Use of Magnetic Field Sensing Coils for Fault Location in Transmission Lines

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ABSTRACT

The detection and location of faults on power transmission lines is essential for protection and maintenance of a power system. Most methods of fault detection and location rely on measurements of electrical quantities provided by current and voltage transformers. These transformers can be expensive and require physical contact with the monitored high voltage equipment. In this work, current transformers were replaced by magnetic field sensing coils. Such coils can be located remotely from substations and switching stations and do not require physical contact with the conductors.. This paper explores the use of the magnetic field sensors as an alternative measurement device for fault detection and location.

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INTRODUCTION

Quick fault detection can help protect equipment by allowing the disconnection of faulted lines before any significant damage is done. Accurate fault location can help utility personnel remove persistent faults and locate areas where faults regularly occur, thus reducing the frequency and length of power outages. Fault detection and location schemes have been developed in the past, a variety of algorithms continue to be developed to perform this task more accurately and more effectively [8-10]. Most analysis methods rely on the values of either current or voltage phasors measured by means of current or voltage transformers at substations or switching stations. To gather this information, at least three transformers are typically required at each end of the sub–transmission or transmission line. These transducers are expensive, especially when the system involves high voltage lines. Some algorithms like fault impedance-based algorithms require both current and voltage information. However, it is possible to monitor a transmission system without using current or voltage transformers through the analysis of the magnetic field near the conductors.

Since each conductor in a transmission line creates a magnetic field due to the current through it, there is the possibility of analyzing the transmission line system based on the resultant magnetic field produced by its conductors. The magnetic detection is performed using two sensing coils at each end of the transmission line. One detects the vertical magnetic field intensity and the other detects the horizontal magnetic field intensity. The two-dimensional magnetic field intensity can then be resolved from this information. In this method faults are detected when unexpected changes occur within the monitored data. The only difference is that this analysis attempts to detect changes in the vertical and horizontal magnetic field intensities rather than individual changes in the monitored voltages or conductor currents. A variety of fault location schemes have been developed over the years.

Common systems include impedance-based locators [1,2], or those which measure the impedance seen by one or both ends of the transmission line, and traveling wave-based locators [8-10], or those which rely on the timing of fault detections.

ANALYSIS USING THE MAGNETIC FIELD

As previously stated, the most obvious coordinate system to analyze a rotating magnetic field is a polar coordinate system, since any changes in the expected total magnetic field will be detected most easily this way. Four algorithms are presented in this section for the detection of faults while examining the system in polar coordinates. All of them involve detecting if the values of rho or theta have exceeded or gone below a set of expected boundaries or have made a significant and unexpected change. Since each of these algorithms has a possibility of incorrectly detecting a fault, the results of these algorithms can be analyzed collectively to better determine whether or not a fault has truly occurred. Also, by taking the earliest fault detection times from each algorithm, the microprocessor which is performing this analysis will be able to determine actual fault detection times more correctly in order to perform the fault location more accurately. As a result, this combined analysis using all of these algorithms will provide a reduced number of “false alarms” as well as more accurate fault location.

The first algorithm estimates the ellipse formed by the magnetic field then detects any significant deviations from this locus. The next algorithm compares the present value of rho to the value detected a fraction of a cycle before it and determines if too significant of a change has taken place. The third algorithm detects the maximum change in rho between data points every quarter cycle and determines if the change in rho between the last two data points has exceeded a multiple of this maximum. Finally, the fourth algorithm detects the maximum and minimum changes in theta every half cycle and determines if the change in theta between the last two data points is significantly higher than the calculated maximum or significantly lower than the calculated minimum.

THE “EXPECTED ELLIPSE” ALGORITHM

Since the magnetic field will typically form an ellipse in steady state, the simplest way for a microprocessor to determine if there is a fault is to sense if the magnetic field intensities significantly change from the elliptical pattern. There are several ways to perform such an analysis. One is to approximate the shape of the ellipse and determine, once a mostly constant ellipse has been found, if and when the instantaneous magnetic field value deviates from that ellipse. Such a deviation from a constant ellipse is shown below in **Figure–1**.

In order to analyze this rotating field in this way, which will be referred to as the “expected ellipse” algorithm, the following steps are performed:

1. The average maximum and minimum magnetic field intensities and any angle of rotation of the field are determined.

2. An ellipse approximating the rotating magnetic field is generated from this information.

3. Ellipses for the minimum and maximum allowable values of the magnetic field intensity based on allowable percentage deviation from the average must be created from the approximation; these are used to detect any sort of abnormal behavior.

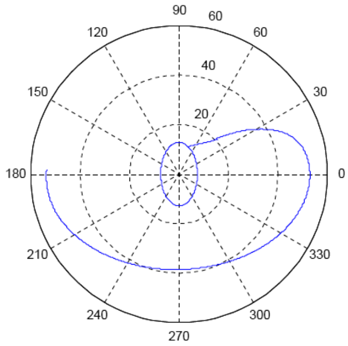


Fig.1: Constant ellipse with a sudden change due to a fault

The "Previous Value" Algorithm

Since the values of rho in the polar coordinate system do not change significantly over a very short time step for a transmission line that is relatively well balanced, each value of rho can be compared against a value that occurred shortly before it to detect sudden changes. In a sense, this effectively compares the magnetic field against rotated and scaled versions of the same magnetic field. An example of an elliptical rotating magnetic field along with some boundaries generated for this "previous value algorithm" is shown in Figure–2.

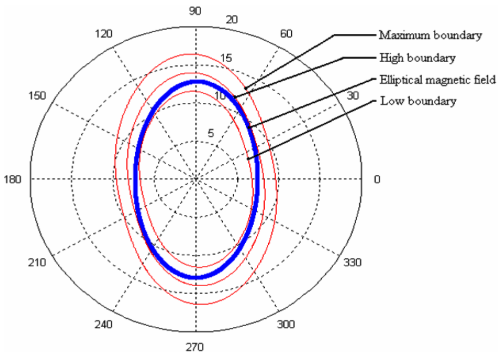


Fig.2: Elliptical rotating magnetic field with boundaries for the "previous value" algorithm

This "previous value" algorithm is especially useful in cases where the magnetic field is not exactly an ellipse and thus cannot be accurately monitored with the "expected ellipse" algorithm. The use of two detection algorithms in conjunction with each other can reduce incorrect fault detections. For example, if the system is fairly imbalanced, faults will be more likely to be incorrectly detected with the "previous value" algorithm, while the "expected ellipse" algorithm will not have as much of a problem with this. Similarly, if harmonics are seen by the sensors and are not properly filtered, the "expected ellipse" algorithm will be much more likely to detect a fault incorrectly while the "previous value" algorithm will not.Figure–3 shows this magnetic field with boundaries based on the "previous value" algorithm while Figure–4 shows the same magnetic field with boundaries based on the "expected ellipse" algorithm.

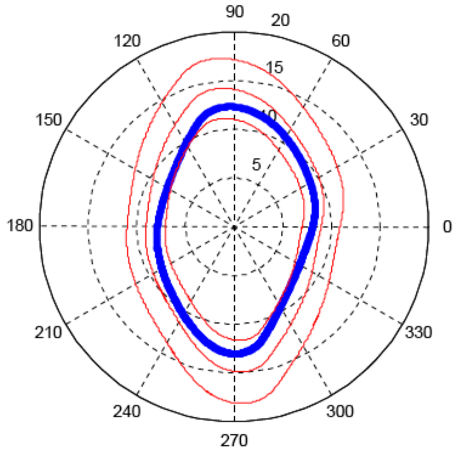


Fig:3 Magnetic field with harmonics

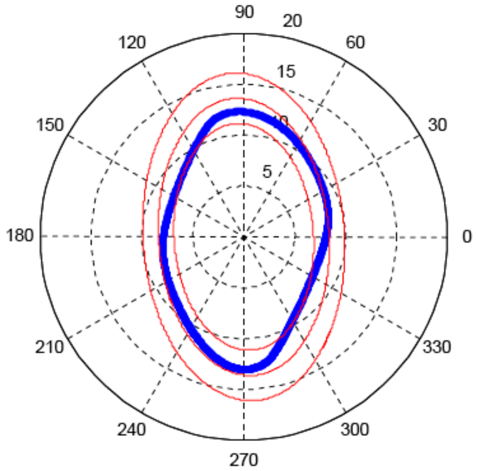
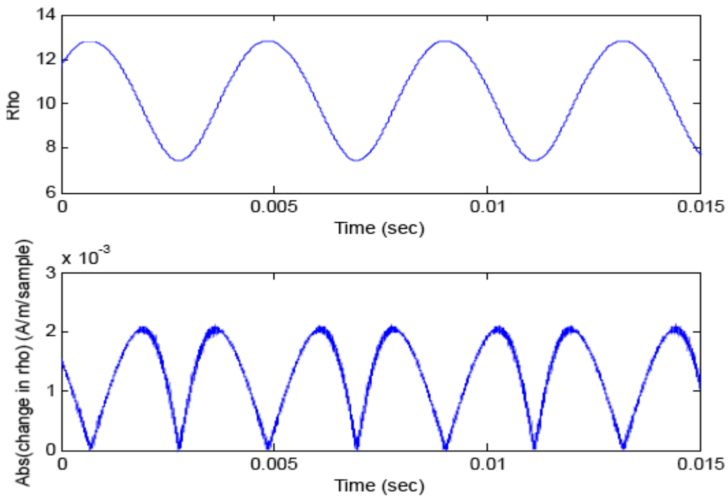


Fig:4 Magnetic field with harmonics

It is clear that the "expected ellipse" algorithm will incorrectly detect faults in this situation. Ideally, all of the harmonics would be filtered prior to analysis, but complete filtering would have negative impacts on the system in other ways including making faults harder to detect. As a result, it cannot be assumed that the magnetic field will be a perfect ellipse. Thus, the fault detection results of the "expected ellipse" algorithm are combined with the results of the "previous value" algorithm in order to better determine if a fault has truly occurred. This example reinforces the idea that performing an analysis of the magnetic field using multiple algorithms in conjunction with one another can reduce the number of incorrect fault detections if the results from each algorithm are compared against those from the other algorithms.

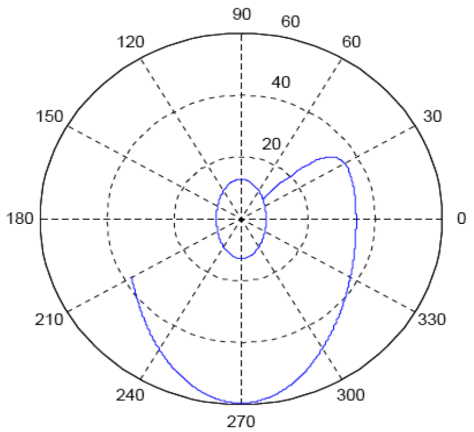
The "Delta Rho" Algorithm

As stated before, when a fault is detected with multiple algorithms, the fault location accuracy can be increased by using the earliest fault detection times at each end of the transmission line. Despite this increased accuracy, the time at which the fault is detected with the "expected ellipse" and "previous value" algorithms is not exactly the time at which the fault propagated to the end of the transmission line due to the space provided between the actual magnetic field and the allowable boundaries. There needs to be this small region of allowable variation for each method in order to reduce incorrect fault detections. However, this makes high impedance faults very difficult to detect. In order to increase the accuracy even more and to improve high impedance fault detection, a third algorithm, which will be referred to as the "delta rho" algorithm, is useful. This algorithm requires less analysis from the microprocessor than the other algorithms, since it simply measures each change in rho between samples against a multiple of the highest change in rho for the unfaulted system. The highest change in rho is assumed to occur halfway between the minimum and maximum values of rho from the “expected ellipse” algorithm for an elliptical magnetic field due to the relationship between the zero crossing of a sine wave and the peak of its derivative which is a cosine. The values of rho and the absolute value of the change in rho for an unfaulted system are shown below in Figure–5. where the absolute value is used since the maximum allowable magnitude of the change in rho is independent of direction of change. If the change in rho between any two samples is greater than this multiple of the maximum value, there has possibly been a fault. This method will detect a fault time before either of the previously described algorithms and in some sense is most similar to the way a human would determine a fault time based on a visual examination of a plot of the magnetic field.



Fig–5: Rho and the absolute value of the change in rho under normal operating conditions

As an example of this algorithm, the plot of the magnetic field during a threephase fault is shown in Figure–6.



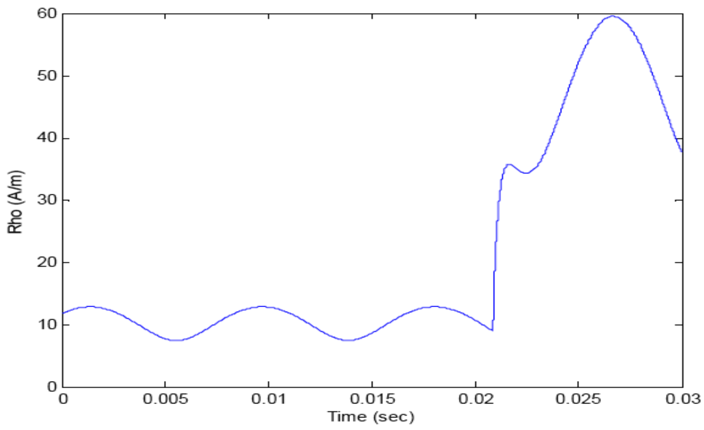
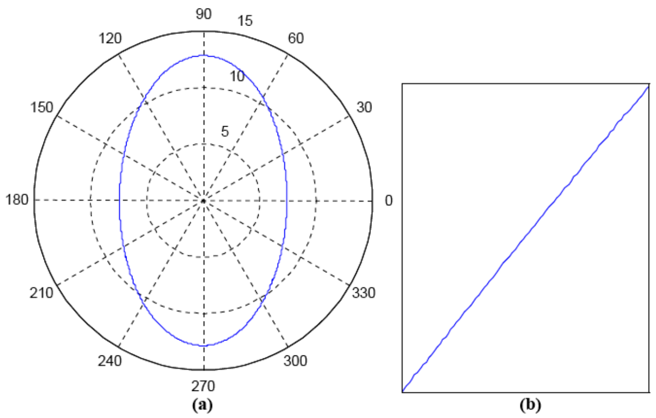


Fig.6: Magnetic field during a three-phase fault Fig.7: Rho during a three-phase fault

It is clear that this is a fault, but the exact time at which the fault caused a change in the magnetic field would be difficult to detect with either the “expected ellipse” algorithm or the “previous value” algorithm. Figure–7 shows the values of rho just prior to and during the fault. Again, it is clear that there is a change, but the exact time might be difficult to determine using boundaries.

The downside of the “delta rho” algorithm is that even a trace of noise can cause an incorrect fault detection. An example of a rotating elliptical magnetic field with some noise added is shown in Figure–8. Even though the noise does not appear to be very significant when compared to the values of rho as seen in the ellipse, the changes in rho due to the noise are easily enough to cause the delta rho algorithm to incorrectly detect a fault.



Fig–8:Rotating elliptical magnetic field under normal conditions with noise added (a) – Full ellipse; (b) – Detail of noise

In order to minimize this risk of incorrect fault detection due to noise, the maximum change in rho is not taken solely from the change in rho over the single time step which would typically create the greatest change, but from an average of the changes per time step over a short period of time. This will significantly reduce the effects of noise, since the noise will be taken into account in this average measurement. There are no negative effects due to this modification under noiseless conditions; under noisy conditions, this change will make the “delta rho” algorithm a bit less likely to detect a fault, but this is clearly superior to the possibility that the algorithm will indicate a fault every time it detects a significant amount of noise. Since this sudden change in rho can occur due to extreme noise even with this modification in place, the “delta rho” algorithm is more likely to incorrectly indicate faults than the previously discussed algorithms. However, if the time at which a fault is detected with the other algorithms is close to the time at which the “delta rho” algorithm detects a fault, the time from the “delta rho” detection is compared to the other times and is used in determining the fault location, thus providing more accurate location of the fault. Also, since this algorithm detects high impedance faults better than the other algorithms, the fault times related to this algorithm that do not correlate with the fault times of other algorithms are stored separately. In the case that a fault is later found to have occurred, this information can then be used to determine the fault location.

4.1.4. The "Delta Theta" Algorithm

The algorithms described above will detect and locate most types of faults quite well; however, line to line faults, especially those that occur when the currents in the faulted conductors are at near-equal values, are still problematic with the above three algorithms alone. As a result, another method must be added in order to detect this type of fault. The most distinguishing characteristic of the initial detection of a line to line fault is a rapid change in the value of the polar angle theta (θ). As a result, the most logical detection algorithm to add is one which detects sudden changes in the value of theta. This algorithm will be referred to as the "delta theta" algorithm.

The change in theta per time step is simply defined as

$$\Delta_{\theta} = \theta_t - \theta_{t-1}$$

The allowable change in theta per time step is between a value slightly higher than the maximum detected change and a value slightly lower than the minimum detected change; if the magnetic field goes beyond either of these boundaries, a fault has most likely occurred. No absolute value is used with this algorithm since a change in the direction in which theta is changing indicates a fault (whereas rho remaining the same or switching from increasing to decreasing is expected under normal operating conditions). Just like rho, theta changes at different rates throughout the ellipse. The maximum change in theta per time step is at the minimum value of rho, and the minimum change is at the maximum value of rho. This is shown in Figure–9; it is important to note that in this Figure the "maximum" value of theta is actually a minimum since theta is always negative (constantly decreasing) for the particular situation. Since the "delta theta" algorithm is prone to the effects of noise in the same way as the "delta rho" algorithm, the same averaging method is used in calculating the maximum and minimum allowable values in order to reduce the number of incorrect fault detections. The magnetic field of a line to line fault is shown in Figure–10; Figure–11 shows the value of theta up to and during the fault. There is clearly an abrupt change in the value of theta when the magnetic field changes its pattern due to the fault current, but the exact time of this change is difficult to determine directly from theta. In contrast, the change in theta is shown in Figure–12. The sudden change due to the fault can easily be located using this information.

Fault Detection

Each algorithm detects faults independently; once faults have been detected by one or more algorithms, the fault location is performed. If there is some kind of abnormal behavior (a field intensity that goes outside of a minimum or maximum, or a change greater than allowed by the "delta rho" algorithm), the detection system will perform the following operations:

1. Record the time at which this occurred.

2. If some abnormality is recorded at both ends of the transmission line, then the location of the fault is computed based on the difference in detection times.

3. If the abnormality is recorded at only one end of the transmission line, then the possibility that an error might have occurred is recorded in the microprocessor memory.

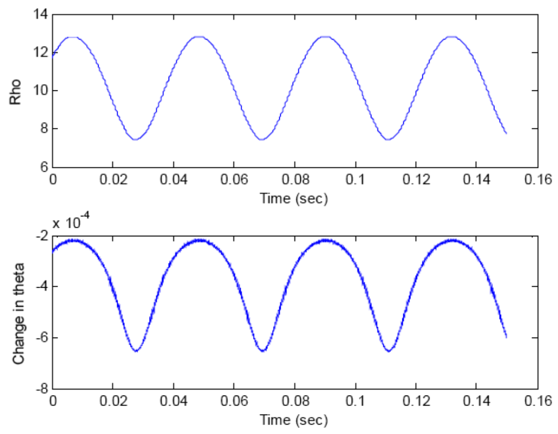


Fig.9: Rho and delta theta compared under normal operating conditions

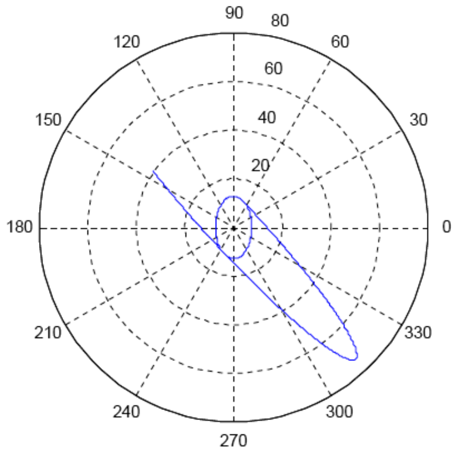


Fig.10: Magnetic field during a line to line fault

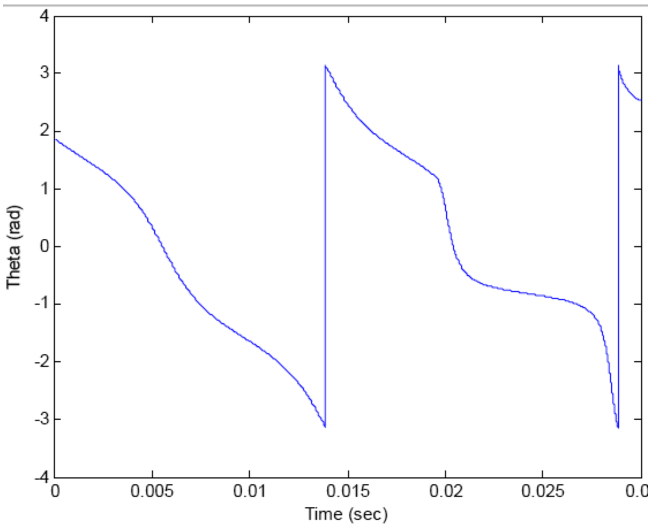


Fig.11: Theta during a line to line fault

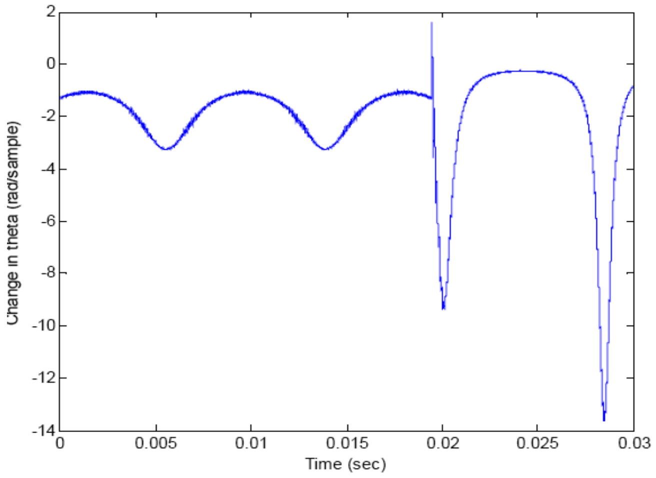


Fig.12: Change in theta during a line to line fault

Testing the Algorithm

The full algorithm was tested to determine the accuracy with which it can detect faults. The system was tested for a 115kV transmission system. Single line to ground faults were used as the main fault for testing since they are by far the most common fault types; the conductor configuration was chosen as a coplanar arrangement. Since the accuracy of calculation is dependent upon the angle of fault incidence, the system was tested for faults at both the zero-crossing of the faulted phase's current, which is the most difficult fault timing to detect, and at the faulted phase's peak current, which is easiest to detect. The testing was based upon a purely resistive fault. The location of the fault was varied linearly along a 20km transmission line for fault resistances of 0.1, 1, and 10 per unit, which are equivalent to approximately 13.225Ω, 132.25Ω, and 1322.5Ω for the 115kV transmission line in question. The fault simulations were conducted using ATPDraw, a free electric power system analysis program; the resulting data was exported into Microsoft Excel using TOP, an output processor for power system analysis programs. The Excel-format data was then processed by MATLAB using the code. The algorithm was also tested for a range of fault resistances for each major fault type, including single line to ground faults (at both the faulted phase's current maximum and current zero-crossing), line to line faults and line to line to ground faults (when both phases' currents are at identical values), and three phase faults (at one of the phases' current zero-crossings). Aside from the slightly low detectable fault impedance for the worst case of single line to ground faults as previously mentioned, the only fault type where moderate fault impedances seem to cause a problem is the line to line fault.

Conclusions

This paper described the theory and methods of traveling wave fault detection and location using magnetic field sensing coils. The concept of the magnetic field for a general and three phase system was explored. This was followed by a presentation of the magnetic fields for a variety of conductor configurations and sensor locations. The four algorithms used in the magnetic field-based fault detection were then described. Finally, the combined algorithm was explained, and the results of accuracy and maximum detectable fault resistance were presented. The magnetic field sensors were shown to be effective in detecting faults conceptually. Additionally, the collective algorithm was tested and was shown to provide accurate fault detection for relatively high fault impedances and for each common type of fault. All of this proves the magnetic field sensor to be a viable tool for power transmission line fault detection. Future research could be performed in applying these algorithms to more complete systems than the single transmission line which was used for analysis in this thesis. Additionally, other fault location algorithms – most specifically, a fault location and classification scheme using the wavelet transform – could be modified to make use of the magnetic field. This will most likely improve the accuracy of fault location and increase the maximum detectable fault impedances. Eventually a prototype of the magnetic field-based fault detector could be built and field tested. This would require more development of the sensor coils as well as harmonic-filtering circuitry. The MATLAB code would also need to be reconfigured since it is currently written to analyze pre-prepared sets of data to test the algorithm rather than to continuously monitor information with which it is provided. The programming language would also most likely need to be changed to a different language which could be compiled directly for use with a microprocessor.

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