.
2. The standby engineer(s) establishes a telephonic connection to the Eskom Intranet and log in to the relevant access control systems. This step takes about one to two minutes, due to the multiple access control systems that have to be logged into, and depends on the alertness of the standby engineer. Let's accept an average of one and a half minutes.
3. Then they enter the DFR software and select the appropriate DFR to dial up, and through the DFR software they obtain the table of contents of records available on that DFR. This step usually takes about half a minute, and is repeated for every DFR to be accessed.
4. Then they scan the DFR table of contents for the relevant fault records and select those. This step can take anything between ten seconds and a minute, depending on the number of recordings that were triggered on the particular DFR and the alertness of the standby engineer. Let's accept an average of half a minute. This step is repeated for every DFR to be accessed.
5. Then they start the download of the selected recordings, which usually takes about three minutes per recording, depending on the length of the recording.
6. Once a record is available on the DFR software, the standby engineer analyses the record by taking measurements of the oscillograph quantities, binary indications and time differences. This step can take anything between two minutes and five minutes, depending on the complexity of the incident depicted in the oscillographic record and the alertness of the standby engineer.
7. Often, another record from the opposite end of the transmission line is also required before an accurate analysis conclusion can be finalised. Thus, assuming an alert standby engineer, National Control will at best receive an answer from the standby engineer after fifteen minutes.

Of course, the fifteen minute human example above assumed that only one transmission line tripped and that only two records are required, one from each end. If all standby engineers were perfectly alert all the time, then a consistent performance of fifteen minutes might have been tolerable, although controllers have indicated that information received after 5 minutes does not aid them in operating decisions. However, experience has shown that the average response time is approximately 30 minutes, and controllers find that unacceptable and of no use at all.

Although this process has been followed for years, recently the increased complexity and dynamics of the transmission network has raised the demand for faster and better information to the network controllers. While human performance could certainly be improved by changing the working conditions of personnel by placing them in rotating shifts and improving their response time through training, vocal resistance to these initiatives by both management and staff indicates that an automatic analysis system may be a more viable solution. An automated analysis system is expected to reduce the overall response time to about five minutes and to provide information to the controllers that can be used to aid them in operating decisions.

There are now two different angles from which to look at the benefits of an Automatic Fault Analysis system. From the first perspective, it could assist in making heads-or-tails from horribly complex crisis situations, by collecting all the raw data, grouping or clustering everything, and pointing stand by engineers towards the really interesting (difficult) problems. From the second perspective, it could save money on all the callouts and overtime worked by standby engineers on mundane, run-of-the-mill little faults (!How casual we get about faults!), for which the *AFA System* could provide controllers with perfectly sound information. Let us look at each of these perspectives in turn.

4.3 Crisis Complications

On 19 February 2006 at about 00:25 a heavy saline (conductive) mist formed and spread over the Western Cape area. Combined with pollution (caused by smoke from bush fires) on the overhead transmission line insulator strings, this mist started a series of flashovers on the southern transmission corridor. These flashovers caused multiple transmission line and bus zone trips that resulted in under-voltage load shedding, line overloads, under-frequency bus bar trips and an out-of-step protection operation. The Western Cape network separated from the rest of Eskom's Integrated Power System (IPS) on two occasions at 02:30 and at 04:26. This occurred because the southern corridor transmission lines tripped due to flashover-induced faults, while the northern corridor transmission lines tripped due to a combination of severe under voltage and severe over current, which the transmission line impedance protection relays perceived as faults.

Over a period of five hours, there occurred altogether 60 automatic circuit breaker trips on transmission lines due to transmission line protection operations, of which 28 were single-ended only. During this time the amount of alarms received by the human controllers in the National Control centre numbered in thousands, and due to data overload on the SCADA system, some alarms and indications were slow in updating. As a result the controllers were not always aware of the exact state of the network, and where transmission line ends that tripped single-ended only, it gave controllers cause for concern that the protection operations may have been false.

With respect to the Fault Investigations attempt, altogether 245 oscillographic records were recorded on the relevant DFRs connected to these transmission lines. At three minutes per record, it would take one engineer more than twelve hours to download all the records.

Certainly the engineer could start analysing as soon as the first record arrives complete, and analyse each record in turn as he receives it, but even so his analyses would be available to the controllers on average three hours too late. The seriousness of the situation was realised soon, and a team of two engineers started analysing together. However, the awkward timing of the incidents, combined with the protracted duration, eventually required handover to another team of engineers, posing its own problems of coordination and cooperation between people.

In hindsight, many of the single-ended trips were due to over-voltage, and correctly so, since the voltages surged as load was lost. A few were also due to real bus bar faults that had occurred in between, although some of the lines on those bus bars had already tripped out due to their own faults. However, quite a large proportion were also due to over-tripping in delayed backup (Zone 2) mode for faults on a line where the protection did not trip, and therefore the long fault duration lead to tripping on other transmission lines. Unfortunately, due to the overload of information, some information was lost, and engineers had not yet determined the root cause (an incorrect protection relay setting) by the 28th of February 2006, when the entire sequence repeated itself almost exactly.

As it were, during the incident, controllers could not be certain where the real faults were, whether they were transient or permanent, and which circuit breakers they could close with confidence. It is for exactly this type of incident that a proper Automatic Fault Analyses system would provide the greatest benefit, with the ability to cluster (group) fault records together, analyse incidents independently, and provide National Control with a brief summary of events and problems. Where the *AFA System* detects problems, anomalies or uncertainties, National Control can then call out engineers to investigate in detail.

Thanks to the clustering done by the *AFA System*, the engineers would be able to hone in on the relevant records speedily, and detail analyses with meaningful decision supporting information can be available quickly.

4.4 Fault Statistics

From another perspective, let's look at the type of faults and incidents that occur on the Eskom Transmission network. Most faults are of transient nature and in ~90% of the time the protection operation is correct. Figure 2 shows the performance of protection of the Eskom Transmission network over the last 5 years.

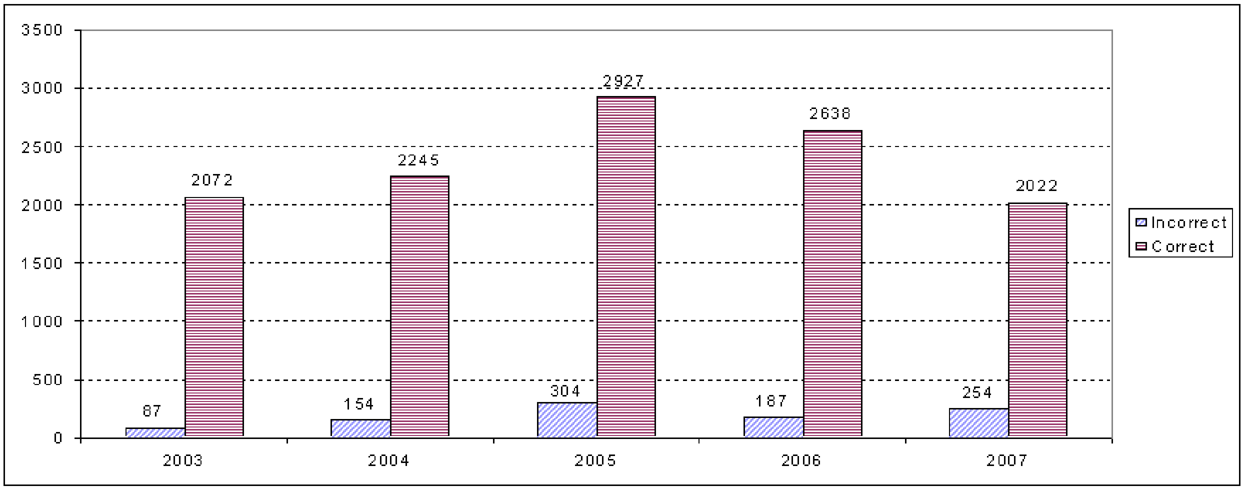

Figure 2: Protection performance statistics (Correct vs. Incorrect)

Incorrect protection operation is not only where a relay fails but any protection operation which is not according to the current Eskom Transmission protection philosophy. Automated analysis should be able to identify the incorrect protection operations and report on them. The controller might need to take action when presented with an incorrect protection operation (eg. Switch the relay off).

Figures 3, 4, 5 and 6 show the distribution of fault types on the Eskom Transmission system. As expected, the majority of faults are single phase to ground faults, followed by phase to phase to ground faults. Figure 7 shows the transient nature of single phase to ground faults, or where a single phase trip is followed by a successful single phase auto-reclose (ARC), while Figure 8 shows the total ARC success rate.

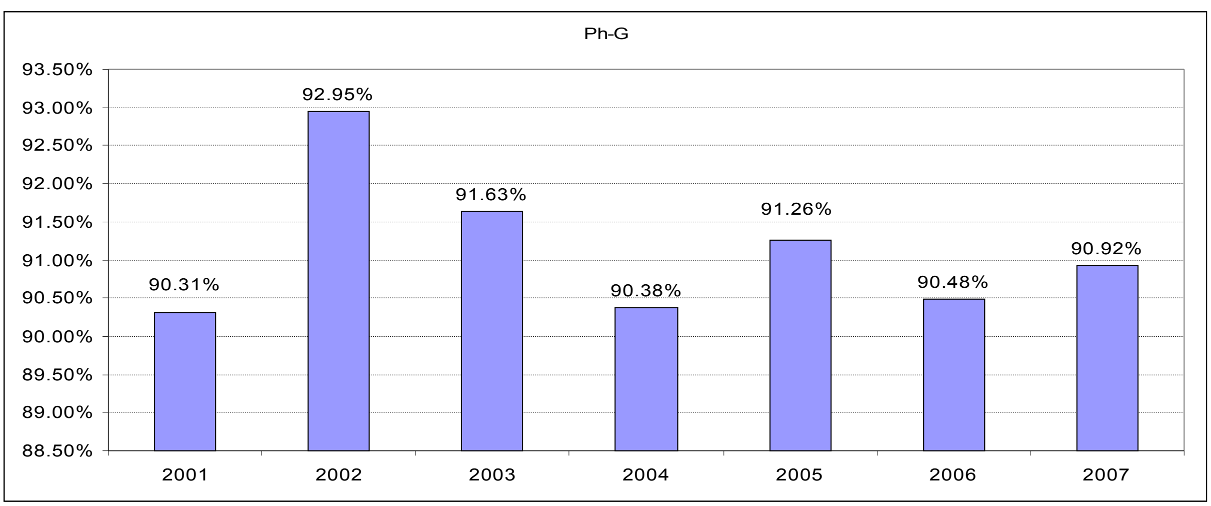

Figure 3: Single phase to ground fault statistics

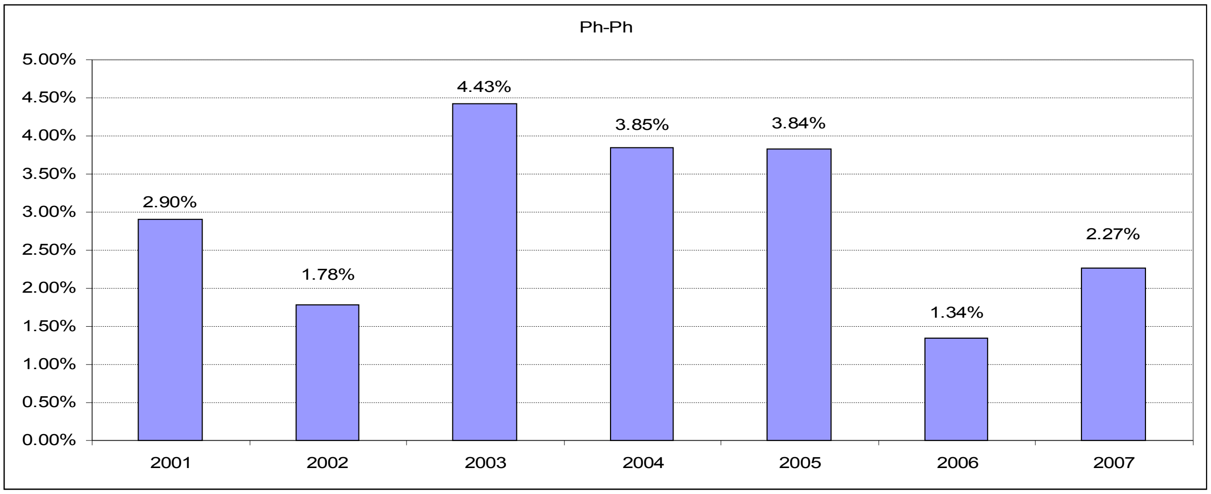

Figure 4: Phase to phase fault statistics

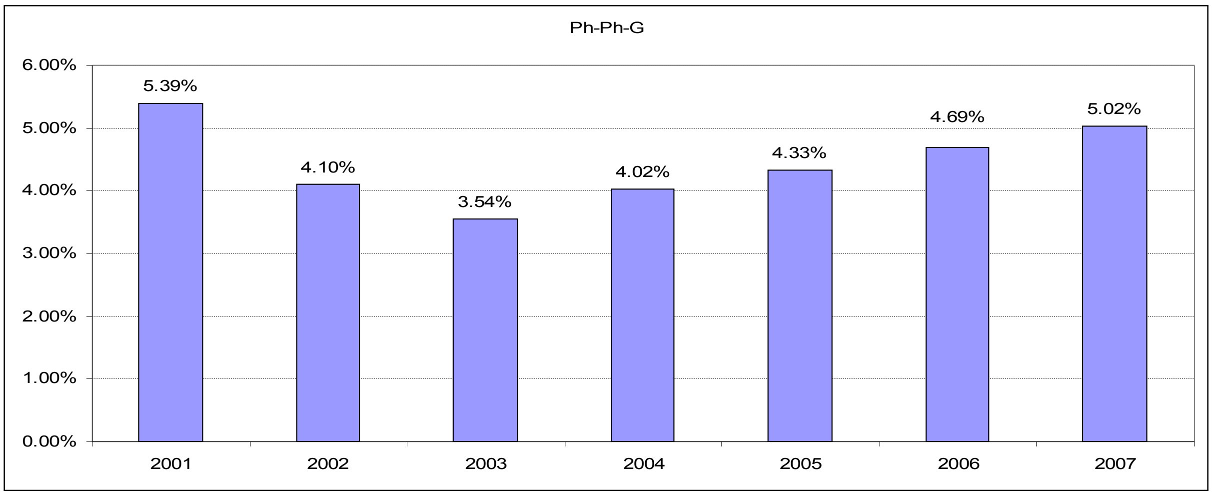

Figure 5: Phase to phase to ground fault statistics

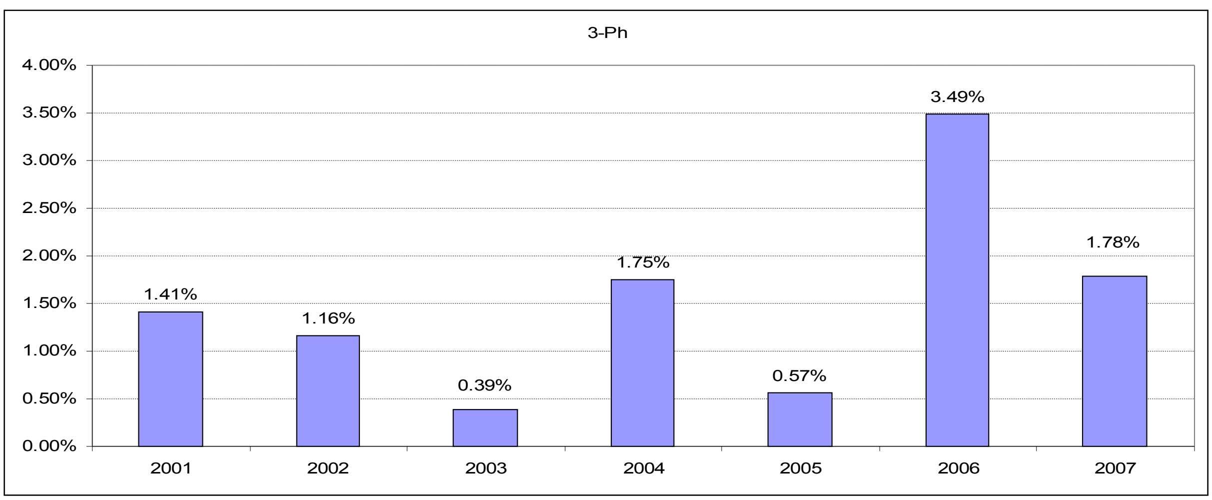

Figure 6: 3-Phase fault statistics

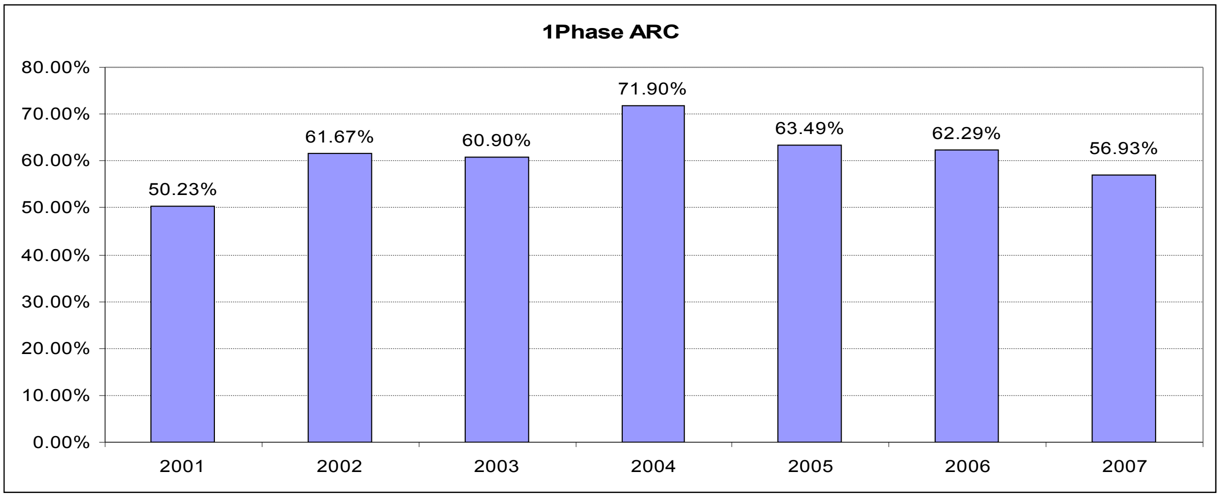

Figure 7: Single phase ARC success rate

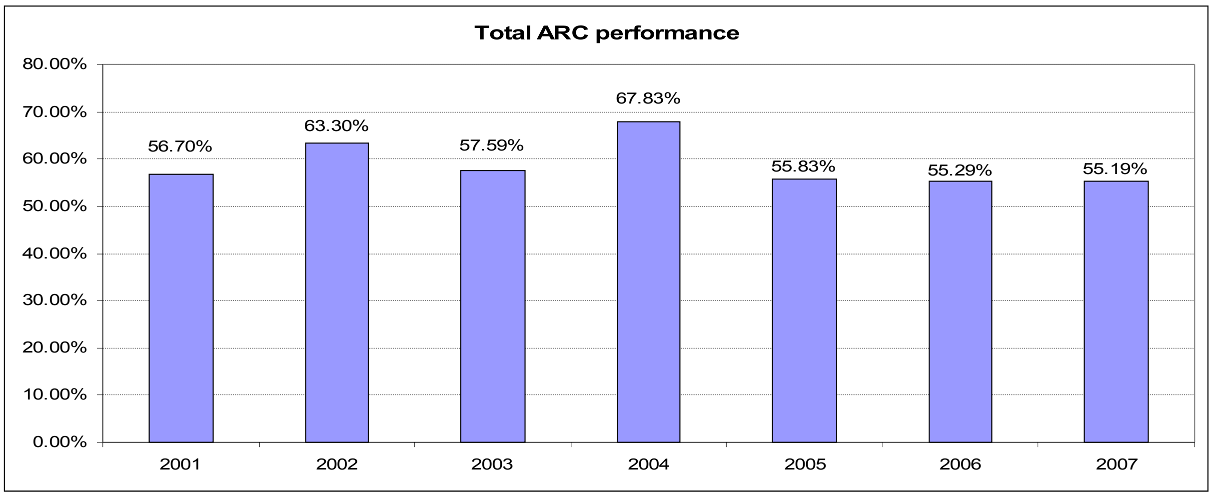

Figure 8: Total ARC success rate

A cost saving can be incurred for all the faults where nothing went wrong. As can be seen from the above graphs the majority of faults are of a transient nature and most protection operations are correct. For these faults the automated fault analysis system can provide information to the controllers without any need to consult standby engineers for these faults. When there is a major system disturbance where multiple lines trip, an automated analysis system will be extremely helpful in providing a clear picture of what happened in a very short space of time. The involvement of the standby engineer/technician during these disturbances might be necessary. When the automated fault analysis system identifies an incorrect protection operation it might also be necessary to involve the standby engineer/technician immediately. This will allow immediate ratification of the automated fault analysis system diagnosis and thereby improve confidence in the system. As the incorrect operations are not as numerous, a monetary saving in payment of overtime can be achieved with an automated system.

5. Objectives of a Automatic Fault Analysis System

Now that everyone is convinced that an Automatic Fault Analysis System is beneficial and even essential, let's take a look at the objectives that we want it to achieve, in descending order of importance:

1. Provide near-real-time information, a term coined by Bartylak (2002), on power system disturbances as recorded by fault recorders on the power system, as well as other types of analysers, in order to assist in operational decision making by National Control in accelerating restoration times, so that the controllers can reduce interruption times and improve system security.

2. Alert personnel to incorrect protection operations.
3. Provide fault locations for line patrols to repair faults.
4. Assist in power system disturbance statistical analysis.

5.1 Providing Near-Real-Time Information

Objective number 1 is quite a mouthful, but we can break it down to three simple sub-objectives:
1.1 Collect and organise all fault recorder data and other reports available
1.2 Identify and classify all faults (location, time, type) and group all relevant data per fault
1.3 Alert controllers to abnormal incidents (breaker failure, breaker re-strike, permanent fault, power swing etc.) so that they can call out the relevant experts to assist them

5.2 Incorrect Protection Operations

Objective number 2 is deceptively concise. Protection relays may mal-operate, thus tripping for faults that occur outside their intended zone of protection, or inversely, a protection relay may fail to operate, ultimately leading to tripping of other relays (in backup fashion) for a fault that this relay should have detected and cleared quickly.

Sometimes the primary fault is of a permanent nature, and the protection relays operate perfectly correctly. In such a case however, all attempts to return the tripped primary equipment to service will lead to repeated faults, voltage disturbances to all customers around and subsequent re-tripping of the same primary equipment.

In all cases the Network Operator who can obtain accurate analysis of incident most quickly will be best able to decide how to restore the network optimally. Optimal restoration in this context would mean return to service of all healthy primary equipment without further unnecessary trips. This implies:

a) Where a protection relay tripped for a fault on another piece of primary equipment, all healthy primary equipment may be returned to service immediately, but the over-tripping relay should be switched off either by remote control or by sending a standby operator to the substation, as soon as possible.
b) Where a protection relay tripped for normal load (whatever level of load is considered within reasonable bounds for the particular piece of primary equipment), the over-tripping relay should be switched off either by remote control or by sending a standby operator to the substation, even before the circuit breaker is re-closed.
c) Where a relay failed to operate for a fault on its own protected primary equipment, and other relays had been forced to trip in backup fashion, but correctly so, all healthy equipment may be returned to service immediately. However, in some cases it may be advisable to delay return to service for a transmission line, especially if the risk of a subsequent fault on the same transmission line is relatively high. This may be the case where it is known that bush fires are raging unchecked in the vicinity of that transmission line, if a severe thunderstorm is passing over that transmission line, or if severe weather conditions have arisen over that transmission line. In addition, the under-tripping relay should be maintained, re-adjusted or re-placed with a very high degree of urgency, since this condition poses a very high risk for complete system collapse, due to the fact that backup protection modes are much less discriminating, such that multiple relays from all over the network may detect the fault and all of them trip simultaneously.
d) Primary equipment with permanent faults should not be returned to service. This is true for almost all underground or underwater cable faults, transformer faults, reactor faults and capacitor faults. For overhead transmission lines most faults are not permanent, but it is not trivial to distinguish between permanent and transient faults. Often ARC functions in protection schemes will restore transmission lines fast and automatically after clearing supposedly transient faults. Subsequent tripping of the protection immediately after the circuit breaker is closed would seem to indicate a permanent fault, although it can be shown that this is no always so. The operator needs an accurate report of whether a fault is permanent or not, since this will determine the decision to return to service or not.

There are therefore basically five possible outcomes for every protection relay operation. The above four, and then the case where the fault is transient and all protection operations are correct and the transmission line is back in service through Auto-Re-Close. This last outcome is trivial, since the operator would be able to see that the transmission line Auto-Re-Closed and is back in service through looking at the SCADA system. In the case that a protection scheme is selected to perform Auto-Re-Closure, and the transmission line does not return to service by means of Auto-Re-Closure, the failure to ARC also needs to be analysed, if no clear reason for a failure to ARC can be detected, the failure to ARC should be flagged as an incorrect operation as well.

5.3 Providing fault locations

While determining exact fault locations as per Objective number 3 is a very interesting subject, and not trivial at all, it is not of the highest priority for the *AFA System*. As long as the fault is located on the correct transmission line, the *AFA System* can perform its further analysis of protection relay operations with confidence. However, if the fault is permanent, a maintenance team will have to drive out to it and repair it, and to save time on that, an accurate fault location would help a lot.

For this reason it is essential that the *AFA System* shall also have access to Travelling Wave recorders, since these have much better fault locating abilities, as shown by Gale, Stokoe and Crossley (1997). The benefit of travelling wave recorders is most evident when fault location must be done on series capacitor compensated transmission lines, where impedance calculations rarely achieve accurate fault locations.

5.4 Statistical Analysis

Once all data has been collected and all analyses have been performed, engineers can perform post-mortem analysis of the incidents and confirm the correctness of all the reports by the *AFA System*. It should then be relatively easy to incorporate or import all the information made available by the *AFA System* into the utility's asset management and performance measurement software system. Obviously, this is not a time-urgent priority, and can take place over days or weeks even. Presently this is done manually by several engineers, who could spend their time more productively on innovative projects and really interesting investigations.

As it happens, many little errors or omissions slip in due to human error, and as a result the utility's asset management and performance measurement software system is left with an incomplete and inaccurate database. Both a saving in man-power and an improvement in asset management performance measurement accuracy can be achieved by automating the transfer of analysis results from one software system to another. One prerequisite for this is that the power system topology and equipment terminology of the two software systems must be consistent.

6. The Robust Evolutionary Expert System Concept

For those who have been introduced to the concept of an Expert System, it is commonly understood that Expert System Rules basically work like condition-based Macros. Condition pattern comparison is done continuously, and once the required pattern of conditions is matched, the Expert System executes the instructions contained in the Rule. The concept of a Robust Evolutionary Expert System is not entirely novel, since Expert Systems have been around for decades. Really all Expert Systems are evolutionary, since the rules will be improved on as the Experts that program it gains experience from incidents where the system behaves undesirably or provides incorrect results.

6.1 Configurable Expert System Rules with Formulas

While there are some standard automatic analysis packages available on the market, a few experimental trials of these packages have determined that they are unable as yet to provide sufficiently detailed analysis to achieve the priority objectives listed above. Often a utility has particularly unique experiences due to the unique setup of its transmission network, its stability, the environmental factors, and the configuration of the protection schemes used on that network. The various unique circumstances and interpretations of correct tripping needs to be incorporated into the analysis, and this can only be done by allowing the utility to optimise the Expert System by adding, removing or changing the rules that execute the analysis.

Rules will need the ability to include instructions for setting variables, which other rules can then make use of in their condition pattern comparison. These variables may be Boolean (true or false for certain conditions), numerical (the magnitude and angle of a certain impedance) or temporal (absolute or relative time marks), among others. The Expert System will need a system to keep track of variables.

Rules will also need to be able to execute the dispatch or broadcast of other outputs as per instructions, such as reports containing results of mathematical calculations or logic in templates, or alert messages (Alarm, E-mail or SMS) that are communicated to outside destinations.

To enable condition pattern comparison, Rules must have the ability to perform numerous mathematical calculations, time-measurements and Boolean logic decisions. It should also be possible to configure each Rule by adding, removing or changing formulas to improve the Rule's condition pattern comparison for its specific task.

Among the standard formula components several mathematical operators will be necessary, operating on phasors, magnitudes or angles of currents, voltages, powers, or on sequence component or harmonic component extracts of currents and voltages. These will have to include at least:
- Algebraic and Calculus (Differentiation and Integration) on Scalars, Vectors and Matrices
- Complex algebraic operators for complex Scalars, complex Vectors and complex Matrices
- Data lookup, reference and format manipulation operators (text to number or vice versa)
- Date and time operators to synchronise diverse fault records from different recorders
- Waveform recognition operators based on Neural Networks / Genetic Algorithms
- Wavelet Transform, Fourier Transform and harmonic component operators
- Trigonometry, Hyperbolic Trigonometry and Power Series operators
- Linear and quadratic equation programming solution operators
- Boolean logic and Fuzzy Logic (influence) operators
- Polynomial equation solution operators
- Statistics calculation operators

6.2 Change Management of Rule and Formula Evolution

Each Rule will have to be named appropriately, and should thereafter be treated as a separate entity. By means of an internal modification process the *AFA System* can be transformed into a Robust Evolutionary Expert System and as such its ability to distinguish incorrect protection operations from correct protection operations and the feedback that it provides to grid controllers will continuously improve in validity.

To deliberately make *AFA System*'s Expert System evolutionary, and also provide it with a high degree of robustness against erroneous programming, it requires a modification process with three basic facilities: Firstly it requires a facility whereby all previous versions of Rules are numbered and stored for later recall. Therefore, any modification to a Rule can only be performed on a new version, and the last version is archived prior to the modification. Secondly it also requires a facility whereby any modification to a Rule needs to be tagged to a particular incident where the latest version of that Rule provided incorrect results. Let's define this particular incident as the trigger incident. Thirdly it also requires a facility whereby any new Rule is tested off-line by means of simulation to see if it now provides the correct results after the modifications, so that a previous version of that Rule can be recalled if necessary. Normally reports by the *AFA System* shall contain only the analysis results. However, when an incorrect result is detected on a report, it shall be possible to trace the incorrect result to the particular Rule that produced that result, by producing a more detailed report that cites results next to the name of the Rule that produced those results. Once the faulty Rule has been identified, an Expert can log in to the *AFA System* and invoke the Modification Process on that particular Rule. The Modification Process should be restricted to designated Experts who have to log in through an access control system.

The Modification Process should capture the date and time, the login name of the Expert, the name of the Rule that is modified, the previous version number, the trigger incident number and the new version number, as well as explanatory notes by the Expert of why and how the modification was performed, and what the result of the modification was. The *AFA System* shall have to employ interlocking so that not more than one Expert may perform corrections to Rules. Once a modification is done, a simulation test should be carried out against a Recommended Test List. All incidents shall have to be numbered of course, and the Recommended Test List contains incident numbers of all the standard test records and all previous trigger records, as well as the latest trigger record for which this occasion of the modification process was invoked. Each Rule should have its own Recommended Test List, with a unique set of standard test records and history of trigger records for that Rule.

Every new trigger record should be added to the Recommend Test List for that Rule. In this way, any future modifications to the same Rule should not lead to regression whereby improvements made for this trigger record are undone. Of course, as the system evolves, the Recommended Test List for a particular Rule may grow very large due to the many modifications required to it. Therefore the Expert who performs the modification should have the option to skip test simulations on selected records in the Recommended Test List and should also be able to edit the Recommended Test List to reduce the number of test records contained therein.

6.3 Change Management Wizard Graphical User Interface

In order to facilitate the Change Management of Rule and Formula Evolution in an organised fashion, the *AFA System* shall need a “Rule Wizard”. What is meant by a “Wizard” here is in essence a structured dialogue window with user friendly menus, selection functions and entry boxes for formula composition and instruction sequencing.

As a dialogue window it should have a well defined and structured Graphical User Interface that displays the vital information about the Rule that is under construction, its sequence of instructions, and the names of formulas and instructions in that sequence. With the click of a mouse button on one of the formulas or instructions in that sequence, another dialogue window should open to edit that formula or instruction.

The view of the formula composition window should be such that mathematical expressions are displayed in direct mathematical notation. It should be possible to make changes or additions to mathematical expressions in direct mathematical notation, with appropriate position and context manipulation tools available to the user.

Inside a Rule, a formula should be treated as an instruction, with its output the continuation of the Rule sequence. However, instructions that produce tangible outputs such as reports, variables or calls to other Rules, should also have the same ability to compose mathematical expression, so that they can calculate the relevant variables contained in their reports or calls to other Rules.

In essence therefore, there should be little difference between formulas and instructions, apart from the fact that formulas basically determine activation of the Rule only, while instructions produce tangible outputs and start other Rules. The sequence of execution within a Rule should of course be that all formulas are executed first, and only when all their conditions are satisfied may the instructions commence.

The Rule Wizard should inform the user if a grammatical mistake is being made in the mathematical expression, or when it detects that the formulas or instructions for this Rule are made identical to the formulas or instructions of another Rule, with sufficient information about the case that the user can follow up and correct the mistake or duplication.

6.4 Examples of Envisaged Expert System Rules and Formulas

In order to facilitate the analysis by the *AFA System*, various Rules will have to be developed. Firstly there needs to be Rules to identify or distinguish protection operations correctness, by means of identification of things such as ARC initiate, ARC time delay, ARC failure, protection operation time delay, protection sympathy trip and protection failures to operate. Secondly there needs to be Rules to identify or distinguish breaker health and fault causes, by means of identification of things such as Fault Phase, Fault Type, Fault Location, Fault Cause, Breaker Failure and Breaker Restriking.

Particular examples of Rules that will be required are:

- Relay type identification and subsequent adjustment of selectable formulas
- Detection of a permanent fault that requires mechanical restoration of the primary plant to enable re-energisation
- Detection of a failure to clear a fault due to persistent secondary arcing, which may appear to be a permanent fault but will in fact clear after sufficiently long downtime
- Detection of breaker restriking or breaker pole disagreement that indicates that the circuit may have to be put on bypass in order to avoid using the maloperating circuit breaker
- Detection of maloperation of a protection relay that will prevent re-energisation of the transmission line due to spurious tripping, which requires the relay to be switched off
- Detection of tripping on Weak Infeed
- Detection of a long second shot ARC delay due to breaker spring rewind

The following might serve as good examples of the type of components used in the formulas for Rules:

- Adjustable “rate of change of voltage level” detection, combined with adjustable timers, per phase, both in rising above an adjustable level or dropping below that level.
- Integrated Negative Sequence “current level” detection, with adjustable set and reset levels and adjustable integration time constants, both in rising above the adjustable levels or dropping below those levels.
- Relative timers between the pickup (and drop-off) of any analogue detection and the pickup (and drop-off) of any binary detection.

7. Operational Risk Analysis

With the modification process in place, at the very worst an Expert may make an erroneous modification, and despite the incorrect analysis results still confirm (possibly due to excess confidence) that the off-line analysis results were all correct. As soon as the Expert (or someone else) then detects an incorrect analysis result of a new incident on-line, the modification process can be accessed again, and the off-line tests can be run again. At some point, the Expert should recognise that the modification that was made caused the incorrect analysis, and then a previous version of the Rule can be recalled from the archive and restored as the active Rule. It is also envisaged that future generations will be able to study the evolution of the *AFA System* and that this will prevent regression into less optimal conditions.

Other particular aspects that may lead to failures or problems that will hamper the system are for instance:
- incorrect interpretation of distinguishing characteristics of correct and incorrect operations
- incorrect translation of distinguishing characteristics into formulas
- incorrect understanding of the *AFA System*'s messages by grid controller personnel

All of these concerns can be addressed by training and education of the relevant staff, much of it in advance. However, some particular problems will have to be identified through monitoring, and only once they have been identified will it be possible to address those problems by focused training and education of the relevant staff.

Aspects from the company background that may impact on the system's effectiveness are for instance:
- Eskom will have to invest in upgrading of communication infrastructure to substations in order to achieve the ultimate goals of this project.
- In-house developments of automated analysis systems are seldom supported by Eskom and an 'off the shelf' solution will have to be acquired.

These aspects can be addressed through continued communication and reporting to the organisation, and liaison between departments.

8. Conclusions

An Automatic Fault Analysis System as proposed in this paper would have far reaching benefits to a utility like Eskom and its customers, by improving restoration times, system stability and system observability. There is evidence that in a few isolated cases around the world, similar systems have been developed and are used with varying degrees of success. Due to the increasing complexity of transmission networks and the increased pressure on manpower resources, automatic analysis is not only becoming more and more viable, but even essential. Its benefits would shine through most apparently during dire emergencies when its ability to organise and identify anomalies would assist engineers in their detail analysis and thus speed up restoration. However, over the long run, it may benefit financially most thanks to its quiet processing of all mundane day to day normal incidents, where its precision and accuracy of reporting would outshine human intervention.

Even when such a system is provided "off the shelf", the vendor should allow utilities the freedom to design and program their own set of Rules in a system like this for the full benefits to be realised. Often a utility has particularly unique experiences due to the unique setup of its transmission network, its stability, the environmental factors, and the configuration of the protection schemes used on that network. The various unique circumstances and interpretations of correct tripping needs to be incorporated into the analysis, and this can only be done by allowing the utility to optimise the Expert System by adding, removing or changing the rules that execute the analysis. This can be achieved by incorporating into the software a Rule Wizard that allows editing of formulas for the condition pattern comparison as well as instructions contained in a Rule.

The main risks posed to such a system would be mismanagement by people and organisational difficulties. These can be addressed by training, education, continued communication and liaison between departments.

9. References

Ackermann W.J., (2002), “The impact of IEDs on the Design of Systems Used for Operation and Control of Power Systems”, IEE 5th International Conference on Power System Management and Control (PSMC), London, UK, 17-19 April 2002

Apostolov A.P., (2004), “Requirements for Automatic Event Analysis in Substation Automation Systems”, IEEE Power Engineering Society General Meeting, 6-10 June 2004

Apostolov A.P., (2006), “Automatic Fault Analysis and User Notification for Predictive Maintenance”, IEEE-IAS/PCA Cement Industry Technical Conference, Phoenix, Arizona, USA, 9-14 April 2006

Barros J., Perez E., Pigazo A., (2003), “Real Time System For Identification Of Power Quality Disturbances”, 17th International Conference on Electricity Distribution, CIRED, Barcelona, 12-15 May 2003

Bartylak A., (2002), “Application of Disturbance Recorders as Near Real Time Information Support for National Control in ESKOM”, DPSP Conference, Amsterdam, Netherlands, 2002

Bernard J.P., Durocher D., (1994), “An Expert System for Fault Diagnosis Integrated in Existing SCADA Systems”, IEEE Transactions on Power Systems, Vol. 9, No. 1, February 1994

Bollen M.H.J., Gu I.Y.H., Axelberg P.G.V., Styvaktakis E. (2007), “Classification of Underlying Causes of Power Quality Disturbances: Deterministic versus Statistical Methods”, EURASIP Journal on Advances in Signal Processing, Volume 2007, Article ID 79747, 2007

Crossley P.A., Hor C.L., (2005B), “Analysis of Substation Data for Knowledge Extraction”, IEEE Power Engineering Society General Meeting, 12-16 June 2005

Crossley P.A., Hor C.L., (2005A), “Extracting Knowledge From Substations for Decision Support”, IEEE Transactions On Power Delivery, Vol. 20, No. 2, April 2005

Crossley P.A., Hor C.L., (2005C), “Reasoning Applied to Substation Data Extracted from Relays and Circuit Breakers”, 15th PSCC, Liege, Session 35, Paper 1, Page 1, 22-26 August 2005

Crossley P.A., Hor C.L., Watson S.J., (2007), “Building Knowledge for Substation-Based Decision Support Using Rough Sets”, IEEE Transactions On Power Delivery, Vol. 22, No. 3, July 2007

Dongyuan S., Xinghua W., Xianzhong D., (2003), “Road to the Integrated Protective Relaying Fault Information System”, IEEE Power Engineering Society General Meeting, 13-17 July 2003

Fukuyama Y., Ueki Y., (1991), “Development of an Expert System for Analyzing Faults in Power System Using Artificial Neural Network Based Waveform Recognition”, IEEE International Symposium on Circuits and Systems, Singapore, 11-14 Jun 1991

Gale P.F., Stokoe J., Crossley P.A., (1997), “Practical experience with travelling wave fault locators on Scottish Power's 275 & 400 kV transmission system”, Sixth International Conference on Developments in Power System Protection, Nottingham, UK, 25-27 March 1997

Hossack J., McArthur S.D.J., McDonald J.R., Stokoe J., Cumming T., (2002), “A Multi-Agent Approach to Power System Disturbance Diagnosis”, Power System Management and Control, 17-19 April 2002.

Huang Y.C., (2002), “Fault Section Estimation in Power Systems Using a Novel Decision Support System”, IEEE Transactions On Power Systems, Vol. 17, No. 2, May 2002

Ibrahim W.R.A., Morcos M.M., (2002), “Artificial Intelligence and Advanced Mathematical Tools for Power Quality Applications: A Survey”, IEEE Transactions On Power Delivery, Vol. 17, No. 2, April 2002

Keller P., Henze C., Zivanovic R., (2005), “Automated Analysis of Digital Fault Records: A Utility Perspective,” SAUPEC Conference, Johannesburg, South Africa, January 2005

Kezunovic M., Djokic T., Kostic T., (2005), “Automated Monitoring and Control Using New Data Integration Paradigm”, Presented at 38th Annual Hawaii International Conference on Systems Science, Waikoloa, HI, January 5-8, 2005

Kezunovic M., Latisko G., (2005), “Requirements Specification for and Evaluation of an Automated Substation Monitoring System”, CIGRE Meeting, Calgary, Canada, 8-16 September 2005

Kezunovic M., Luo S. (Shanshan), Sevcik D.R., (2002), “A Novel Method for Transmission Network Fault Location Using Genetic Algorithms and Sparse Field Recordings”, IEEE PES Summer Meeting, Chicago, July 2002

Kezunovic M., Philippot L., (2003), "Future Trends in Utilizing Advanced Technologies for Fault and Disturbance Data Analysis," CIGRE Colloquium, SC B5-Protection, Sydney, Australia, September 2003.

Kezunovic M., Popovic T., (2002), "Integration of Data and Exchange of Information in Advanced LAN/Web Based DFR Systems", Fault and Disturbance Analysis Conference, Atlanta, Georgia, USA, April 2002

Luo X. (Xu), Kezunovic M., (2005), "An Expert System for Diagnosis of Digital Relay Operation", 13th International Conference on Intelligent Systems Application to Power Systems, IEEE, Washington DC, USA, 6-10 November 2005

Minakawa T., Ichikawa Y., Kunugi M., Shimada K., Wada N., Utsunomiya M., (1995), "Development And Implementation Of A Power System Fault Diagnosis Expert System", IEEE Transactions on Power Systems, Vol. 10, No. 2, May 1995

Phadke A.G., Thorp J.S., (1996), "Expose hidden failures to prevent cascading outages", Computer Applications in Power, IEEE , Vol. 9 , No. 3 , pp. 20-23, July 1996

Sevcik D.R., Lunsford R.B., Kezunovic M., Galijasevic Z., Banu S., Popovic T., (2000), "Automated Analysis of Fault Records and Dissemination of Event Reports", Texas A&M 53rd Annual Conference for Protective Relay Engineers, College Station, Texas, April 2000

Sidhu T.S., Cruder O., Huff G.J., (1997), "An Abductive Inference Technique For Fault Diagnosis In Electrical Power Transmission Networks", IEEE Transactions on Power Delivery, Vol. 12, No. 1, January 1997

Stokes-Waller E., (2000), "Automated Digital Fault Recording Analysis on the Eskom Transmission System", Southern African Conference on Power System Protection, South Africa, 2000

Sun Y., Jiang H., Wang D., (1998), "Fault synthetic recognition for an EHV transmission line using a group of neural networks with a timespace property", IEE Proc.-Gener. Transm. Distrib., Vol 145, No. 3, May 1998

Ukil A., Zivanovic R., (2005A), "Abrupt Change Detection in Power System Fault Analysis using Wavelet Transform" , International Conference on Power Systems Transients (IPST'05) in Montreal, Canada on June 19-23, 2005

Ukil A., Zivanovic R. (2005B), "Application Of Abrupt Change Detection In Relay Performance Monitoring", International Universities Power Engineering Conference, Cork, Ireland, Sept 2005

Yongli Z., Yang Y.H., Hogg B.W., Zhang W.Q., Gao S., (1994), "An Expert System for Power Systems Fault Analysis", IEEE Transactions on Power Systems, Vol. 9, No. 1, February 1994.

Yuehai Y., Yichuan B., Guofu X., Shiming X., Jianbo L., (2004), "Fault Analysis Expert System for Power System", 2004 lnternational Conference on Power System Technology - POWERCON 2004 Singapore. 21-24 November 2004

Zhang N., Kezunovic M., (2004), "Verifying the Protection System Operation Using an Advanced Fault Analysis Tool Combined with the Event Tree Analysis", IEEE Northern American Power Symposium, NAPS 2004, Moscow, Idaho, USA, 9-10 August 2004

Zhang N., Kezunovic M., (2006), "Complete Fault Analysis For Long Transmission Line Using Synchronized Sampling", IFAC Symposium on Power Plants and Power Systems Control, Kananaskis, Canada, 2006

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