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A PARAMETER-BASED PROCESS FOR SELECTING HIGH IMPEDANCE FAULT DETECTION TECHNIQUES USING DECISION MAKING UNDER INCOMPLETE KNOWLEDGE

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Abstract— The behavior of high impedance faults is variable and not consistent. Under similar conditions, faults show different characteristics in behavior and may draw less harmonic current than other faults on the same soil surfaces. Most detection techniques have considered and focused on only one detection parameter without respect to system conditions. However, the behavior of high impedance faults is affected by many outside factors. Therefore, a single detection technique cannot provide effective fault detection in all cases. With varying environmental parameters and non-adapting detection techniques, we propose a generic method to choose the technique or techniques which are most appropriate for a given set of conditions. This result is achieved using a decision making method under incomplete knowledge. With this method, the performance of each detection technique is derived under various conditions and environments. This method is not yet complete because the performance outcome of all techniques is not fully defined. However, this generic selection method provides a head start when attempting to optimize detection given consideration of a wide variety of techniques, parameters, and environmental parameters.

Keywords: High impedance fault, decision making method, environmental parameters, detection techniques, decision making under incomplete knowledge, inductive reasoning.

INTRODUCTION

There is a problem which currently exists in the electric utility industry with the detection of high impedance faults. High impedance faults can be described as those distribution feeder faults that do not draw sufficient fault current to be detected by conventional protective devices such as overcurrent relays. Such faults may be caused by a downed conductor on the ground or in contact with a grounded object. Arcing is often associated with these faults, which may result in a fire or safety hazard. The harmonic current characterized by an intermittent arc is variable, transitory, and thus unpredictable in its behavior[1].

The behavior of high impedance faults can be characterized by a large relative amplitude increase in harmonic current through the duration of the arcing burst. However, the behavior of high impedance faults is not consistent. Under similar conditions, faults show different characteristics in behavior and may draw less harmonic current than other faults on the same soil surfaces. On surface types such as grass, asphalt, and concrete, the behavior of faults can be very similar to the phenomenon of switching events. Moreover, when a capacitor bank is present on a distribution feeder, certain harmonics are increased in some cases and eliminated in other cases[2]. Hence, the detection and classification of high impedance faults, switching events, and the normal state is a complex problem.

While several techniques to detect high impedance faults have been proposed, and some progress has been made, a complete solution has not been found. Most fault detection techniques have considered and focused on only one detection parameter without respect to system conditions. However, the behavior of high impedance faults is affected by many outside factors such as feeder configuration, surface conditions, and weather conditions. Therefore, a single detection technique cannot provide effective fault detection in all cases.

With varying environmental parameters and non-adapting detection techniques, here we propose a generic method to choose the technique or techniques which are most appropriate for a given set of conditions. This result is achieved using a special decision making method: decision making under incomplete knowledge[3]. With this method, the performance of each detection technique is derived under various conditions and environments. The next two sections present the various environmental parameters and detection techniques currently under consideration. It is necessary to determine the set of techniques which can provide the most complete detection of

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all fault types if implemented concurrently in a relay system. Selection must be made as a function of the external environmental parameters affecting fault behavior. Selection is complicated because no one technique or set of techniques is 100 % effective for any set of conditions.

ENVIRONMENTAL PARAMETERS

From the study of high impedance faults, it has been found that there are certain factors or parameters which affect fault behavior in such areas as fault current and burst duration[2].

The typical high impedance fault on an insulating surface such as asphalt, grass, or concrete, shows randomly large energy increases which last only a few cycles. There are some similarities between these faults and the switching events with respect to the magnitude increase and the duration of bursts. For example, the presence of a capacitor bank will depress the activity of high frequency components during fault conditions. Also, the surface condition at the fault site will change the characteristics of the harmonics and sub-harmonics.

These factors, which are called "environmental parameters," are those which change the behavior of high impedance faults and thus will affect the performance of any detection techniques whose frequency components are vulnerable to these parameters. Four environmental parameters are chosen for study and the reasons of their choice are as follows:

1. System Unbalance: load level can change rapidly and will cause misoperation of certain techniques which monitor the ground current magnitude variation for detecting high impedance faults.
2. Feeder Configuration: the presence of capacitor banks attenuates high frequency components.
3. Load Types: certain loads produce harmonics which have somewhat similar behavior to high impedance faults, and which might lead certain techniques to make wrong decisions.
4. Surface Conditions: surface conditions affect the behavior of the high impedance faults in magnitude and burst duration of harmonic and sub-harmonic fault currents.

DETECTION TECHNIQUES

Many techniques have been proposed to detect high impedance faults. A brief summary follows of several detection techniques: energy technique, randomness technique, phase relationship technique, sequence component technique, and amplitude ratio technique.

The energy technique was proposed by Texas A&M researchers in 1977. The term "energy" refers to the summation of the squared sample values of current over one 60 Hz cycle. An early energy approach used the amplitude increase of the high frequency (2 - 10 KHz) current to detect high impedance faults[4]. Later, a revised energy technique was developed which used certain low frequency components as detection parameters in a hierarchical detection scheme[5].

The sporadic nature of high impedance faults causes problems for many proposed techniques which rely on a consistent increase in magnitude over some predetermined period of time. A new technique was developed to solve the problem and in fact to use this randomness as an indicator of an high impedance fault[6].

High impedance fault current has a characteristic "notch" on the leading edge of each half-cycle. This ensures that the current will be rich in odd harmonics. With this in mind, a phase relationship technique based on third harmonic current was developed. This technique monitors the relative third harmonic phase angles between each of the three phases with respect to either the fundamental frequency current or the fundamental frequency voltage[7, 8].

It is assumed that the degree of unbalance is small under normal operating conditions on a three-phase system, and that this unbalance will increase due to any single phase fault. Thus, the non-characteristic sequence current components of the fundamental, third, and fifth harmonics can be monitored and a high impedance fault can be recognized by noting a sudden change in these components. Based on this idea, a harmonic sequence component technique was proposed[9].

The even harmonic currents are very small in a system under normal conditions. During a high impedance fault, with an active arc, "even" harmonic currents increase due to the unsymmetrical characteristics of the arc current. A technique which monitors the ratio of the even to odd harmonic currents at the range of the first to seventh harmonic has been proposed[10]. Another technique senses the ratio of the second harmonic to fundamental current[11].

From this brief summary of the existing detection techniques, it is noted that while each technique may offer a solution to some degree, none to date has proven to be a singularly powerful technique. This is summarized as follows:

1. No single technique covers all the cases of high impedance faults.
2. Each technique is very well formulated and based on theory and experiments, but might work only under certain and/or specific conditions.
3. Each technique has at least one weakness with respect to the environmental parameters.
4. The techniques do not provide adaptability to the environment.

5. Technique selection with respect to the environmental parameters is necessary to compensate for the environmental effects.

The previous two sections examined fault behavior factors and detection techniques. With varying environmental parameters and non-adapting detection techniques, the subject of our next section is how we incorporate all these in an improved detection scheme. The general theory of a decision making model and its approach under conditions of incomplete knowledge are hereafter discussed. Using this model, we will select a set of techniques for an assumed set of environmental parameters.

DECISION MAKING MODEL

One of the principal concerns of decision making is the development of analytical method for guiding the choice of a single course of action from among a series of alternatives. The classical decision model assumes that a decision maker can select one of a number of strategies open to it. As the performance of each technique under various situations is uncertain, the selected technique must operate under one of a number of mutually exclusive and exhaustive states of nature or environmental parameters. The eventual outcome of the selected technique will depend on the state of nature which happens to arise. The classical decision model with 3 techniques and 3 states of nature, for example, is shown below[3]:

$$\begin{array}{c c} & \begin{array}{ccc} E_1 & E_2 & E_3 \end{array} \\ \begin{array}{c} T_1 \\ T_2 \\ T_3 \end{array} & \begin{pmatrix} O_{11} & O_{12} & O_{13} \\ O_{21} & O_{22} & O_{23} \\ O_{31} & O_{32} & O_{33} \end{pmatrix} \end{array}$$

where

T_i: Technique

E_j: Mutually exclusive and exhaustive states of nature.

O_{ij}: Outcome of technique T_i given state of nature E_j.

The framework of the decision problem forms a common starting point for three approaches to decision making, which are distinguished by the amount of information they assume to be available about the probabilities with which the states of nature are likely to occur.

The first approach assumes that the decision maker is working in conditions of complete uncertainty about the future, i.e., that no information about the probabilities is available to him. When it is unable to make any statement about the vector of probabilities of the states of nature, this situation is referred to as a decision making under uncertainty.

The second approach takes the view that probabilities of the states of nature can be specified uniquely, either by repeated experimentation or by eliciting unique subjective probabilities from the decision maker. When it is able to specify exact values for all the vectors of probabilities of the states of nature, it is referred to as decision under conditions of risk.

The third approach attempts to strike a balance between two approaches. It assumes that in many decision problems, some information is available about the probabilities of the states of nature, but that it is not comprehensive enough to enable exact specification of the probabilities. This is called decision making under conditions of incomplete knowledge. Some real problems may be classified as decision making under conditions of incomplete knowledge.

In decision making under incomplete knowledge, it is assumed that the decision maker was able to rank states of nature in terms of their importance. With two given techniques, T_1, T_2, each technique may have to operate in one of $j = 1, ..., n$ environmental parameters and a subjective *a priori* ranking of the importance of the environmental parameters exists, $E_1 \geq E_2 \geq ... \geq E_j \geq ... \geq E_n$.

Then this approach seeks to determine under what circumstances the expected value (or performance) of T_1 will exceed or equal that of T_2, i.e., $E[T_1] \geq E[T_2]$, so that the first technique could be said to dominate the second, and vice versa. The conditions for statistical dominance are determined indirectly. Exploiting summation identity, the following theorem was derived[3].

If $E_1 \geq E_2 \geq ... \geq E_n$, then $E[T_1] \geq E[T_2]$, and
if $(\sum_{k=1}^{j} O_{1k}) \geq (\sum_{k=1}^{j} O_{2k})$ for all $j = 1, ..., n$

However, its principal practical drawback is clear. Only on a very small number of occasions are the $[O_{ij}]$ in a decision problem likely to obey the very stringent requirements of this theorem. It can easily happen that T_1 performs better than T_2 under the most likely environment, i.e., $O_{11} > O_{21}$, but T_2 may be preferential to T_1 under the second most likely environment, i.e., $O_{22} > O_{12}$. If some practical decision making aid is to be developed, a more general result than this is required, even if it is ambiguous in its interpretation. Two practical methods are listed[3]:

Derivation of maximum and minimum expected values given weak ranking of importance: The extreme expected outcomes of any technique, given an *a priori* ranking of the importance of the environmental parameters, may be found by computing n partial averages.

$$\bar{O}_j = \frac{1}{j} \sum_{k=1}^{j} O_k, \quad j = 1, ..., n \tag{1}$$

The largest such partial average will be the maximum expected outcome and the smallest will be the minimum expected outcome.

Derivation of maximum and minimum expected values given strict ranking of importance: This case has more information about ranking of importance, i.e.,

$$E_j - E_{j+1} \geq K_j, j = 1, 2, ..., n,$$

where $E_{n+1} = 0$, and K_j are positive constants.

The optimum values of $E(T)$ may be found by evaluating the below equation for $j = 1, 2, ..., n$. The largest of these gives the maximum $E(T)$ and the smallest the minimum.

$$E(T) = \frac{1}{j} Y_j (1 - \sum_{j=1}^{n} j K_j) + \sum_{j=1}^{n} K_j Y_j \qquad (2)$$

where

$$Y_j = \sum_{k=1}^{j} O_k$$

The next section presents the procedure of technique selection using the decision making method we discussed.

TECHNIQUE SELECTION PROCESS

Existing techniques have considered and focused only on one parameter for the detection of a high impedance faults under given conditions. As previously stated, the behavior of a high impedance fault is affected by many environmental parameters such as feeder configuration, surface condition, system unbalance, and load type. Therefore, a single technique cannot provide effective fault detection. Moreover, each technique has at least one weakness. To improve overall detection and discrimination under a wide variety of conditions, a generic technique selection for a given situation is desired.

For a set of alternative techniques, five major techniques were chosen. The environmental parameters are taken to be states of nature. For each parameter, the best and second best techniques are chosen using the approach of decision making under incomplete knowledge. When the most important parameters in a given situation are chosen, those corresponding techniques are to be chosen.

The reason that a method of decision under incomplete knowledge is used is that the information and the performance outcome of each technique is available but incomplete. It is very difficult or impossible to specify exactly each performance outcome under a given condition.

The electrical parameters are chosen by experience. The selected electrical parameters must positively identify high impedance faults and at the same time, possess an ability to discriminate transients associated with normal system events. Harmonic current components are the major electrical parameters.

As was mentioned above, a technique selection process starts with the existing techniques. The detection techniques used in this study were:

T1: Energy Technique.
T2: Randomness Technique.
T3: Phase Relationship Technique.
T4: Harmonic Sequence Component Technique.
T5: Amplitude Ratio Technique.

The electrical parameters are not restricted, but the behavior of high impedance faults is characterized and well indicated by harmonic currents. The electrical parameters are:

P1: Odd Harmonic Current.
P2: Even Harmonic Current.
P3: Sub-Harmonic Current.
P4: High Frequency Current (2 - 10 KHz).
P5: Third Harmonic Current.
P6: Third and Fifth Harmonic Current.
P7: Second Harmonic Current.

In the inductive reasoning method, for example, the activities of these electrical parameters are monitored and indicated as independent variables to select the most indicative parameters[12].

In its original form, each technique uses only one parameter to indicate the system status. Because the behavior of parameters vary situation to situation, it is desirable to use the most active parameter to indicate high impedance faults. Therefore, one parameter can be replaced by another; however, every technique cannot use all the parameters for detection. For example, the phase relationship technique uses only a single odd harmonic current to detect high impedance faults.

The next step is to find a best technique for each parameter. To find a technique, a specific decision making method is used. While the information and the performance of each technique is available but incomplete, it is not impossible to rank the importance of the environmental parameters with experts' knowledge and subjective ratings. For the states of nature, environmental parameters are used, which are the factors affecting the performance of the techniques and the behavior of high impedance faults. The environmental parameters as the states of nature are:

E1: System Unbalance.
E2: Surface Condition.
E3: Feeder Configuration.
E4: Load Type.

Each environmental parameter is important, but some are more important than others. It is assumed that the environmental parameters above are listed by the order of level of importance. From these, the outcome matrix of each technique-environmental parameter pair is formed. This is done with respect to the advantages/disadvantages of each technique under a given condition.

Here is an example outcome calculation. For parameter P2, even harmonic current, the energy technique is not substantially affected in its detection performance by the system unbalance because the energy technique is based on the arcing phenomenon characteristic of a high impedance fault. However, because of this, the energy technique is affected by the surface condition, since this surface condition determines the arcing behavior in terms of the amplitude increase and the length of arc burst duration. In general, even harmonic currents do not vary under changed feeder configurations such as presence/absence of a capacitor bank. Usual load and some solid state devices generate odd harmonics, thus the energy technique using even harmonics is not affected by the load type except in the case of arc producing processes (e.g. welding).

With these discussions and assumptions, and inevitably also by subjective ratings, the outcomes of the energy technique for environmental parameters are:

$$\begin{array}{cc} & \begin{array}{cccc} E1 & E2 & E3 & E4 \end{array} \\ T1 & \begin{pmatrix} 90 & 60 & 90 & 70 \end{pmatrix} \end{array}$$

From this matrix, the partial average of the energy technique is derived using Equation (1).

$$O11 = 90/1 = 90, \quad O12 = (90+60)/2 = 75$$
$$O13 = (90+60+90)/3 = 80, \ O14 = (90+60+90+70)/4 = 78$$

Therefore the maximum is 90 and the minimum is 75 for the energy technique. The outcomes of other techniques for the parameter P2 can be obtained similarly. The largest partial average gives the maximum performance and the smallest the minimum. Selecting a technique with their own maximums and minimums uses maximin partial average to indicate the best technique and maximax for the second best in case of extreme optimism.

Quantifying the performance outcome is a subtle problem. While it is possible to predict the performance variation in each environmental parameter, it is a different matter to quantify it. Therefore, we have chosen to rely on data from previous fault studies and our experts' subjective or *a priori* ratings. Then, an example outcome matrix for a given parameter can be rated as below:

$$\begin{array}{cc} & \begin{array}{cccc} E_1 & E_2 & E_3 & E_4 \end{array} \\ \begin{array}{c} T_1 \\ T_2 \\ T_3 \\ T_4 \end{array} & \begin{pmatrix} 80 & 80 & 80 & 50 \\ 80 & 50 & 40 & 80 \\ 80 & 20 & 80 & 70 \\ 80 & 10 & 10 & 80 \end{pmatrix} \end{array}$$

This table shows that T_2 shows 80 percent performance when it is exposed to the E_1 environmental condition, 50 percent for E_2, and so on. It is assumed that the order of the importance of the environmental parameters is $E_1 \geq E_2 \geq E_3 \geq E_4$, and this rating is weakly ordered. Then, the partial average of each technique can be calculated as below in terms of environmental parameters:

For T_1:
$O_1 = 80/1 = 80, O_2 = (80+80)/2 = 80$
$O_3 = (80+80+80)/3 = 80, O_4 = (80+80+80+50)/4 = 72$
Therefore the maximum is 80 (for E_1) and minimum is 72 (for E_4).

For T_2:
$O_1 = 80/1 = 80, O_2 = (80+50)/2 = 65$
$O_3 = (80+50+40)/3 = 56, O_4 = (80+50+40+80)/4 = 62$
Therefore the maximum is 80 (for E_1) and minimum is 56 (for E_3).

For T_3:
$O_1 = 80/1 = 80, O_2 = (80+20)/2 = 50$
$O_3 = (80+20+80)/3 = 60, O_4 = (80+20+80+70)/4 = 62$
Therefore the maximum is 80 (for E_1) and minimum is 50 (for E_2).

For T_4:
$O_1 = 80/1 = 80, O_2 = (80+10)/2 = 45$
$O_3 = (80+10+10)/3 = 33, O_4 = (80+10+10+80)/4 = 45$

Therefore the maximum is 80 (for E_1) and minimum is 33 (for E_3).

From all the partial average values, the maximax is 80 at all the T's and the maximin is 72 at T_1. Thus, the first technique is chosen as best one for a given parameter.

The partial averages of the techniques for other parameters are obtained similarly. Even though the matrices of partial average can be obtained, the matrix for each parameter is not complete. It seems that there is no possible way to get a complete outcome matrix. This outcome matrix needs many experiments and tests for its refined form. This matrix will be changed and refined by several real operation experiences. However, this research of technique selection provides a generic method to select appropriate technique(s) to be installed at an initial stage. From the matrix for each parameter, the technique selection database is formed.

Technique selection is performed with the most indicative parameter using the technique selection database. This parameter can be found by any means, such as, a general description of the site of a distribution feeder or a decision rule of an inductive reasoning method[12].

Figure 1 shows an example of important parameters, a technique selection database, and selected techniques. The

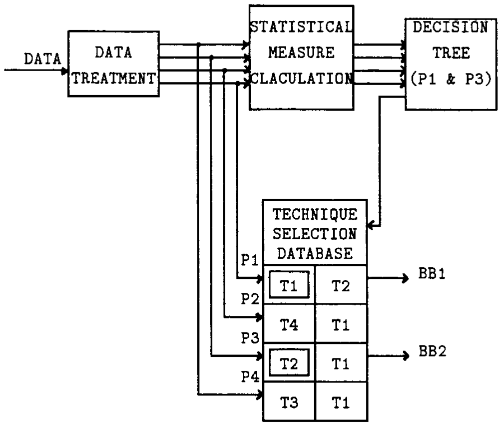

Figure 1. An Example of Technique Selection Process.

best and second best techniques are connected to a corresponding parameter; for example, for even harmonic current signal, a randomness technique and an energy technique are directly connected.

Then, by a decision rule which has important indicative parameters for detection purposes, the parameter list will trigger and activate techniques to be run with the parameters. In this example, the chosen parameters are P1 and P3. The decision rule activates the techniques T1 and T2. T1 will be run with the parameter P1 and T2 with P3. A combination of multiple techniques and their use in adaptive fault detection is the topic of another paper in preparation.

Selection is updated whenever a decision tree structure is changed and thus the active parameter list is updated. Thereafter the techniques to be run are changed. The other case in which the selection update occurs is when the outcome matrices are changed by any means.

CONCLUSIONS

The detection and classification of high impedance faults, switching events, and normal state is a complex problem. Many techniques have been proposed to detect high impedance faults, a complete solution has not been found. The behavior of high impedance faults is affected by many environmental parameters, therefore, a parameter-based generic technique method is necessary to choose a technique or multiple techniques in a given situation. While the most indicative parameters can be obtained by several different ways, an inductive reasoning process and its decision rule have been used.

By using a method of decision making under incomplete knowledge, an initial technique selection database was formed. When a parameter was chosen, which indicates surrounding environments, a corresponding technique will be chosen for use. These choices are not yet complete because the performance outcome matrix of the techniques for a given parameter is not fully defined. However, this generic selection method provides a head start attempting to optimize detection given consideration of a wide variety of techniques, electrical parameters, and environmental parameters.

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BIOGRAPHY

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