AN ADAPTIVE HIGH AND LOW IMPEDANCE FAULT DETECTION METHOD

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ABSTRACT:

An integrated high impedance fault (HIF) and low impedance fault(LIF) detection method is proposed in this paper. For a HIF detection, the proposed technique is based on a number of characteristics of the HIF current. These characteristics are: fault current magnitude, magnitude of the 3rd harmonic current, magnitude of the 5th harmonic current, the angle of the third harmonic current, the angle difference between the third harmonics current and the fundamental voltage, negative sequence current of HIF. These characteristics are identified by modeling the distribution feeders in EMTP. Apart from these characteristics, the above ambient (average) negative sequence current is also considered. An adjustable block out region around the average load current is provided. The average load current is calculated at every 18000 cycles (5 minutes) interval. This adaptive feature will not only make the proposed scheme more sensitive to the low fault current, but it will also prevent the relay from tripping during the normal load current. In this paper, the logic circuit required for implementing the proposed HIF detection method is also included.

With minimal modifications, the logic developed for the HIF detection can be applied for the low impedance fault(LIF) detection. A complete logic circuit which detects both the HIF and LIF is proposed. Using this combined logic, the need of installing separate devices for HIF and LIF detection can be eliminated.

KEYWORD: Open conductor, down conductor, 3rd and 5th harmonics, negative sequence current, high impedance, low impedance, high fault current, low fault current.

INTRODUCTION

A High impedance fault(HIF) is of great concern to all utilities for public safety reasons. An energized conductor laying on the ground can create safety hazards if the protective device on that feeder did not operate. HIF may occur when a " Bare Conductor" makes contact with a dry tree limb, rock, sand, gravel, asphalt, concrete or insulators. HIF generally produces very low fault current due to the high fault impedance. The fault current in a HIF may range from zero to the pickup setting of overcurrent relays. Therefore, the overcurrent relays can not detect the HIF.

HIF detection, due to its nature of difficulty, has been investigated by many researchers in recent years. Aucion and Russell[1] performed a number of staged tests and observed that an arcing down conductor fault produces a marked increase in the level of high frequency (2-10khz) current. They also developed a detection scheme utilizing the high frequency burst noise phenomenon[2]. Jeerings and Linders[3] provided a more complete analysis about the harmonic in HIF. They also developed a scheme to detect the down-conductor faults[4]. Their scheme is based on the changes in the magnitude and the phase angle of the third harmonic fault current with respect to the fundamental phase voltage (60hz). Cokkinides and etc. [5] have developed an "Open Conductor Detector System". This device detects the conductor phase voltage at the remote end of the feeder. When the voltage of any phase drops below the specified threshold, then a transmitter sends a signal (5-15hz) to a receiver at the substation. Huges Aircraft [6] proposed a fault detector which was based on the changes in the third harmonic current and the phase angle shift. Kwon and etc.[7] utilized the incremental variance of the normalized even order harmonic power to detect the HIF. Emanuel and etc.[8] proposed to monitor the second-order harmonic current in HIF detection. Ebron and etc.[9] applied the artifical neural network approach for HIF detection . Kim and Russell[10] proposed an intelligent computer relay for HIF detection. All of these previous works have revealed many hidden corners of HIF and increased the possibility of the HIF detection.

A more reliable and more practical solution to solve the HIF detection problem is proposed. This new scheme is based on the characteristics of high impedance fault. These characteristics are: the fault current magnitude, magnitude of the 3rd harmonic current, magnitude of the 5th harmonic current, the angle of the third harmonic current, the angle difference between the third harmonic current and the fundamental voltage, the negative sequence current of HIF. In this proposed method, the average load current and the average negative sequence current are calculated and stored. These average currents are calculated at every 5min interval. The measured rms load and negative sequence current are compared with the stored average value. If there is an increase or a decrease in the load current by 20% (adjustable) or an increase in the negative sequence currents by 20% (also adjustable), then that phase is declared as a candidate for HIF. This feature will make the proposed scheme more sensitive to the HIF, low impedance fault currents and also prevent the tripping during the normal load conditions. The magnitudes of the 3rd harmonic current and the 5th harmonic current are also examined in order to distinguish the capacitor switching, the load switching, or the arc furnace from HIF.

A fault current above the maximum expected load current is defined as low impedance (high fault current) faults[LIF]. LIF is a normal fault for distribution or transmission systems. About 85% - 98% of the faults are low impedance faults. LIF current can be easily detected by the overcurrent relays. With minimal modifications, the logic developed for the HIF detection can be applied to the LIF detection. A complete logic circuit required for implementing the proposed HIF and LIF detection is discussed in the paper. Using this logic, the need for separate devices for HIF and LIF detection can be eliminated.

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HIGH IMPEDANCE FAULT MODEL IN EMTP

Most of the pervious studies in HIF fault detection are based on field tests and experiences with fault current. These studies are limited to specific conditions and circumstances. Since the characteristics of HIF are so diverse and complex in nature that simple field tests at given locations and under specific conditions can not solve the mystery of HIF.

There is need for a more comprehensive distribution system which can study a variety of HIFs. Using EMTP, such a system has been developed in this study. This system includes the typical distribution components, such as, feeders, distribution transformer, capacitor, breaker, and loads. In order to examine the diverse and complex characteristics of HIF, any combination of nonlinear fault impedance can be applied. To further distinguish the HIF current from the normal load current, the harmonic characteristics generated from the load switching, the capacitor switching, the arc furnace switching, and the transformer inrush current are also studied. The following are a list of data for various distribution system components used in our studies.

Feeder Length: 1 - 10 miles; 3ph 4 wire; 13.09kv or 4kv
Transformers : voltage 13.09kv or 4kv; power range; 5mva -25mva, Impedances 4% - 8%; connections Δ–Yg, Yg - Δ–Yg.

Capacitor: power range 1.2kvar - 4.8 kvar; 3ph; Yg connected.
Arc furnace: 3ph; 4kv; power range 1500kva -4000kva; Also time step variable resistors were modeld in each phase of arc furnace in order to represent the melting down period. Arc furnace transformer is Δ–Δ connected.
Source amps: range 2000 amps - 10000 amps at 13.09kv.

The switching of capacitors and arc furnace is done randomly regardless of the voltage magnitude by 3-phase time controlled switches. More detailed description of the modeling techniques of various distribution system components in EMTP can be found in [11]. EMTP is a general purpose computer program for simulating high speed transient effects in electric power system, switching analysis, lightning surge analysis, insulation coordination, shaft torsional oscillation analysis, ferroresonance analysis, power system fault analysis and many other applications in power system.

TEST CRITERIA IN EMTP

1- All currents and voltages are measured at substation.

2- The fault impedance are assumed to be nonlinear and varied every cycles. The nonlinear impedance model is based on the voltage cycle; as voltage increases during the positive or negative half cycle, the impedance also decreases. The increase in impedance is nonlinear. Figure 1 represents the characteristics of the typical nonlinear impedance modeled in the study. There are 16 different nonlinear fault impedance, Zf1.....Zf16, shown in the figure. Each impedance has different characteristics and each impedance has a variable magnitude ranging from zero to 5000ohms during a half cycle of the voltage. Among the 16 impedance, it can be seen that Zf7 to Zf11 have a higher degree of nonlinearity. The voltage wave form used in the Figure 1 has a peak value of 10.7kv. Figure 1 shows that arcs begin anywhere between 5kv to 10.5kv. This assumption is based on that most of the previous studies indicate that the arc is most likely formed during 80% to 90% of the peak voltage.

3- Cosine filtering of the fault current and voltage is done at the zero crossing of the faulted phase voltage. Therefore, phase angles of the voltage and the third harmonic current are calculated based on the cosine wave form.

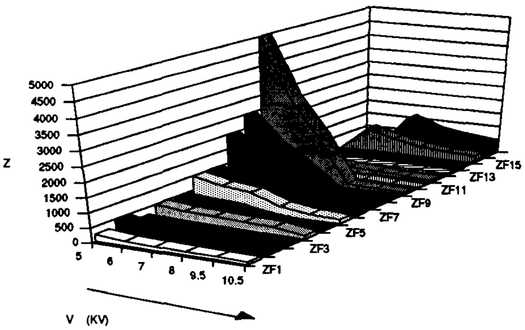

Fig.1 Nonlinear Fault Impedance

Where:
V: Voltage wave form, Peak value is 10.7kv and rms value is7.5kv
Z : Magnitude of the nonlinear fault impedance, Zf1.......Zf16.

CHARACTERISTICS OF HIGH IMPEDANCE FAULTS IN EMTP MODEL

Extensive simulations have been performed in order to determine the following characteristics of HIF for different combinations of nonlinear impedance under various loaded and unloaded conditions.

Magnitude of HIF Current

The HIF current varies nonlinearly with the nonlinear impedance as shown in Fig. 2 The magnitude of HIF current depends on the magnitude of the fault impedance and the connectivity of the load current under faulted conditions. During the fault, two scenarios might happen to the downed conductor .

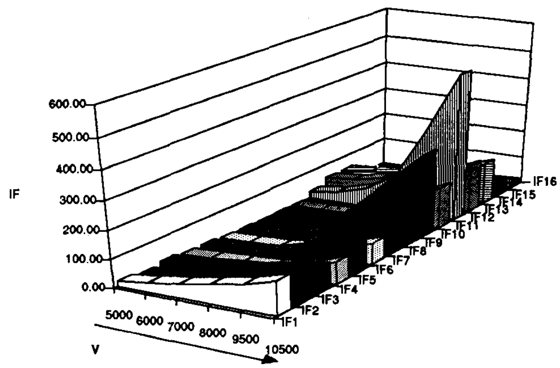

Fig. 2 Nonlinear Fault Currents (IF,... IF16 = Nonlinear Fault Currents.)

Case A- The Energized Conductor is down and broken and, the conductor makes contact with the linear or nonlinear impedance.

Case B- The Energized Conductor is down but not broken and, the conductor makes contact with the linear or nonlinear impedance.

Case "A"

When an energized conductor is downed and broken, the load current in the broken phase downstream from the fault becomes zero and, therefore, the load current at the substation will be reduced (assuming low fault current compare to downstream load). A typical voltage and current wave forms at the substation for the Case A is shown in Figure 3.a In this figure, the load current L1 is measured at the substation prior to the fault occurs. IaL1 and IaL2 are the fault currents for two different nonlinear impedance. The magnitudes of these fault currents are lower than the magnitude of the load current. Figure 3.b shows the current and voltage wave forms of a different test. The nonlinearity in IaL1 is less in Figure 3.b than in Figure 3.a. The reason for applying different fault impedance in the simulation is to represent the dynamic impedance changes, such as dynamic changes in the soil moisture, during the fault.

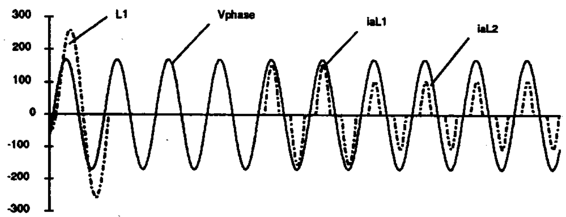

Fig- 3a HIF (higher nonlinearity) for The Broken Conductor

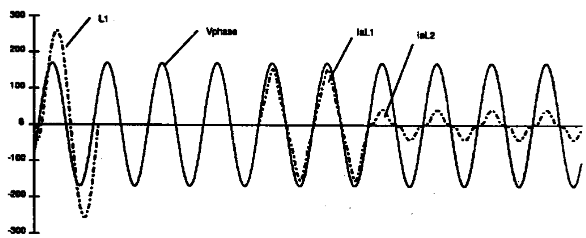

Fig- 3b HIF (nonlinear) for The Broken Conductor

Case "B"

When an energized conductor is down but not broken, then the current at the substation equals the load current plus the HIF current. The current and voltage wave forms of a Case B study is shown in Figure 4. Comparing Figure 4 with Figure 3, it can be noted that, due to the load current, the nonlinearity in the currents IaL1 and IaL2 is less in Case B than in Case A.

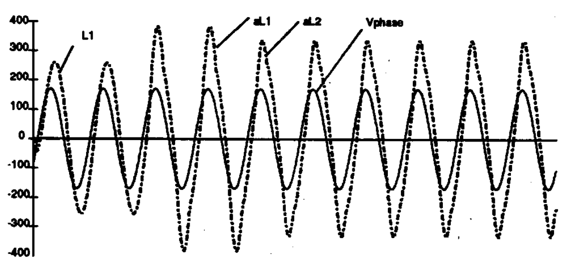

Fig- 4 HIF Current for The Unbroken Conductor

Magnitude of 3rd Harmonics Current

Figure 5 shows the simulation results of the magnitude of the fault current and the 3rd harmonic current under various fault impedance. The percentage of the 3rd harmonic current with respect to the fault current is also provided in this figure.

It can be seen that the magnitude of the 3rd harmonic fault current depends on the nonlinearity of the arcing impedance. It can also be noted that the magnitude of the 3rd harmonic current is higher if the applied fault impedance have a higher degree of nonlinearity, such as ZF7 to ZF11. The % of the 3rd harmonic current depends upon the magnitude of the load current and the nonlinearity in the fault impedance. From the simulations, it is also evident that the % of the 3rd harmonic current is higher in Case A than in Case B.

Current Magnitude Comparison Between the 3rd Harmonic and the 5th Harmonic

Due to the formation of the arc, the 3rd and higher order harmonic currents are present in the fault current. EMTP study shows that the magnitude of the 3rd harmonic currents is the highest. This result is shown in figure 6 . Figure 7 shows the comparison of the % of the 3rd harmonic current and the % of the 5th harmonic current under various nonlinear HIF impedance.

The Phase Angle of the 3rd Harmonic Current

Our study, as shown in Figure 8, indicates that the phase angle of the 3rd harmonic current under various HIF conditions lies between 50 and 90 degrees. Our study also indicates that the 3rd harmonic current lags the corresponding phase voltage by

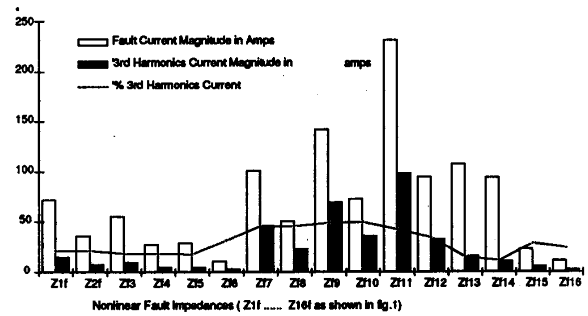

Fig- 5 Magnitude of The Fault Current and The 3rd Harmonics Current

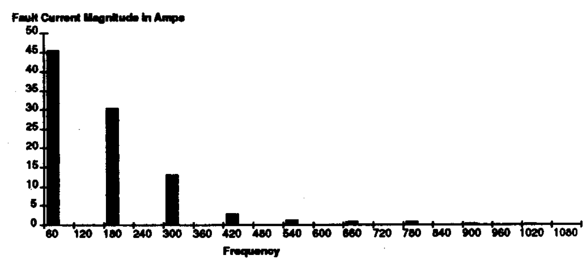

Fig- 6 The Harmonic Currents of A HIF

180 to 220 degrees. This angle difference is measured based on the cosine voltage wave form. Figure 8 also shows that the angles of the 3rd harmonic current are lower if the applied HIF impedance have a higher degree of nonlinearity. The angle of the 3rd harmonic HIF current can also be affected by the capacitor bank. The study shows that the angle of the 3rd harmonic HIF current is higher if a smaller size of the capacitor bank is installed. This characteristic can be seen in Figure 9.

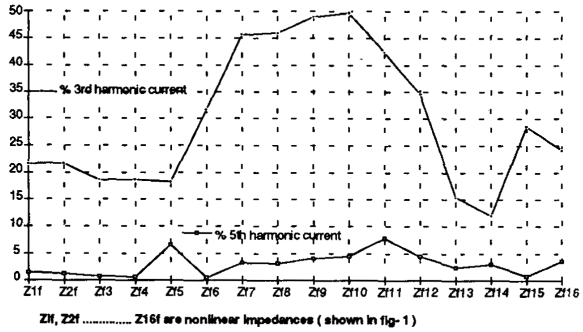

Fig- 7 Comparisons Between The % of The 3rd Harmonic Current and The % of The 5th Harmonic Current

Figure 9.b shows that for the same load and the same nonlinear fault impedance, the angle of the 3rd harmonic current is 80.6 degrees if a 2.4 mvar capacitor bank is installed; while that angle will decrease to 73.9 degrees if a 4.8 mvar capacitor is installed. Furthermore, our study shows that applying the same HIF impedance , the angle of the 3rd harmonic current is smaller in Case B than in Case A.

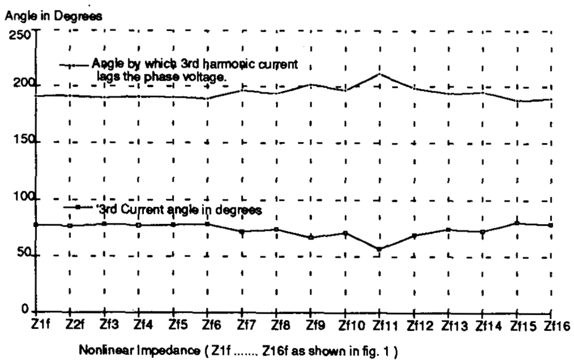

Fig- 8 The Angles Related to The 3rd Harmonic Current.

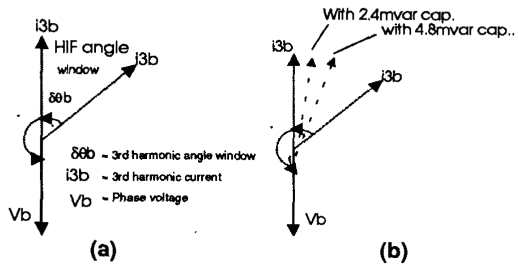

Fig-9 Vector Diagram For the Angle of the 3rd Harmonic Current

Negative Sequence Current

During the normal load conditions, due to the unbalance loads in the distribution system, the negative sequence current is always present. The study indicates that this negative sequence current will be superimposed with the negative sequence fault current when a HIF occurs. Therefore, the magnitude of the negative sequence current will increase during the HIF.

CHARACTERISTICS OF THE LOAD AND CAPACITOR SWITCHINGS

In order to distinguish the HIF from the normal load switching activities, different sizes and combinations (Mvar, Mw, single phase, or three phase)of load are switched, and the characteristics of the load switching are analyzed. It is found that very high frequency contents are usually present during the load switchings. Unlike the HIF activity, the magnitude of the 3rd harmonic current in the load switching is always lower than the magnitude of the higher order (5th, 7th .....) harmonic. These harmonic last about 1 cycle.

The harmonic from different sizes(1.2, 2.4mvar,...) of the capacitor switching are also examined in this study. In the capacitor switching, the magnitude of the harmonic current is very high in comparison with the load switching, especially, for the higher harmonic. Similar to the load switching, the magnitude of the 3rd harmonic current in the capacitor switching is lower than the magnitude of the higher order (5th, 7th,..) harmonic. These harmonic last about 2-3 cycles. Figure 10 shows the magnitude of the harmonic currents in all three phases due to a capacitor switching activity on the distribution feeder. In this particular simulation, the size of the capacitor bank is chosen to be 1.2 mvar, and the load is 3mva with a power factor 0.85 lagging.

This study also examines the harmonic characteristics of the transformer inrush current. It is observed that within the harmonic spectrum of the transformer inrush current, the magnitude of the second order harmonic current is higher than the magnitude of the 3rd and higher order harmonic currents. The characteristics of an arc furnace switching is also analyzed. The harmonic magnitude due to the arc furnace load switching on the distribution feeder is shown in Figure 11. It can be seen that the magnitude of 3rd harmonic current is greater than the magnitude of the higher order harmonic currents.

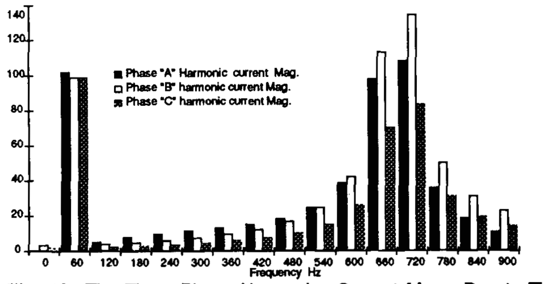

Fig- 10 The Three Phase Harmonics Current Mag. Due to The Capacitor Switching

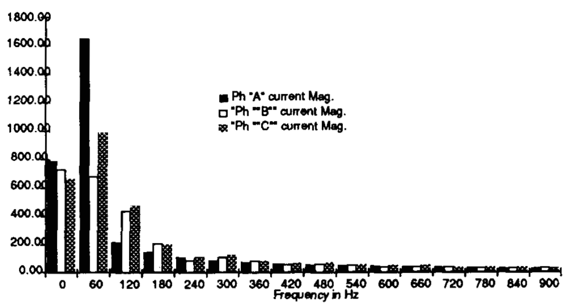

Fig- 11 The Three Phase Harmonics Current Magnitude Due to *The Arc Furnace Switching*

LOGIC FOR THE PROPOSED HIF DETECTION METHOD

From the information obtained above, it can be seen that a reliable HIF detection scheme will have to take many factors into considerations. In this section, a microprocessor based logic, which incorporates all the previously observed HIF characteristics, is built for the HIF detection.

DESCRIPTION OF THE LOGIC DIAGRAMS

Logic Diagram for Representing The Magnitude of The Fault Current

As mentioned in the previous section, the HIF current varies nonlinearly with the nonlinear impedance. The magnitude of HIF depends on the magnitude of the fault impedance and the connectivity of the load current under faulted conditions. When an energized conductor is downed and broken, the load current in the broken phase, downstream from the fault, becomes zero. Therefore, the magnitude of the current measured at the substation will be less than the average normal load current. When an energized conductor is down but not broken, then the current at the substation equals the normal load current plus the HIF current. Therefore, the magnitude of the current measured at the substation will be greater than the average normal load current. In both cases, the current measured at the substation will be less than the overcurrent relay pickup value. The logic for detecting such a abnormal current magnitude factor is shown in Figure 12.

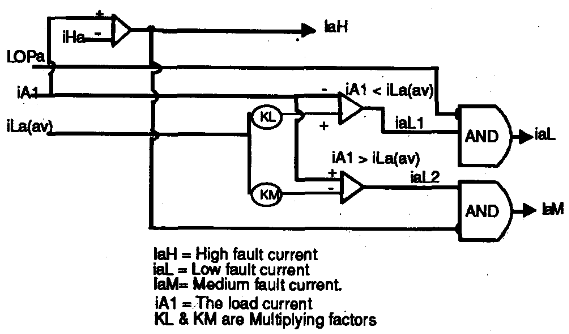

Fig- 12 Logic For Detecting Abnormal Current Level phase "A"

In Figure 12, the load current iA1 measured at the substation is compared with the overcurrent relay pickup value iHa for LIF detection and iA1 is also compared with the normal average load current iLa(av) for HIF detection. If iA1 is greater than iHa, then it is a candidate for LIF and the logic output IaH is true. If IaH is true, then HIF detection will be blocked. If the magnitude of iA1 is greater than the normal average load current times an adjustable KM factor, IaH is false and, LOPa is false, then the output logic IaM is true. If the magnitude of iA1 is less than the normal average load current times an adjustable KL factor, IaH is false and, LOPa is false, then the output logic IaL is true. LOPa represents a loss of potential in the phase A. If either iaL or iaM is true, then iA1 is declared as a HIF candidate. The logic iaM will also used to distinguish the arc furnace load current from the HIF current, which will be explained later.

The normal average load current iLa(av) is calculated and stored every five minutes interval. The logic diagram for calculating the iLa(av) is shown in Figure 13. Figure 13 also shows that the iLa(av) calculation will stop if the normal average load current can not be obtained. This goal is achieved by the three blocking variables(LOPa, IaH, and i2a). All three variables represent system abnormal states. i2a provides an excessive negative sequence current indicator, which will be explained later.

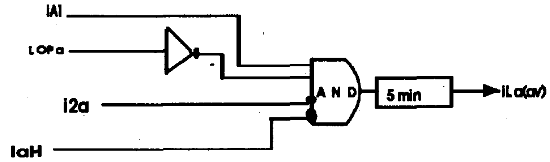

Fig- 13 The Logic Diagram for Calculating The Normal Average Load Current phase "A"

Logic Diagram for Representing The Magnitude of The 3rd Harmonic Current

As mentioned before, the 3rd harmonics current during the HIF is higher than the 3rd harmonics current when a load switching occurs. Furthermore, when HIF occurs, the 3rd harmonics current is higher than the 5th harmonics current. The logic diagrams for implementing these two observations are shown in Figures 14 and 15.

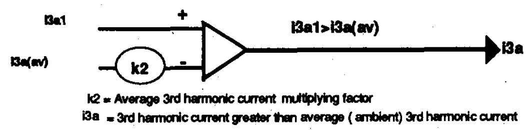

Fig- 14 The Indicator for Representing The Above Ambient 3rd Harmonic Current

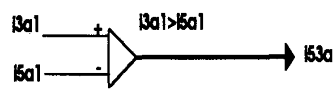

Fig- 15 Comparison of 3rd and 5th harmonic

In Figure 14, the 3rd harmonic current i3a1 will be compared with the normal average 3rd harmonics current i3a(av). If i3a1 is greater than i3a(av) times a factor k2, then the indicator i3a is true. The calculation of i3a(av) is similar to the calculation of the normal average load current iLa(av). In Figure 15, the magnitudes of the 3rd and the 5th harmonic currents are compared. If i3a1 is greater than i5a1, then the indicator i53a is true.

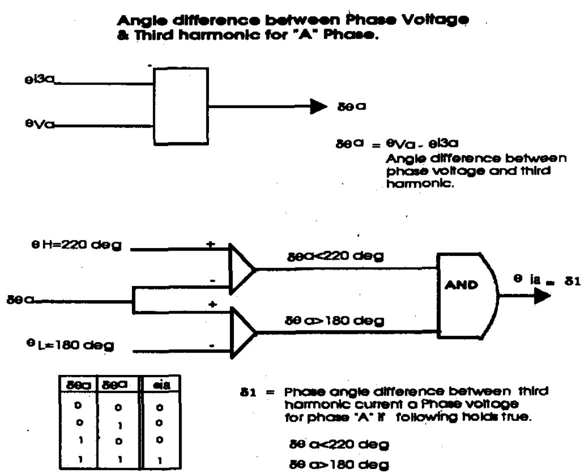

Fig- 16 The Logic Diagram for The Angle Difference Between The 3rd Harmonic Current and The Phase Voltage

Logic Diagram for Representing The Angle of The 3rd Harmonic Current

As noted before, our study indicates that the 3rd harmonic current, under the HIF, lags the corresponding phase voltage by about 180 to 220 degrees. This angle difference is measured based on the cosine voltage wave form. The corresponding logic diagram is shown in Figure 16. In this figure, it can be seen that if the 3rd harmonic current lags the corresponding phase voltage by about 180 to 220 degrees, then this logic output will be true.

Logic Diagram for Representing The Negative Sequence Current

Our study indicates that this negative sequence current will be superimposed with the negative sequence fault current when a HIF occurs. Therefore, the magnitude of the negative sequence current will increase during the HIF. The logic diagram for implementing the negative sequence current indicator is shown in Figure 17. In this figure, it can be observed that if the negative sequence current i2A1 is above the normal negative sequence current i2a(av) by a certain factor k1, then the indicator i2a will be true.

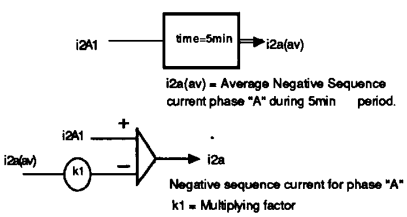

Fig- 17 The Logic Diagram for The Negative Sequence Current Indicator

THE HIGH IMPEDANCE FAULT DETECTION LOGIC

Combining the previously described logic diagrams together, a completed logic diagram for the three phase HIF detection can be built as shown in Figure 18. In this figure, iaL represents the magnitude of the HIF current indicator. Both logic outputs , iaL and iaM , are entered here. i2a is the negative sequence current indicator. i3a is the magnitude of the 3rd harmonic current indicator. i53a is the indicator representing the comparison of the magnitude of the 3rd harmonic current and the 5th harmonic current. δ represents the indicator of the angle relationship between the 3rd harmonic current and the phase voltage.

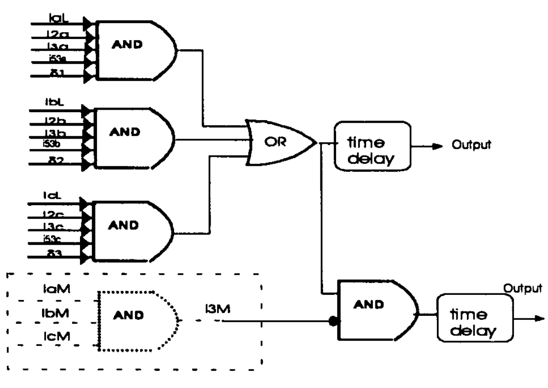

Fig- 18 The Complete Logic Diagram for The Three Phase HIF Detection

The first three AND gates represent each of the three phases. The bottom AND gate represents a possible arc furnace operation. As mentioned before, the characteristics of an arc furnace switching are very similar to the characteristics of HIF. The magnitude of the three phase arc furnace load current is about equal to iaM, ibM, and icM of the HIF. Therefore, if all three iaM, ibM, and icM are true, then the proposed logic diagram can not detect whether there is a HIF or an arc furnace switching. Therefore, an alarm should be sent to the operator, but the relay should be blocked.

LOW IMPEDANCE FAULT DETECTION LOGIC

As mentioned earlier, a fault with current above the overcurrent relay pickup value is defined as low impedance (high fault current) faults[LIF]. LIF is a normal fault for distribution or transmission systems. About 85% - 98% of the faults are low impedance faults. LIF current can be easily detected by the overcurrent relays. The proposed logic diagram for the LIF detection is shown in Figure 19. In this design, iaH, ibH, and icH represent the fault current above the threshold value. This LIF detection scheme can also be set adoptive if the pickup threshold settings is based on the average load current. The sensitivity of adoptive settings is adjusted by "K" factor. The relay tripping can be instantaneous (50H), definite time(51HD) or inverse time (51H).

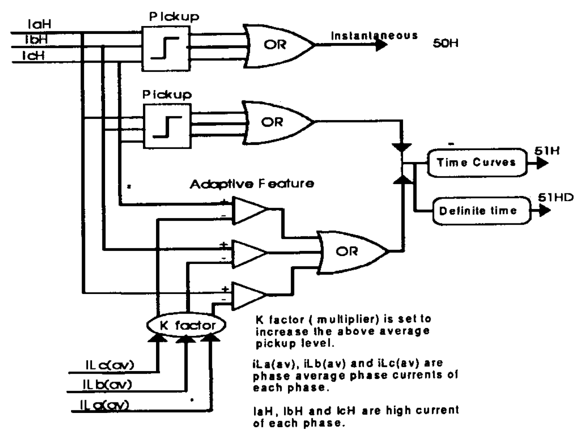

Fig- 19 Low Impedance Fault Detection Logic.

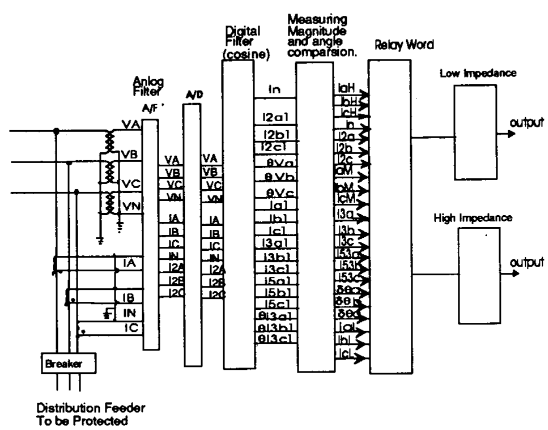

Fig- 20 The Integrated Block Diagram For HIF & LIF

THE COMBINED BLOCK DIAGRAM FOR THE PROPOSED HIF AND LIF DETECTION

The logic diagrams for both HIF and LIF can be easily integrated. The block diagram for the integrated HIF and LIF detection is shown in Figure 20. Using this combined logic, the need for separate devices in order to detect HIF and LIF can be eliminated.

CONCLUSION

An combined high impedance fault (HIF) and low impedance fault(LIF) detection method is proposed in this paper. For the HIF detection, the proposed technique is based on a number of characteristics of the HIF current. These characteristics are: fault current magnitude, magnitude of the 3rd harmonic current, magnitude of the 5th harmonic current, the angle of the third harmonic current, the angle difference between the third harmonic current and the fundamental voltage, negative sequence current of HIF. These characteristics are identified by modeling the distribution feeders in EMTP. Apart from these characteristics, the above ambient (average) negative sequence current is also considered. In this proposed method, the average load current and the average negative sequence current are calculated and stored. These average currents are calculated at the every 5min interval. The measured rms load and negative sequence current are compared with the stored average value. If there is an increase or a decrease in the load current by 20% (adjustable) or an increase in the negative sequence current by 20% (also adjustable), then that phase is declared as a candidate for HIF. This feature will not only make the proposed scheme more sensitive to the HIF low fault current, it will also be able to prevent tripping during the normal condition. The magnitudes of the 3rd harmonic current and the 5th harmonic current are also examined in order to distinguish the capacitor switching, the load switching, or the arc furnace from HIF.

In the paper, several logic diagrams based on the characteristics of HIF are constructed. The logic diagrams includes a logic for differentiating the magnitude of the fault current, a logic for examining the magnitude of the 3rd harmonic current, a logic for examining the angle of the 3rd harmonic current, and a logic to indicate the level of the negative sequence current. These logics are used as components for building the three phase HIF detection logic.

A fault with current above the maximum expected load current is defined as low impedance (high fault current) faults[LIF]. LIF is a normal fault for distribution or transmission systems. About 85% - 98% of the faults are low impedance faults. LIF current can be easily detected by the overcurrent relays. With minimal modifications, the logic developed for the HIF detection can be applied to the LIF detection. A complete logic circuit required for implementing the proposed HIF and LIF detections is discussed in the paper. Using this logic, the need for separate devices for HIF and LIF detection can be eliminated.

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BIOGRAPHIES

David C Yu (S'78-M'84) received his Ph.D. degrees in EE from University of Oklahoma in 1983. Currently, he is an associate professor in the Department of Electrical Engineering and Computer Science at University of Wisconsin - Milwaukee.

Shoukat H. Khan (M'91) was born in Pakistan, August, 1956. He received B.Sc Eectrical Engineering from University of Engineering & Technology Lahore Pakistan in 1982. He worked for Water and Power Development Authority (WAPDA), Lahore, Pakistan from 1983 to 1988 in "Power Production" and "System Protection" departments. He received M.S. in Electrical Engineering from University of Wisconsin Milwaukee in 1993. Since 1990, he has been working for Puget Sound Power and Light Co. Bellevue, Washington, as a Protection Engineer. His major area of interest is Transmission and Distribution System Protection and Power System Planning and Analysis.

Discussion

John R. Linders, Nordon Technologies, Inc. Sarasota,FL This is an interesting paper and the authors are to be congratulated for offering there thoughts to the protection engineers of the Institute. Eventually the use of EMTP in HIGF studies will prove to be quite valuable. For this to occur the authors will need to express their ideas in a manner which permits one to confirm the reported work. This the authors have not done.

As the authors note a specific field test of a HIGF is limited to the specific conditions of the test site, and therefore is not a valid base for a general solution. Having raise the point about a single test condition, the authors then propose a specific and unique set of fault harmonic impedances. No justification for these specific values is given nor is the rational for this approach to the problem discussed. Subsequently, these values are changed to explore various aspects of the problem. Again no rational is given for these new values, nor are the new values given.

A few questions on the data that is presented: What is the rational to the impedance changes to represent different soil moisture conditions? I do not understand Fig. 5, "Magnitude of the fault current and the 3rd harmonics current". What is the meaning of the scaling of the absicca in harmonic order if the graph is a plot of the 3rd Harmonic? Similar question on Fig. 7 and 8. What was the magnitude of the fault current and its phase angle in Fig.6? Also in Fig. 3, the 3rd harmonic is shown to be 2/3rds of the fundamental. We have never observed it over 1/3rd. What did the wave shape look like?.

Is it correct that in Fig. 8 you are showing there is an interaction between the several harmonics in the HIGF current? I agree with your statement that the 3rd harmonic current lags the phase voltage by 180 to 220 degrees. But what is the other 50 to 90 degrees phase angle? The comment that the negative sequence current always increases during a HIGF needs rephrasing. The phase relations must be treated and the specific phase unbalance with respect to the HIGF faulted phase must be considered before any conclusion can be drawn as to the magnitude change. With the arc furnace buffered by a delta/delta transformer, why is it of interest when measuring the current in L-G events?

It would be counter productive to comment on the logic section of this paper since I do not understand some of the statements upon which the logic is based. Also, there are other subtitles to HIGF detection which need treatment before a secure logic chain can be developed.

Manuscript received February 17, 1994.

C. L. Benner and **B. D. Russell** (Dept. of Electrical Engineering, Texas A & M University, College Station, TX): The authors of this paper are to be commended for their efforts to solve the long standing problem of high impedance fault detection. While their proposed technique is not new, it reinforces the discovery of other researchers that a multi parameter approach is necessary for reliable fault detection.

When describing their EMTP model parameters, the authors show capacitance from 1.2 to 4.8 kvar. We believe that this should be 1200 to 4800 kvar (or 1.2 to 4.8 Mvar).

The authors have not adequately referenced prior research in this area and their brief analysis of previous investigations is incomplete. For instance, the authors' method of comparing the phase angle of the third harmonic current to the fundamental frequency voltage was first proposed and implemented by Jeerings and Linders [authors' reference 3]. Although the authors mention that Jeerings and Linders "provided a more complete analysis about the harmonics in HIF . . . [and] developed a scheme to detect the downconductor fault," they make no mention of the fact that the authors' technique is virtually identical to that presented in the earlier work.

Also, previous work on multi parameter detection methods was noticeably absent in the introductory analysis. The authors are directed to discussion reference [D1].

We also take exception with the authors' third paragraph of the Introduction, which begins "a more reliable and more practical solution to solve the HIF detection problem is proposed." There is no basis given for this statement in the paper. No normal system field testing, staged fault testing, comparative testing to other schemes, or similar methods are presented in the paper to support this conclusion. In fact, previously published research has shown that several of the fault detection techniques proposed are *not* the most reliable indicators of high impedance faults [D2].

It is probable that the authors' technique for combining the various techniques proposed by the authors will not yield a more reliable system. We have concern that such indicators as the magnitude of third or fifth harmonic current (or their ratio to one another) may lead to false indications of a fault from naturally occurring events or switching events. Space does not allow a detailed analysis of the proposed method, but the work of previous researchers would dispute the use of certain of these parameters, for example reference D2.

Other concerns include unsupported statements such as, "about 85%–98% of the faults are low impedance faults," but no citation or other foundation is given for this statement. The work of several researchers would dispute these estimates [D1].

Further, significant concern exists over the use of an EMTP model for the selection of detection criteria. Despite the authors' implications to the contrary, over a period of 15 years, hundreds of staged faults have been studied with the final conclusion that it is virtually impossible to create a model that is sufficient and accurate for analytical use. Most certainly, an EMTP model is inadequate. While it may give gross indications of performance, it cannot accurately reflect the dynamic and random nature of an arcing downed conductor. Hence, the problems associated with certain of the selection criteria selected by the authors are not revealed in EMTP analysis. The authors are encouraged to use actual staged fault data and long term normal system monitoring for evaluation of the performance of their system, because only then can the susceptibility of the approach to "false tripping" be determined. Since security issues are of primary concern to utilities, this step is mandatory.

We have further concerns with certain assumptions used by the authors in developing their detection logic. For example, they determined that negative sequence current from the fault will be superimposed on "normal" negative sequence current, thereby increasing the negative sequence component during an HIF. Based on the placement and type of load, amount of load loss, placement of capacitor banks, load distribution and unbalance, and other factors, the negative sequence current cannot be predicted. It is stated that this parameter along with variations in load currents will be used as requirements for indication that an HIF exists. Based on investigation of hundreds of staged faults, this approach will significantly desensitize the HIF detection and result in failure to detect many faults.

Other problems exist with the fault detection method and assumptions of the authors. It is not always true that "the third harmonics current during the HIF is higher than the third harmonics current when a load switching occurs." It is also not true that third harmonic current is necessarily higher than fifth harmonic current during an HIF. The study of many faults indicates that there can be random and opposite relationships between these parameters than those indicated by the authors. Their conclusions are probably drawn from the EMTP model used, which is an inadequate representation of many fault scenarios.

Although not stated directly, the authors seem to have made certain assumptions about the characteristics of normal systems. First, they seem to assume that normal system currents do not contain significant harmonics. Current harmonics (particularly low order odd harmonics) often are very substantial on a normal distribution system. In fact, currents containing up to several tens of percent of harmonics are not uncommon.

All of the five detection techniques given above are ANDed together to provide a fault detection output. Given this, even if each detection technique taken singly was 75% effective, the chance of all of the techniques giving a positive indication for a given fault would be only $(0.75)^5 = 24\%$. Given past experience with measured field data for the parameters considered, 75% average effectiveness for these individual techniques is probably optimistic.

The authors are encouraged to continue their work, but more care should be taken to properly reflect the true nature of high impedance faults before performance claims are made about "a more practical and more reliable solution." The EMTP model should be abandoned in favor of actual fault data under a wide variety of fault scenarios. The performance evaluation of the proposed system should be made using actual fault data before conclusions are drawn concerning its superiority and reliability in fault detection. The authors are directed to the following references which should assist their future investigation.

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L.L. Lai and K.H. Chu, (Energy Systems Group, City University, London EC1V 0HB, England, UK): The authors are to be congratulated for an interesting paper. It would be appreciated if the following points are clarified:

From the test criteria in EMTP, could the discusser say that no measurements have actually been done? The currents and voltages are purely calculated by using the EMTP only.

It is not clear to the discusser what transformer model has been used, for example, whether BCTRAN or saturable transformer etc. Has the nonlinear characteristic of transformer been considered? If so, how does this nonlinearity affect the proposed method?

What is the reasoning behind to declare whether it is a high or low impedance fault. It is not clear how did the authors obtain the figure of 20%. Is this an optimal figure? The paper should be self-supporting in this point.

How quick could the logic circuit be switched from the detection of high to low impedance fault or vice versa?

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David C Yu and Shoukat H Khan: The authors are grateful to the discussers for their valuable comments. This paper was written to identify the characteristics of different variables involved in high impedance fault (HIF) and use these variables and their characteristics to formulate logic scheme for HIF fault detection.

Response to John R Linder:

We have modeled different nonlinear fault impedances to represent the variation in arcing impedance. This variation in the impedance might be due to different soil conditions or compositions, change in moisture contents, physical or chemical changes during arcing. In the paper, figure 5 represents the comparison between magnitude of fault current and magnitude of 3rd harmonic current. The x-axis in figure 5, 7 and 8 represent the different nonlinear fault impedances Z1f, Z2f.... Z16f and not scaled for harmonic order as Mr. Linder pointed out. In this study more than two hundred different nonlinear impedance were modeled; however, for simplicity, only the results from sixteen different nonlinear impedances were shown in the paper. Figures 3a and 3b show the waveforms of fault current and phase voltage for broken and unbroken conductor, respectively. There are two curves shown in figure 8. One curve represents the angle by which 3rd harmonic currents lags the corresponding phase voltage for various nonlinear impedances (Z1f, Z2f..... Z16f), the other curve shows the corresponding angle of 3rd harmonic current.

Response to Carl L. Benner and B. Don Russell

The authors wish to thank the two discussers for pointing out an important typing error in the paper. The size of the capacitor bank modeled in EMTP should be ranged from 1.2Mvar to 4.8 Mvar which is evident in figure 9 and other statements in our paper. The authors also agree that staged faults give the true picture of HIF for specific locations and feeders. However, it is our belief that the EMTP model for HIF is more flexible than staged faults in modeling different distribution systems and their components and different types of nonlinear impedances.

It is true that Jeerings and Linder 's HIF detection scheme was based on 3rd harmonic current angle and phase voltage angle but their study was based on some specific field tests. Our study is based on broad spectrum of high impedance faults modeled in EMTP. In this study, not only the 3rd harmonic current angle and magnitude are examined, but also the 5th harmonic current, load current and negative sequence current magnitudes are also examined. The purpose for including all these variables in the proposed detection scheme is to increase the confidence and reliability of the method.

It is true that harmonics are always presents in the distribution feeders. In the proposed method the harmonics are constantly monitored and their average value is calaculated over specified time period (typical 5 minutes). In order to measure the change in harmonics the average value of 3rd and 5th harmonic currents are compared with corresponding new value of 3rd and 5th harmonic current. It is also true that during the normal switching activity the magnitude of the 3rd harmonic current is greater than the magnitude of 5th harmonic current. This phenomenon is similar to the characteristics in HIF. Since a switching period is typically very short (few cycles), a time delay is implemented in the proposed scheme to distinguish normal switching from HIF.

The negative sequence current is also included in HIF detection scheme in order to provide additional reliability. Due to the unbalanced loads in the distribution feeders, the negative sequence current is always present. However, it was noted that magnitude of negative sequence current will likely increase during HIF. The negative sequence current is very difficult to predict. In the proposed scheme, the negative sequence current is constantly monitored, and the average negative sequence current is calculated for a selectable time period (typical 5 minutes). This average current is compared with the new RMS value of the negative sequence current in order to detect the change. The statement 85% to 98% of fault are low impedance fault is taken from previous studies and this may not be true or applicable to all utilities feeder system, but it should not effect the proposed method. The proposed scheme has not been tested with any field data. The authors plan to carry out field data testing in next phase of study.

Response to L. L. Lai and K. H. Chu:

The saturable transformer model was implemented in this study. Normally distribution power transformers do not saturate during a L-G fault, therefore, the nonlinear characteristics of the transformer are not considered.

The 20% above and below load current figure is adjustable and is taken as typical blackout region where the HIF tripping is not required. This value can be set to 0% after getting more confidence in HIF fault detection scheme. The logic for HIF and LIF does not require any switching.

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