# Advanced Approaches for Detecting and Diagnosing Transients and Faults

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***Abstract:*** This paper introduces two new techniques: one for fault detection and classification and one for fault location. The techniques are quite unconventional and have numerous advantages over the existing techniques used for the same purpose. In a combination, the two techniques may be used to improve either the protective relaying of transmission lines or the off-line fault analysis. Some simulation results used to demonstrate the performance characteristics of the proposed techniques are also enclosed.

***Keywords:*** *electromagnetic transients, fault classification, fault location, learning systems, neural networks, pattern clustering methods, power system faults, protective relaying, synchronized sampling.*

## I. INTRODUCTION

THE problem of fault detection and classification is very important for both protective relaying and fault analysis of transmission lines. In the traditional solutions used in protective relaying and fault analysis solutions, this task is accomplished based on the analysis of the measured impedances [1]. This approach has some disadvantages since the decision is based on a comparison of the measured impedance to a set of thresholds (settings). If either the measurement or settings are inaccurate, which may happen in some specific case, the whole procedure performs poorly for such applications.

The next important issue is fault location. In the relaying applications, the location is established based on the line segment (zone) determined by the fault impedance measurement and a selected threshold (setting). In the off-line fault analysis applications, the fault location is determined much more accurately by using phasor formulation and related impedance measurements [2]. This technique is quite accurate if the phasors from both ends of the transmission line are utilized [3]. However, if the available data window is too short, the accuracy of calculating phasors may be compromised and the results may be pretty inaccurate.

This paper gives new approaches to solve both problems: fault detection and classification, as well as fault location. Besides describing the new approaches and providing the test results demonstrating the improvements, the paper also introduces a new concept of using the two techniques in a combined way to improve both the relaying and the fault analysis capabilities.

A new technique proposed for fault detection and classification is based on a specific Neural Network (NN) capable of providing the decision about the fault existence and fault type as discrete outputs [4]. By using this NN solution, the performance of the function is pretty good while the implementation is indeed straightforward. Most interestingly, this technique does not use the traditional settings and hence is not vulnerable to the inaccuracies in the measurements and/or settings.

The fault location approach proposed in this paper is quite different from the other approaches proposed for the same purpose in that it uses synchronized samples from two ends of the transmission line [5]. By doing so, the technique becomes transparent to many phenomena that make the traditional techniques to lose accuracy. This technique as well does not have any settings so it does not dependent on any inaccuracies associated with either the measurements or settings.

The paper first introduces the ways of using the two techniques in a combined fashion to accomplish new ways of implementing the traditional applications. After that, each of the techniques is discussed in detail providing some simulation results. At the end, conclusions and references are given.

## II. NEW APPROACHES TO TRADITIONAL APPLICATIONS

The traditional applications of interest are protective relaying and off-line fault analysis.

The protective relaying application needs to be executed in real-time, and because of this, a trade-off between the accuracy and speed of decision-making has been taken into account when selecting and designing the algorithms. As a result, the traditional protective relaying algorithms rely on a very crude determination of the location of the fault by just determining the transmission line section (zone) of the fault occurrence. In doing so the algorithms, based primarily on impedance measurement, also determine the fault type, which is needed for determining the tripping and/or reclosing actions that need to take place. In same rare occasions, both fault type and fault location function of the protective relaying algorithm may loose accuracy and the relays are known to miss operate as a consequence. Therefore, improving fault detection and classification as well as fault location in real-time is an important goal for a protective relaying application.

Performing off-line fault analysis is very important for the purpose of restoring the system as soon as possible. In this case the accuracy of finding the fault is the most important goal. The traditional approaches are quite accurate as long as the samples are obtained from both transmission line ends and there is a sufficient data window to obtain accurate phasor measurements [3]. In some special instances, the data window is not long enough and the traditional techniques may under perform. Finding some new ways of making the fault calculation very accurate under all application circumstances is an important goal for the off-line analysis.

The new approach proposed in this paper use the two new techniques, namely the NN and synchronized sampling, to improve both the relaying (real-time) and fault location (off-line) decision making. In both applications, it is critical that fault detection, classification and location are determined as accurately as possible. One way of improving the detection and classification as well as fault location functions in protective relaying applications is to avoid using traditional concept of thresholds (settings). The NN and synchronized sampling techniques are an example of such an approach. For the off-line applications, it is important to have extremely accurate fault location. It appears that the use of synchronized sampling allows for this to be accomplished as long as there is accurate fault detection and classification technique, which is implemented using the NN approach.

The new relaying scheme, therefore, uses NN approach for fault detection and classification, and the synchronized sampling approach for accurate fault location. The time required to transfer the data (samples) from one end of the line to the other makes the fault location scheme unsuitable for real-time applications. To accommodate for this shortcoming, a new philosophy in relaying is proposed where the NN based technique is used to make the decision and trip the line while the new fault location is performing the computations, which allows the line to be reclosed in a corrective manner after a very accurate determination about the fault location becomes available. Hence, combining the two schemes provides advantages of very fast relaying operation using the NN approach that does nor depend on settings' accuracy as well as very accurate synchronized sampling fault location used as a corrective action for the line reclosing.

The new off-line fault analysis approach simply takes advantage of very accurate fault location obtained by using synchronized sampling combined with accurate fault detection and classification implemented using NN. The NN detection and classification is needed to initiate a particular set of fault location computations used for providing the most accurate results for a given fault type. Combining the NN algorithm with the synchronized sampling algorithm makes both schemes independent from any network settings and hence transparent to any inaccuracies produced by errors in determining settings.

## III. Neural Network Algorithm

### A. The Structure of Used Neural Network

A special type of neural network that belongs to the group of self-organized neural networks, ideally suited for classifying large and diverse set of input data, is used [4,6]. The protection algorithm is based directly on local measurements without extraction of traditional features like impedance or phasor computing. The patterns of input signals (sampled current and voltage measurements of the three transmission line phases) are recognized as features of the events in the power network. This neural network tries to produce a concise representation of system's behavior through identifying natural groupings of data from large data sets. The aim of this procedure, called clustering, is to allocate input patterns into groups called clusters such that each pattern is assigned to unique cluster. Patterns belonging to the same cluster should be as similar as possible, while patterns belonging to different clusters should be as different as possible. The cluster centers are recognized as pattern prototypes (prototypes of typical events presented at neural network inputs). The algorithm discovers the most representative positions of prototypes in the pattern space. The cluster (prototype) positions are dynamically updated during presentation of input patterns. The initial number of clusters and their positions are not specified in advance. A class symbolizes a group of clusters with a common characteristic, and class label is assigned to each cluster, meaning that each cluster belongs to one of possible classes. The number of classes corresponds to the desired number of neural network outputs, determined by the given classification task. One illustrative example of a reference set of clusters is shown in Fig. 1. It is significantly simplified and given in only two dimensions.

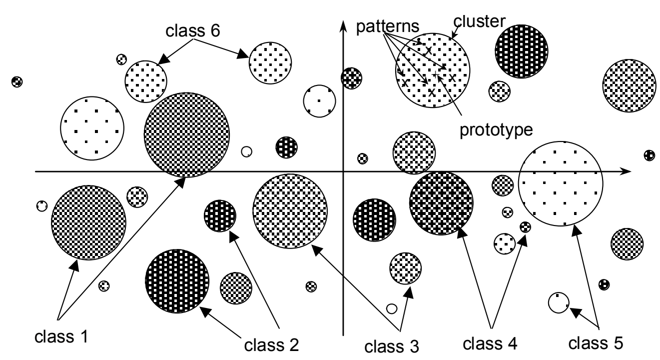

Fig. 1. The structure of "clean" clusters with patterns and prototypes.

In this study neural network based protection algorithm is located at the one end of selected line and takes voltage and current measurements from that end of the line. The new classification approach has to reliably conclude, in a very short time (one cycle or less), whether and which type of the fault occurs under a variety of time-varying operating conditions. In this way the new relay does not have traditional settings, and hence it will not be susceptible to the wrong settings being present.

### *B. Preprocessing of Input Signals*

Input into the neural network is in the form of a moving data window containing samples of phase currents and voltages. Selection of sampled data for training in a desired data window may include: either three phase currents, or three phase voltages, or both the three phase currents and voltages. Phase current and voltage measurements are sampled with corresponding sampling frequency. Each pattern is extracted from the samples obtained in a desired length of the moving data window, normalized, and arranged together to form a common input vector with feature components.

Optimal values of preprocessing parameters should be determined in each particular implementation. The training has to be repeated several times using various values for mentioned parameters, until the combination of their optimal values is achieved offering the lowest classification error. The parameter values determine the number of neural network inputs, and influence the trade-off between performing the fault characterization more accurately and making the decision in real time.

### *C. Training*

The proposed neural network combines unsupervised and supervised learning techniques in an appropriate way to give the best performance. The neural network firstly uses unsupervised learning with unlabeled data to form internal clusters. The labels are then assigned to the clusters during the supervised learning stage. The neural network training usually consists of few hundreds of iterations with consecutively alternating unsupervised and supervised learning phases, until prototypes of typical events (patterns) are established.

The initial data set, containing all the patterns, is firstly processed using unsupervised learning. During unsupervised learning, patterns are presented without their class labels. This procedure tries to identify characteristic (typical) patterns or prototypes that can serve as cluster centers. It does not require either the initial guess of the number of cluster, or the initial cluster center coordinates, but only a strong distance measure between cluster centers is specified. The outcome of unsupervised learning is stable family of clusters, defined as spheres in an *n*-dimensional space, where the space dimension is determined by the length of input pattern. Unsupervised learning forms both "clean" (having patterns with the same class label) and "mixed" (having patterns with two or more class labels) clusters.

In the supervised learning the class label is associated with each input pattern. Supervised learning separates "mixed" clusters from the "clean" ones. It assigns class labels to the "clean" clusters, and they create a reference set of labeled clusters, recognized as typical prototypes of presented input data set. The patterns from "clean" clusters are extracted from further iterative training process. Set of remaining patterns (patterns in "mixed" clusters) is transformed into new, reduced data set of training patterns. Vigilance parameter is a tuning parameter and is being consecutively decreased after each iteration. It controls the number and size of generated clusters. The whole procedure, including unsupervised and supervised learning, is being repeated many times until only "clean" clusters exist.

The example of three different clusters with allocated training patterns and constructed prototypes is shown in Fig. 2.

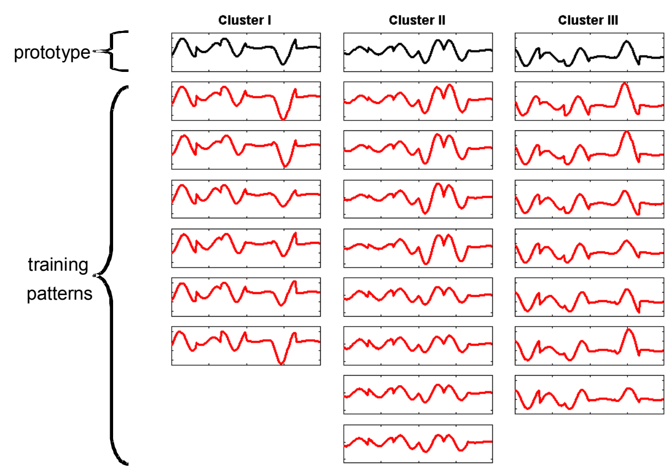


Fig. 2. The prototypes of similar patterns.

### *D. Testing*

The test patterns might be very heterogeneous and quite different from the training patterns, since there are many operating states and possible events in the power network. Test patterns will be classified according to their similarity to prototypes adopted during training. Classification of testing patterns is performed by using the cluster structure established during training and subsequently classifying a test pattern based on the majority of class labels of selected number (usually very small, odd number) of nearest clusters. Thus, output of this neural network is in the discrete form inherently reflecting different types of faults common in protective relaying. This procedure is efficiently implemented since the expected number of optimized prototypes is significantly smaller then the number of training patterns.

Propagation of classification error during testing for one typical case of power system and corresponding transmission line is shown in Fig. 3. Parameters used for forming the patterns are three phase voltages and currents taken in data window of one cycle and sampled with 2 kHz sampling frequency. In the beginning of testing, presented number of testing patterns is still small and classification error considerably varies, but then slowly converges to the final stable value.

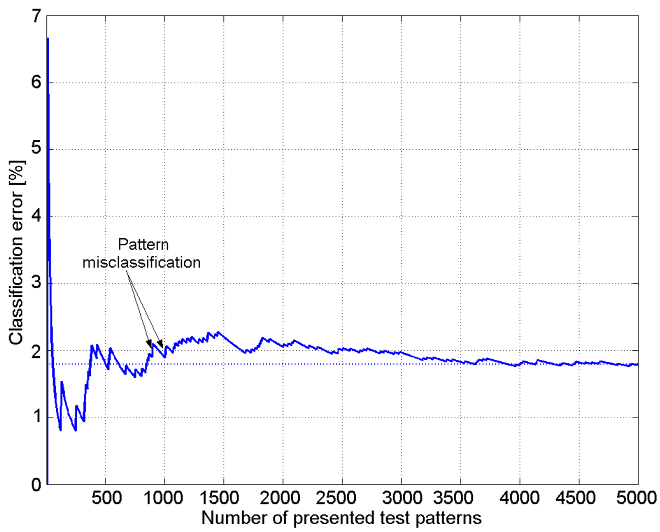


Fig. 3. Propagation of classification error during testing.

## IV. Fault Location Using Synchronized Sampling

Fault location problem is to determine the location of a fault by using available measurements and power system data.

Fault location techniques can be classified into those that use data from one end of the transmission line and those that use data from both ends of the line. Two-ended fault location techniques are more accurate than single-ended methods. Recently, the cost of the necessary hardware has been decreasing rapidly, which makes implementation of two-ended fault location techniques cost effective for critical transmission lines [7].

Fault location techniques that use data from both ends of the transmission line either use post-fault steady state values of the voltages and currents or actual transient data, to compute the fault location. Algorithms in the second category [8,9] use raw samples of voltage and current data synchronously taken from the ends of the transmission line. This can be achieved using GPS (Global Positioning Satellites) receivers, which will generate the sampling clock for the data acquisition equipment. Such algorithm requires less than a cycle of voltage and current data and can be used for real-time monitoring, control and protection applications. Two versions of time-domain algorithm were developed to handle short line and the long line cases and can be improved using the fault type information [5].

In order to derive fault location equations, a long transmission line can be considered. Shunt capacitance $C$ cannot be neglected for such lines and the distributed parameter line model is used for calculations.

In existing fault location algorithm, the fault location problem is formulated as the process of finding the point on the line where the voltage computed using the sending end data and the voltage computed using the receiving end data are the same or closest to each other comparing to other points on the line.

The voltage and current along the line are functions of the distance x from the end of the line and the time t. Partial differential equations of the line can be solved using The Method of Characteristics [10]. To develop an expression for the voltage and current at the point $x_j$ at time $t_k$, x-axis is discretized by the index j and the t-axis by the index k in the x-t plane:

$$\Delta x = x_j - x_{j-1} \tag{1}$$

$$\Delta t = t_k - t_{k-1} \tag{2}$$

where $\Delta t = \sqrt{LC}\Delta x$, and the following explicit expressions can be obtained for voltages and currents

$$v_{j,k} = \frac{1}{2}\left[v_{j-1,k-1} + v_{j-1,k+1}\right] + \frac{Z_c}{2}\left[i_{j-1,k-1} - i_{j-1,k+1}\right] + \\ + \frac{R\Delta x}{4}\left[i_{j-1,k-1} + i_{j-1,k+1}\right] - \frac{R\Delta x}{2} i_{j,k} \tag{3}$$

$$i_{j,k} = \frac{1}{2Z_c}\left[v_{j-1,k-1} - v_{j-1,k+1}\right] + \frac{1}{2}\left[i_{j-1,k-1} + i_{j-1,k+1}\right] + \\ + \frac{R\Delta x}{4Z_c}\left[i_{j-1,k+1} - i_{j-1,k-1}\right] \tag{4}$$

where $Z_c = \sqrt{L/C}$ is the surge impedance of the transmission line.

From a three phase coupled system, three decoupled single-phase transmission lines are generated using modal transformation. The method of characteristics can be applied on those modes. The samples of phase voltage and current are transformed into ground mode (Mode 0) and aerial modes (Mode 1 and Mode 2) values using transformation matrices.

The algorithm contains the following steps:

- Modal decomposition
- Discretization of the transmission line
- Selection of the approximate fault point
- Improvement in the fault location using the short line algorithm for the adjacent segments of the approximate fault point.

After discretizing the transmission line, the voltages on discrete segments are estimated using sending-end and receiving-end voltage and current measurements. The discrete point with the lowest error is picked as the approximate fault point. The voltage and current data at the two adjacent points to the approximate fault point are reconstructed. Then the short line algorithm is applied for the $2\Delta x$ segment around the approximate fault point to calculate the actual fault location.

Each mode of transmission line is discretized based on the sampling frequency. The lengths of the discrete segments are

$$\Delta x_i = \frac{\Delta t}{(\sqrt{LC})_i} \qquad i = 0,1,2 \text{ (Modes)} \tag{5}$$

where $\Delta t$ is sampling interval, and $1/\sqrt{LC}$ is the surge velocity of the line. Since the surge velocity may have different values for each mode and accordingly the lengths of the segments may be different for each mode.

The length of the segment should be as short as possible to increase the accuracy of the algorithm. To obtain the segment of small length, one approach is to use high sampling frequency. A sampling frequency of 20 kHz is possible using specialized data acquisition equipment. The second approach is to use the mode that has slower surge velocity for discretization. Generally the velocity in Mode 0 is slower than the velocities in other modes. Using this Mode, more discrete segments can be obtained. But an algorithm based on Mode 0 cannot be used for every fault type (for example phase to phase faults).

### *A. Fault type unknown*

Since every fault has effect on the Aerial Mode, this mode can be used at discretization step of the existing algorithm. Then the improvement of fault location can be achieved by applying short line algorithm for the adjacent segments of the fault point. Under the case of a transposed line, Clarke transformation can be used as a suitable transformation in order to de-couple phase components of signals [11]. When the fault is Phase B to C fault, fault location using Mode 1 cannot give the correct results and when the fault is Phase A to Ground fault, Mode 2 is not suitable to locate the fault. Therefore single Mode is not enough to locate all types of fault.

### *B. Fault type known*

If the fault type is known, Mode selection can be performed according to fault type information very accurately.

Using fault type information, the accuracy of the existing fault location algorithm can be improved. In the new approach, the computational burden is kept lower and the accuracy can be improved for phase to ground faults.

New approach is to use Mode 0 for discretization for the phase to ground faults. For the other faults, Aerial Mode can be used for discretization. If the short line part of the long line algorithm is applied as single phase in considered mode without transforming the voltage and current data at the two adjacent points to the phase domain, fault location calculation can be performed faster than the unknown case of fault type.

### *C. Simulation Results*

An actual 345 kV power system section, from Reliant Energy (RE) HL&P, was modeled for simulation [4]. Electromagnetic transient program ATP is used for simulating various fault scenarios on STP-SKY Line of 167.44 miles long, by varying fault parameters like type of fault, fault location, fault impedance (for grounded faults), and fault incidence angle. No filtering or preprocessing of the raw data was used and the samples of voltages and currents were from one cycle long window of data, starting from the fault inception.

The comparison of the existing fault location algorithm and new approach, which uses fault type information for calculation of fault location was performed by calculating the average and maximum errors. The fault location error was expressed as a percentage of the total line length.

Fig. 4 shows the calculated average errors using error values obtained for 25 different fault locations for Phase A-to ground and Phase A-to Phase B-to ground faults.

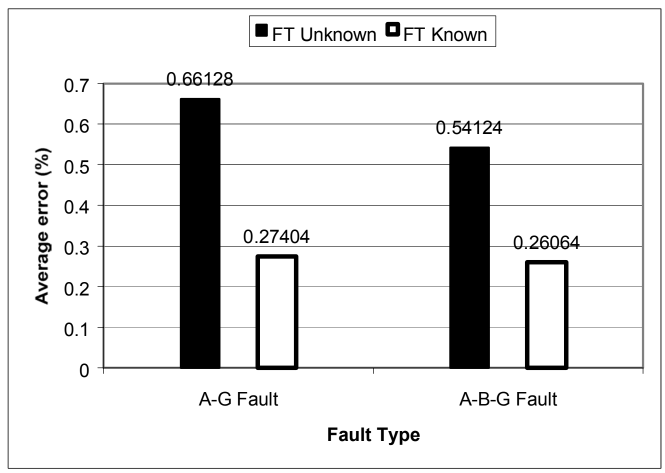


Fig. 4. The average error (%) of fault location.

Fig. 5 shows the calculated maximum errors using error values obtained for 25 different fault locations for Phase A-to ground and Phase A-to Phase B-to ground faults.

The results given in the Figures were obtained by taking the fault resistance as 20 ohms and fault incidence angle as 0 deg.

It can be seen from Fig. 4, that the average error can be reduced approximately 59% from 0.66% to 0.27% using fault type information for Phase A-to ground fault. The reduction for Phase A-to Phase B-to ground fault is 52%.

The maximum errors given in Fig. 5 for Phase A-to ground fault reduce 61% using new approach based on fault type information. Similarly for Phase A-to Phase B-to ground fault the reduction is 51%.

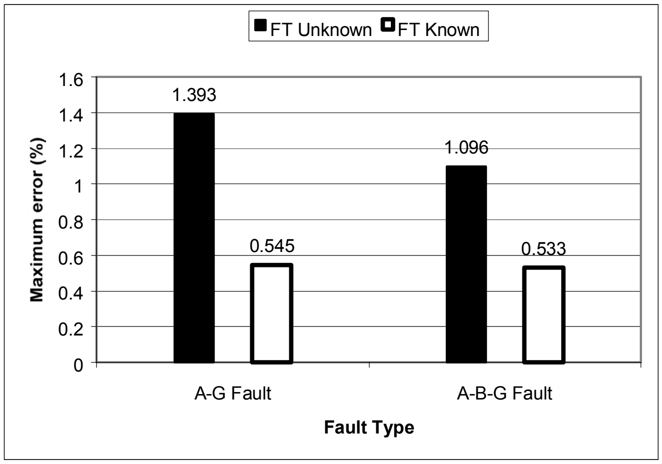


Fig. 5. The maximum error (%) of fault location.

According to the results of simulations, the average and maximum errors obtained with the new approach are less than 0.27% and 0.54%, respectively.

Using proposed approach better accuracy of fault location can be obtained for phase-to ground fault, which is a type of faults that represents about 90% of all the transmission line faults, and phase-to-phase to ground fault.

## V. Conclusion

Based on the discussions given in the paper, the following conclusions may be drawn:

- Traditional relaying depends on accurate determination of network settings while the off line fault location depends on sufficient data window length
- The new NN algorithm for fault detection and classification as well as fault location (section determination) does not depend on the use of traditional settings and hence provides more accurate approach
- The new synchronized sampling fault location approach also does not depend on traditional settings and hence represents a more accurate approach for relaying applications
- The synchronized sampling fault location does not require a long data window, which makes it suitable for off line applications in the case when there is no sufficient data window length to apply the traditional methods accurately
- Combining the two techniques allows for implementation of new approaches for both relaying and off-line fault analysis that are superior when compared to the traditional approaches.

## VI. Acknowledgment

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## VIII. Biographies

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