The Application of Fault Signature Analysis in Tenaga Nasional Berhad Malaysia

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***Abstract*—Unplanned electrical power outages are a major concern to power utilities throughout the whole world. Unfortunately, power outages will continue to occur and they cannot be fully prevented. It could be the result of lightning strikes, tree encroachment, or equipment failure. However, the impact can be reduced if power system operators are equipped with the appropriate tools to analyze the root cause of the failure. Without sufficient tools to identify the nature of a fault, the restoration process could be delayed because the operator does not know whether it is safe to normalize the isolated line. This paper describes the new and simplified fault signature analysis approach on Tenaga Nasional Berhad using a digital fault recorder. The research focuses on the contribution of the lightning strike and tree encroachment to the overhead line tripping in Malaysia.**

***Index Terms*—Blackout, digital fault recorder (DFR), fault signature analysis (FSA).**

I. INTRODUCTION

THESE DAYS, the requirement of an uninterrupted power supply has become a regulation imposed by governments to the power utilities throughout the whole world. Electricity is no longer a luxury item. It was an essential commodity, which has now become an economic and security issue. Power outages and blackouts have become more painful in our daily lives and routine activities in this challenging 21st century.

In 2003, the world experienced at least five major electrical power blackouts affecting a few countries either partially or total national blackouts. The famous wide-scale power outages are as follows.

1) August 14, 2003 at 16:10 h, Northeastern U.S. and Central Canada [1]–[3].
2) August 28, 2003 at 18:26 h, Central U.K. [1]–[3]
3) September 1, 2003 at 09:58 h, Northern Malaysia [4].
4) September 23, 2003 at 12:35 h, Eastern Denmark and South Sweden [1]–[3].
5) September 28, 2003 at 03:28 h, entire nation of Italy and South Switzerland [1]–[3].

All of those blackouts caused great financial losses that were estimated to be more than 1 $U.S. billion [1]. Blackouts can be initiated for so many reasons, including the demand was not balanced with the generation output, the failure in protection

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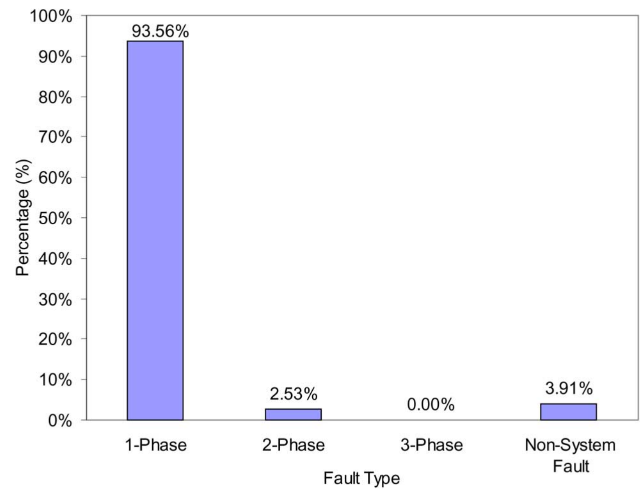

Fig. 1. Tenaga Nasional Berhad's transmission overhead line faulted phase (until February 14, 2006).

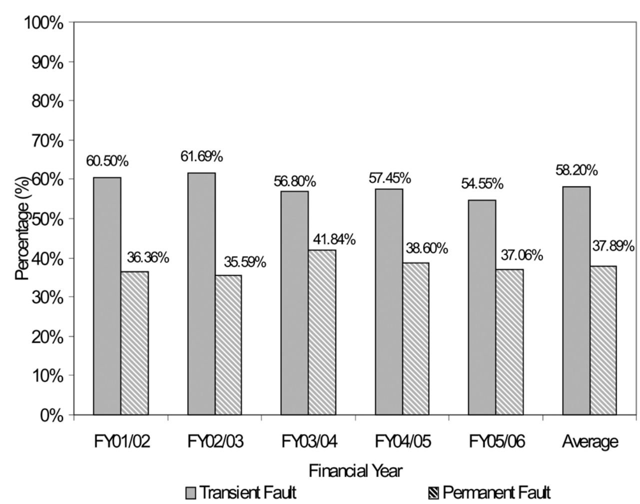

Fig. 2. Transient and permanent fault on a transmission overhead line (until February 14, 2006).

system, wrong or slow decision making made by the system operator, and so forth. In general, the blackouts are due to a combination of circumstances that stress the network beyond its limits. The most difficult part is to seek solutions that will prevent such cascading of tripping that lead to a partial or even total national blackout.

During any system fault on an overhead line, power system operators do not know the cause of the tripping immediately after the incident has occurred. This is because they have to dispatch the maintenance crew to walk along the overhead line using the fault-location equipment to identify the reason of the flashover. However, if the incident occurs at night, they either have to wait until the next morning and leave the line on outage

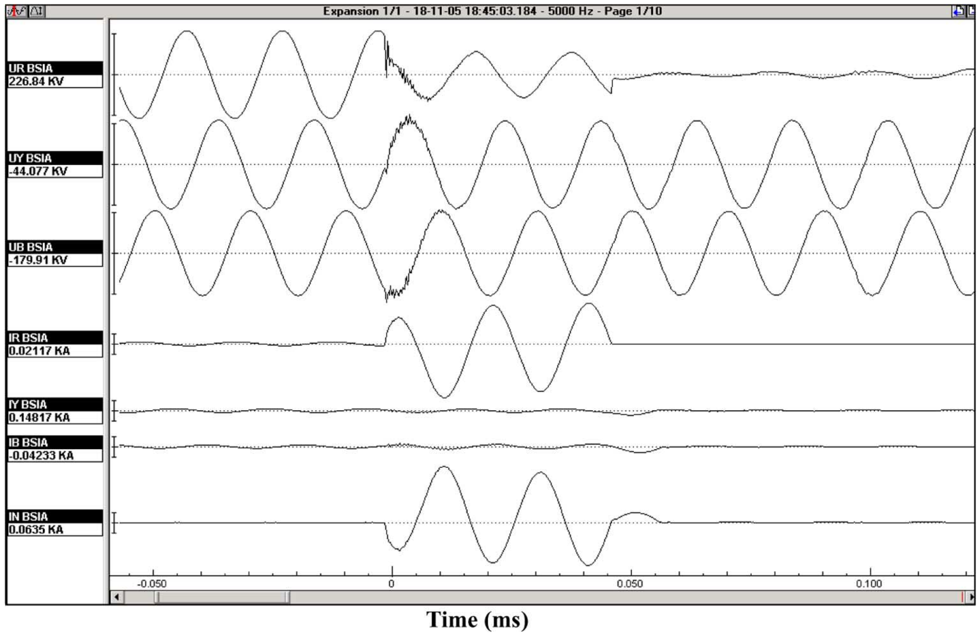

Fig. 3. Lightning signature with the fault location of 20.1% and 3.1-W primary loop impedance.

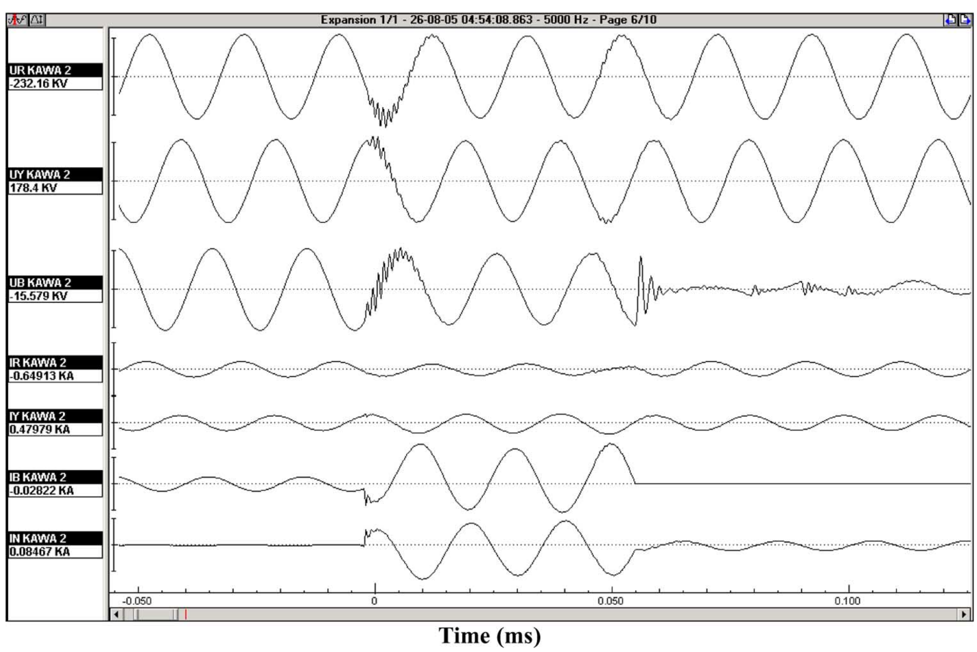

Fig. 4. Lightning signature with the fault location at 81.2% and 4.9-W primary loop impedance.

or try to close back the line based on their own judgment. On the other hand, if they have been equipped with the fault signature analysis (FSA), they can normalize the isolated line immediately without having to wait for the maintenance crew to identify the cause of the tripping.

II. Overhead Line Fault Category

From Tenaga Nasional Berhad's (TNB's) five-year (2001 to February 14, 2006) tripping statistics, the most frequent type of fault on TNB's overhead transmission lines was a single-phase to ground fault. Fig. 1 shows the five-year statistics of which 93.56% of the line tripping was a single-phase-to-ground fault, 2.53% was a two-phase fault, 0.00% was a three-phase fault, and the remaining 3.91% was a nonsystem fault. From the system fault category, 58.20% of the circuit breaker (CB) was reclosed successfully and 37.89% caused the CB to be locked out. The failures to reclose a CB were either due to a permanent fault, a multiple fault during the autoreclose reclaims time, a failure in the autoreclose scheme, or a major separation of the power system. The detail tripping statistics for each financial year are shown in Fig. 2.

Since the transmission overhead line system faults were transient in nature, they can be cleared by opening the appropriate circuit breakers. After the autorecloser dead time has elapsed, the breaker restores the supply automatically.

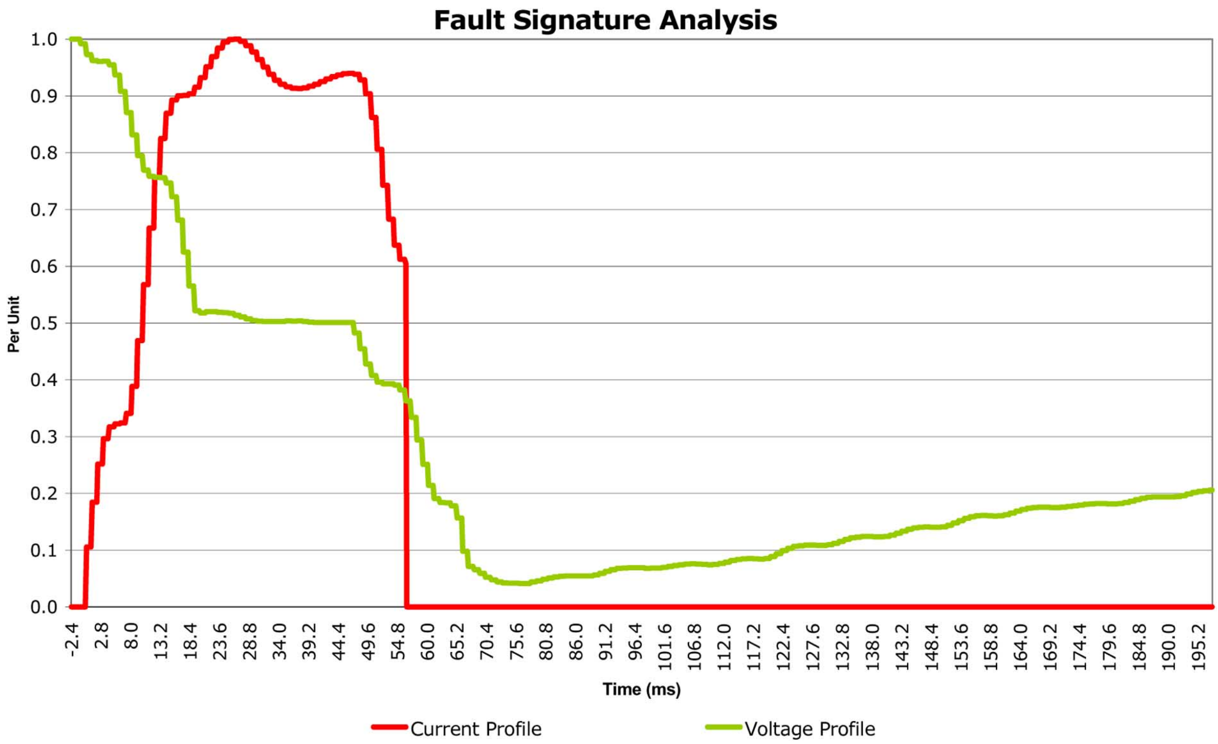

Fig. 5. Current and voltage profile from a lightning strike.

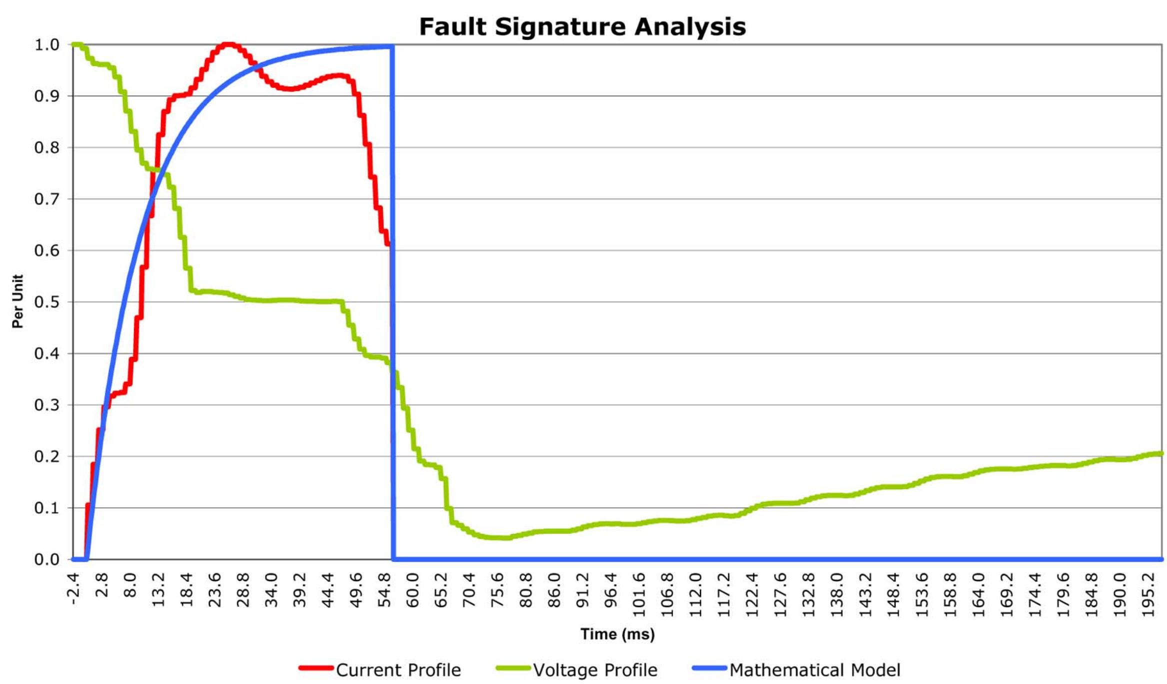

Fig. 6. Lightning strike pattern compared with the mathematical model $l = 0.1$ and voltage dip $= 0.244\%$.

For the last five years of failure mode analysis on TNB's overhead line tripping data, it was found that the common causes of tripping are as follows:

- lightning strikes;
- tree encroachment;
- defective primary equipment (e.g., current-transformer explosion);
- protection system failures during a system fault;
- crane;
- others (subsidiary system failure, such as TNB generation, TNB distribution, utility failure, such as Singapore and Thailand, and IPP failure).

During the data collection and analysis, it was discovered that the major problem faced by TNB is a lightning strike. Although a lightning strike is a transient fault, during heavy lightning activity, it can cause a permanent isolation of the line due to other

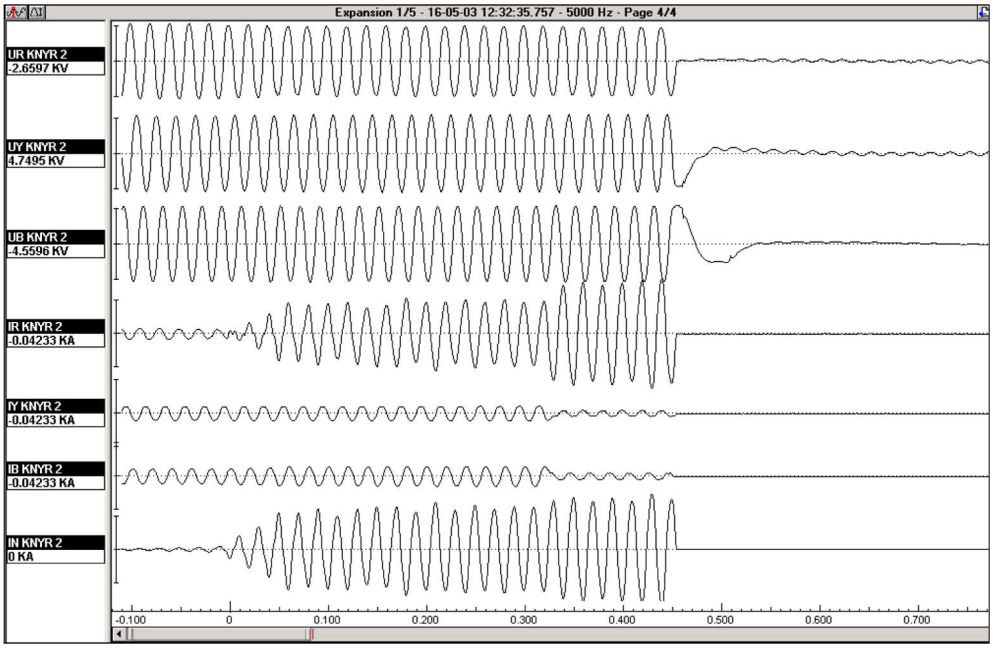

Fig. 7. Tree encroachment signature with the fault location of 15.9% and 53.2-W primary loop impedance.

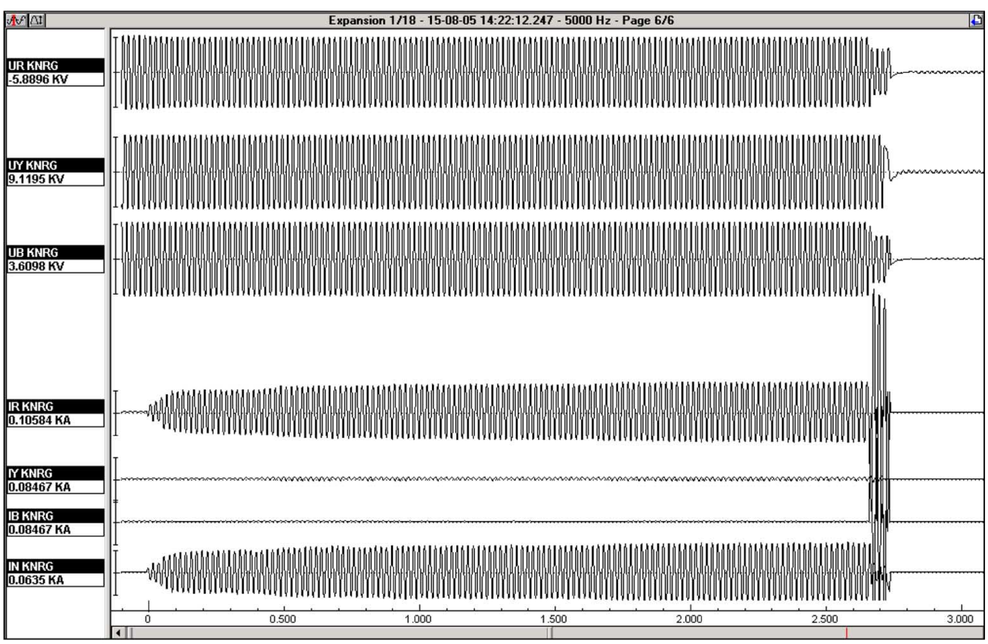

Fig. 8. Tree encroachment signature with the fault location of 45.6% and 91.6-W primary loop impedance.

strikes occurring during the autorecloser reclaim time. The decision to restore the supply requires fast and accurate judgment. At this point, the fault location alone will not be of much help.

Since Malaysia is a tropical country, the fast-growing trees below the transmission line cannot be totally avoided. However, a proper rentice management is required in order to control the tripping due to a tree encroachment. This type of tripping is a concern to a TNB transmission maintenance crew because they have to know the fast-growing tree area.

Therefore, it is an urgent requirement for TNB to have an analysis tool to identify the lightning and tree encroachment fault signatures.

III. FSA Tool

Since the implementation of electricity deregulation, most power utilities have been operating their grid to a maximum capability limit due to commercial reasons. Therefore, consistent monitoring of the power system operation and performance have become mandatory to most of the countries throughout the world.

However, system operators have to depend mainly on the relays operation through supervisory control and data-acquisition (SCADA) information flow. This information sometimes leads to inaccuracy in a fault analysis due to the uncertainty of the

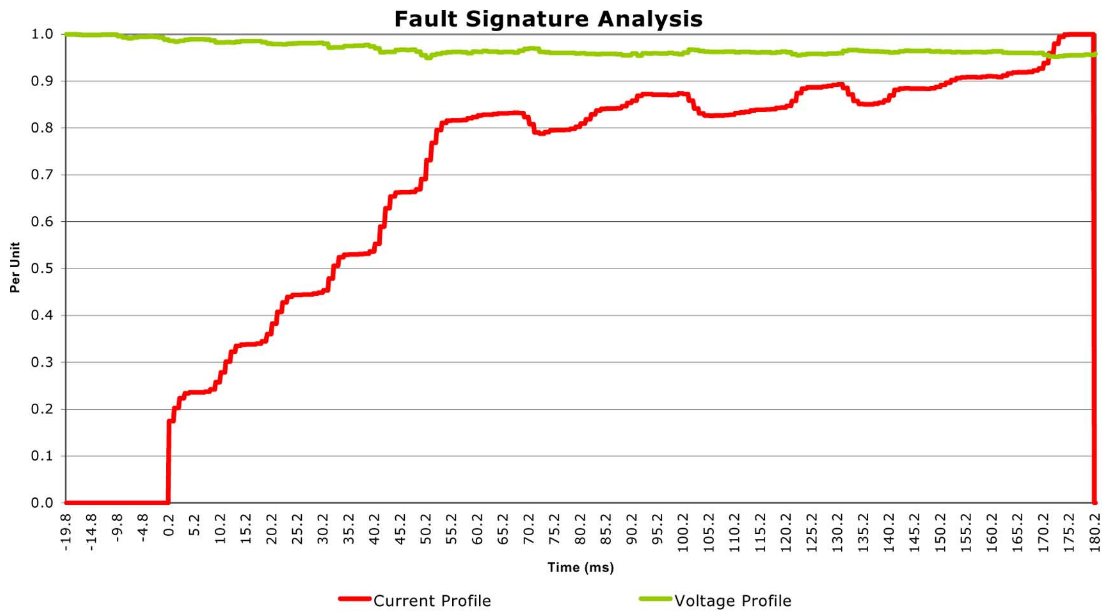

Fig. 9. Current and voltage profile from a tree encroachment.

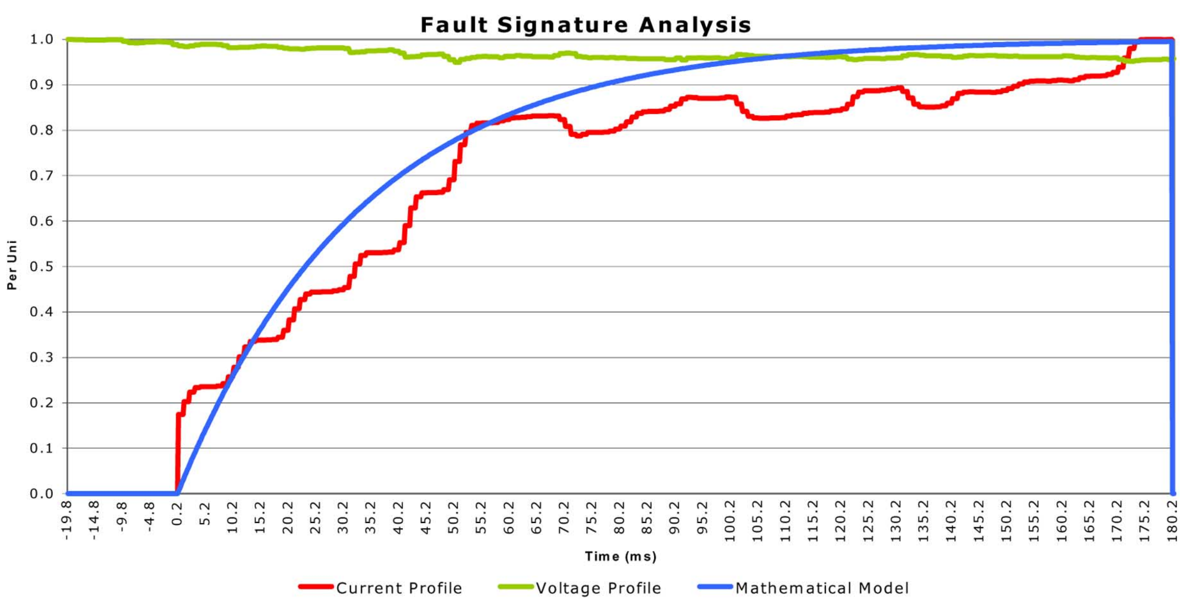

Fig. 10. Tree encroachment pattern compared with the mathematical model. $l = 0.03$ and voltage dip $= 0.037$.

correct relays operation [5], [6]. Unfortunately, with all of the complicated disturbances in the power system, they have to perform critical decision making in order to minimize the economic impact to the system despite the unknown nature of the fault and minimal relevant data that are available.

In 1995, Keerthipala *et al.* [7] proposed the implementation of a neural network to identify the faulted phase by using a simulation from the Electromagnetic Transients Program (EMTP) result. Since there is a great demand to identify the fault characteristic in the electrical power sector, Sazali [5] conducted his research and attempted to categorize the fault signature by analyzing data from the protection relays and CB operations using a knowledge-based expert system in 1995. In his findings, Sazali utilized the hypothesis approach which consisted of different combinations of prepared simulated events. This approach is relatively similar to the model-based approach that had been discussed by Mc Arthur *et al.* [8]. However, the disadvantage of this approach is that the system requires an ideal protection system without any relay maloperations.

In 2002, Xu and Kezunovic [9] utilized a wavelet transform to identify a transient fault, capacitor switching, motor starting, line switching, and transformer energizing. They successfully identified the faulty phase using the aforementioned techniques but not the fault signature as what the power utilities aspire to have.

In 2001, a paper presented by Noor Azlan *et al.* [10] highlighted their experience on utilizing the recorders' information. They observed that a few signatures could be extracted from the

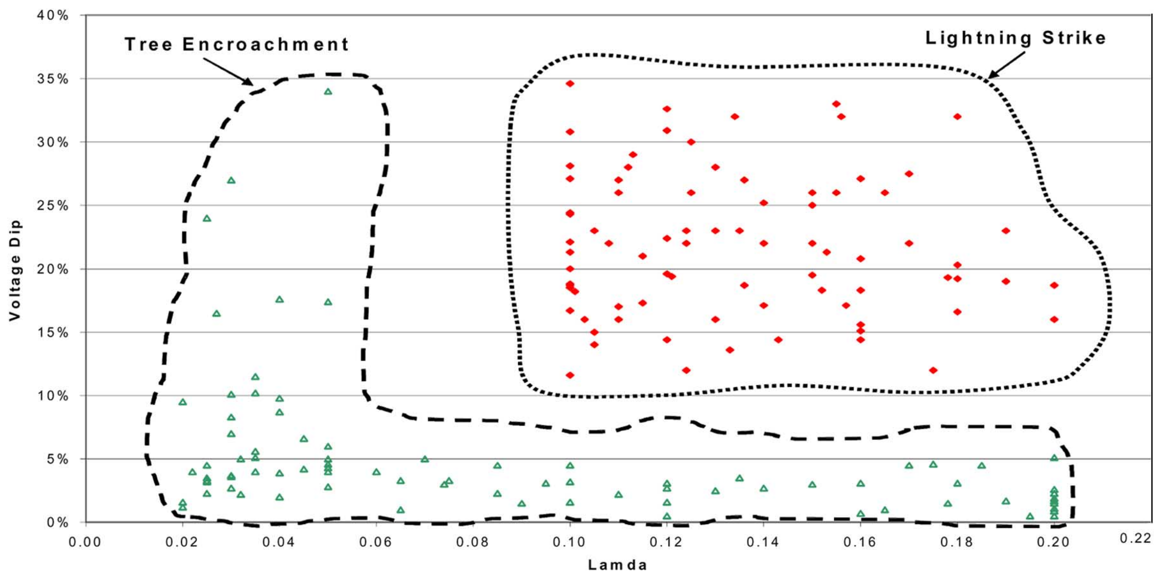

Fig. 11. Pattern recognition.

recorder traces, such as tree encroachment, contamination, and lightning. In their paper, they did not highlight any scientific technique to be used in order to identify the fault signatures.

An FSA in a power system using the digital fault recorder (DFR) is a new approach discovered in this research to understand the fault triggering element. Failure to understand the nature of the fault can cause a delay in power-supply restoration to the consumers. The approach being used in this research is based on pattern recognition through cluster analysis.

A. Lightning Strike

A lightning strike is a phenomenon of an electrical discharge in the clouds or between clouds and the ground. If the lightning strikes near a transmission line or at a tower top, it can cause a flashover between the phase conductor and the tower through an arcing horn. Whenever a flashover occurs, the protection system detects the system fault and gives a signal to open the CB. In this section, there is no intention to explain the lightning or switching impulse in detail through the physics theory as elaborated in [11]–[14]. However, this research will examine the uniqueness of the lightning strike compared with tree encroachment flashover.

Based on the tripping data compilation and analysis from 2001 until 2006, this research manages to extract the lightning signature captured by a DFR installed in the transmission system. The lightning signatures are shown in Figs. 3 and 4.

From the previous signatures, it was found that the most significant information observed was that the neutral current pattern remains the same regardless of the location and the loop impedances. Therefore, the focus should be on the neutral current and to be translated into the root mean square (rms) in a per-unit value. This approach will eliminate the contribution by the arc resistance and the frequency response.

From the first lightning's signature shown in Fig. 3, translated into rms in per-unit value, it will produce a pattern as shown in Fig. 5. An equation can be formulated from Fig. 5 to correlate the flashover measured by the protection relay due to a lightning strike by the equation

$$f_c(t,\lambda) = 1 - e^{-\lambda t}|_{t=t_0-t_n} \quad (1)$$

where

$f_c(t,\lambda)$	calculated root mean square (rms) in per-unit value flashover current for every sample taken with a constant "λ;"
E	exponential curve function;
t	sampling time in milliseconds;
t_0	time at the initial sampling;
t_n	time at the "n" data sampling;
λ	gradient or rate of change of the curve;
n	number of samples.

Equation (1) will be used to estimate the closest value with respect to the actual value captured by a DFR. The deviation between the measured and calculated value is defined by

$$\Delta f_d = |f_m(t) - f_c(t,\lambda)|_{t=t_0-t_n} \quad (2)$$

where

Δf_d	deviation function;
$f_m(t)$	measured rms in per-unit value by a DFR;
$f_c(t,\lambda)$	calculated rms.

The extrapolation for a lightning strike is shown in Fig. 6. From this example, the extrapolation gives the value of $\lambda = 0.1$. Another observation was the faulted phase experience that a voltage dips of 0.244 p.u.

B. Tree Encroachment

A tree encroachment is a situation where the clearance between the bottom conductor and the tree shoot is less than the minimum stipulated distance. The factors that contribute to the

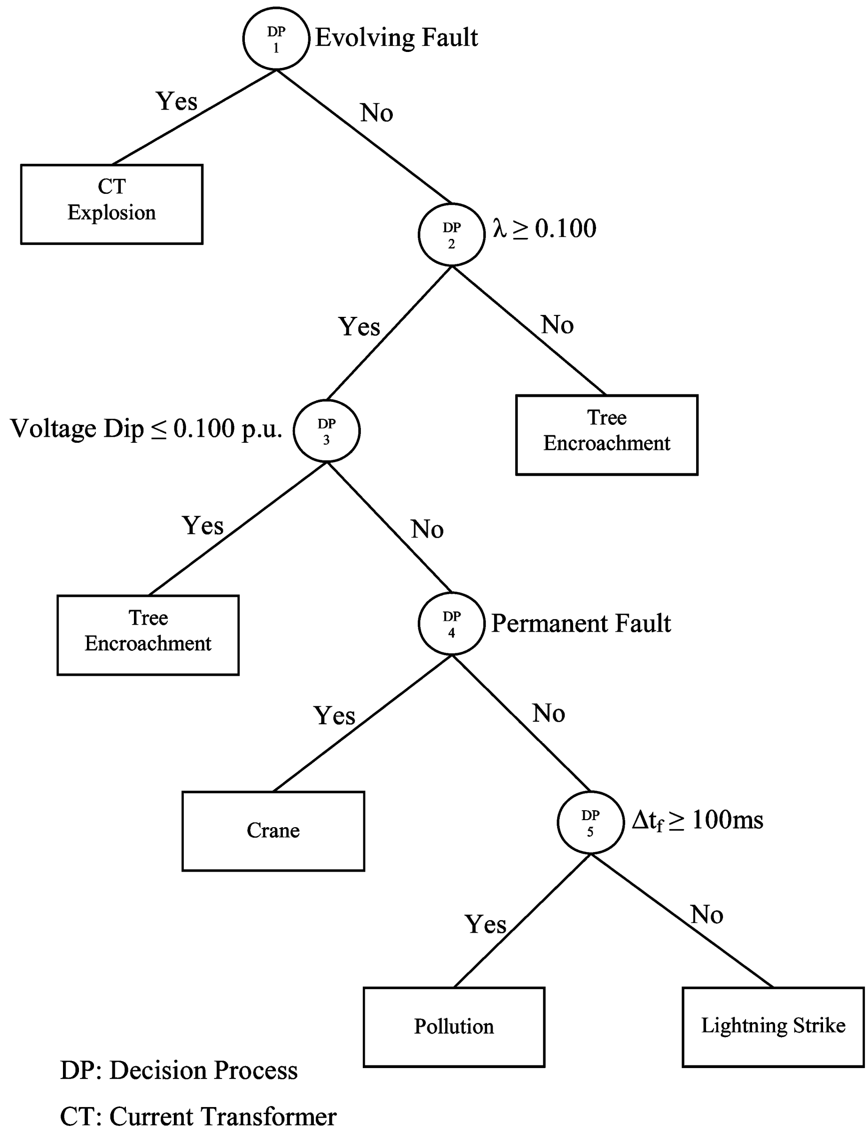

Fig. 12. Decision tree in the expert system (ES).

situation are heavily loaded line, high ambient temperature, and a tall tree. For the 275-kV line, the minimum safety clearance is 3.048 m between the bottom conductor and any object beneath the overhead line. A tree should not be allowed to grow more than 3.3528 m from the ground. When the line is heavily loaded, the conductor will sag and cause a flashover.

Since the conductor will gradually sag due to the above phenomenon, the fault current will also increase gradually until the line protection isolates the fault. The tree encroachment signatures are shown in Figs. 7 and 8. These signatures were captured by a DFR.

The same approach can be applied for a tree encroachment's signature as shown in Fig. 7 to be translated into rms in per-unit value. From the approach, it was discovered that the tree encroachment pattern is as shown in Fig. 9.

By applying (1) and (2), the extrapolation for a tree encroachment is shown in Fig. 10. From this example, it was found that the tree encroachment produced the value of $\lambda = 0.03$. However, the voltage dipped 0.037 p.u. The lower constant value and voltage dip were due to the gradual increase of the arcing current which slowly reduced the arc impedance. Unlike the lightning strike, the fault current increases very fast due to lower fault impedance.

C. Pattern Recognition

The main objective of pattern recognition is to reveal the tripping pattern into practical clusters which allows the user to discover the differences. This approach has been successfully implemented in the medical and security fields. However, in a power system, it is a new field to be discovered. By exploring the two parameters from before (λ and voltage dip), it is able to classify the tripping pattern due to lightning and tree encroachment. The five years of tripping data on overhead lines were tested and classified into clusters using this new approach. The causes of the trippings were made known to identify the characteristics. With more than 1000 overhead lines tripping data, it is possible to verify the flashover pattern. The result of the cluster analysis is shown in Fig. 11. After the pattern has been identified, a few

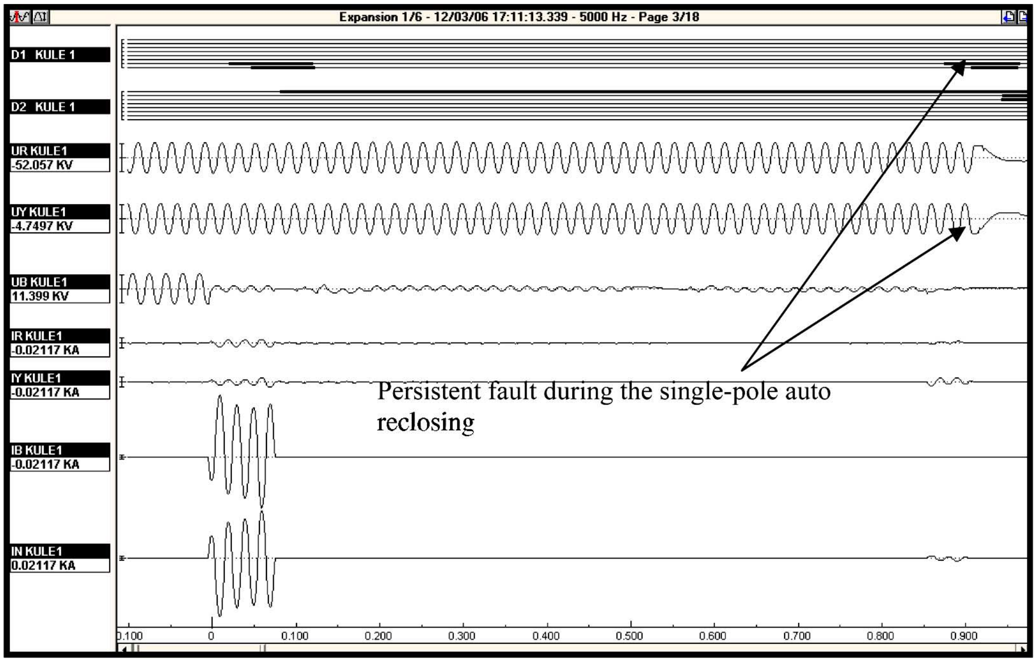

Fig. 13. Crane signature with the fault location 18.8% and 0.5-W primary loop impedance. It is a permanent fault.

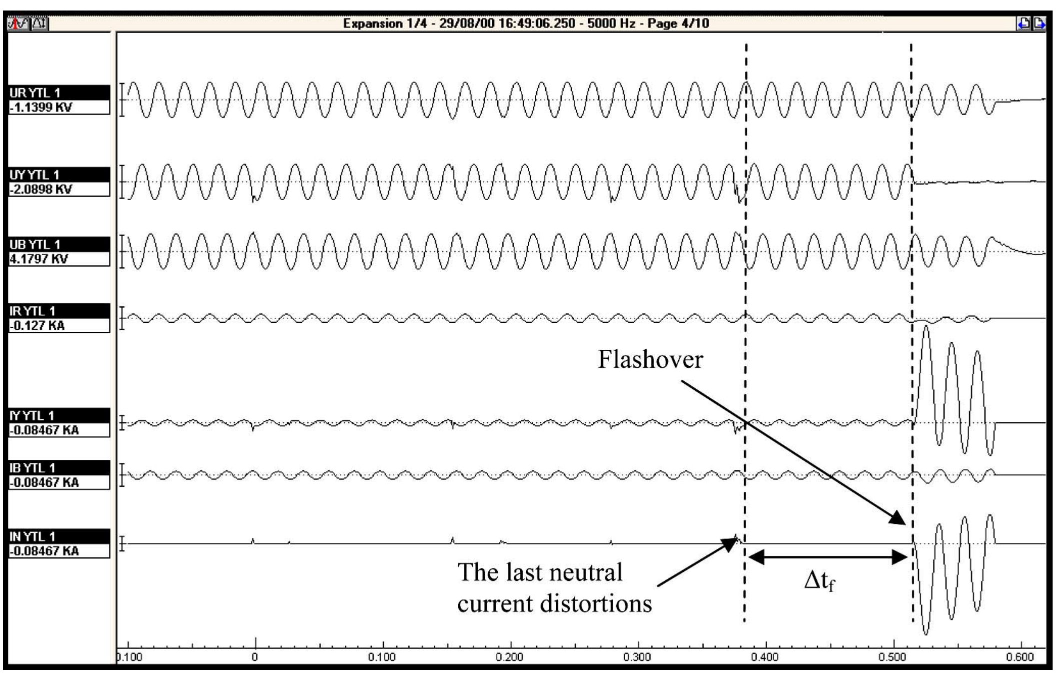

Fig. 14. Polluted insulator signature with the fault location 83.3% and 0.3-W primary loop impedance.

sets of the latest trippings, which were not given earlier, have been tested using pattern recognition. The actual causes of the trippings have been validated and confirmed by TNB. All of the trippings due to lightning and tree encroachment have been correctly identified using the new approach.

From the cluster analysis, it can be deduced that

1) a lightning strike in a cluster of
   a) $0.100 \leq \lambda \leq 0.200$ with voltage dips of more than 10%.
2) tree encroachment in a cluster of
   a) $0.050 < \lambda \leq 0.200$ with voltage dips of less than 10%;
   b) $0.010 \leq \lambda \leq 0.050$ with voltage dips ranging between 1% and 35%.

IV. Enhancement of Fault Signature Analysis

Further research on the tripping pattern has been conducted and it is found that with additional parameters (such as evolving and permanent fault phenomena; and Δt_f which is the time interval between the last neutral current distortions and a

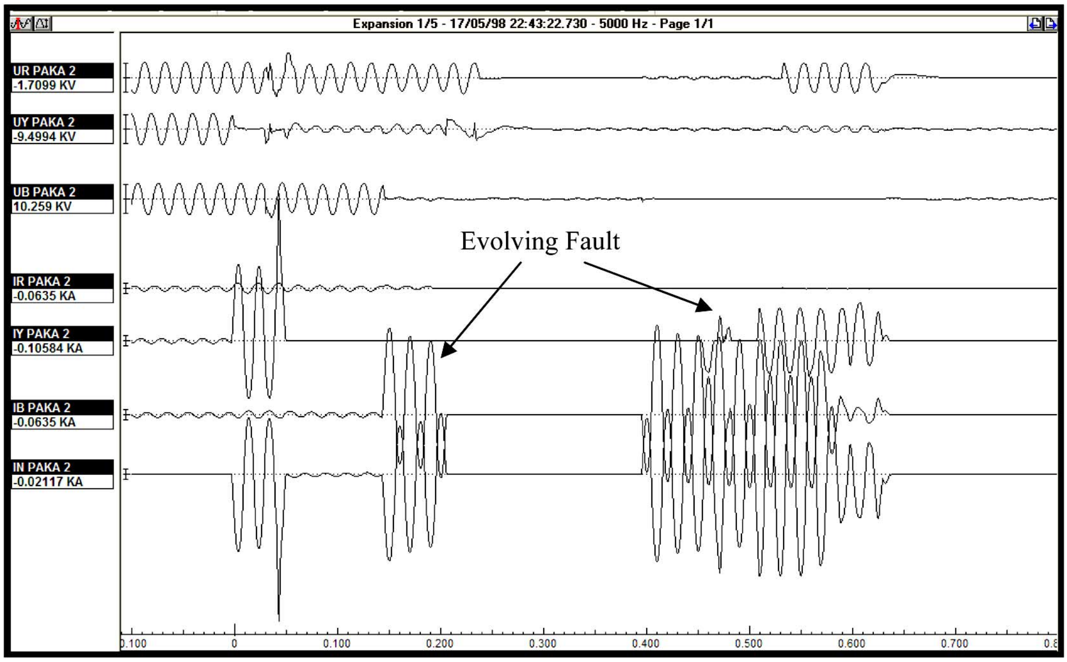

Fig. 15. Current-transformer explosion signature at the local substation with the fault location 0.0% and 0.3-W primary loop impedance.

flashover), more fault signatures can be revealed in a power system. An evolving fault is defined as a fault that occurs on another healthy phase after the clearance of the first-detected fault during the dead time of the first-detected fault [15]. To solve this problem, an expert system (ES) has been deployed to differentiate with the two flashovers which have been discussed earlier. Fig. 12 shows that a decision tree, which is utilized in the ES decision making processes. The recorded fault signatures due to a crane, polluted insulator, and current-transformer explosion are shown in Figs. 13–15.

V. Conclusion

The use of FSA in TNB is a new approach introduced through a research collaboration between TNB and the Universiti Teknologi Malaysia (UTM). The objective of this FSA is to equip the system operators with an appropriate tool to understand the fault initiation during decision making. Before the application of FSA, the decision making was based entirely on relay operations captured by the SCADA system [16], [17]. Moreover, the information from SCADA sometimes does not provide the system operators with meaningful information. Therefore, the system operators are subjected to many uncertainties and this could lead to an incorrect analysis. The consequences of this action could be detrimental to the system security which might lead to a cascading operation. The benefits of FSA have been proven in the efficiency during the decision-making process. After implementing the new FSA, the decision-making process has become much easier and faster without any doubt. As a result, TNB has reduced the operational cost for each tripping that occurs in the grid system.

Acknowledgment

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Mr. Abdul Karim received an award from the Malaysian Government which was presented by the H.M. the King for his contribution in analyzing the protection system during a power crisis which saved the country from a major blackout. He also received international recognition when his paper "Tenaga Nasional Berhad Experience on the Application of Fault and Disturbance Recorders" won the 1999 Best Paper Award at the Fault and Disturbance Analysis Conference in Atlanta, GA. He is currently a member of Board of Engineers Malaysia (BEM) and a Corporate Member of The Institution of Engineers Malaysia (IEM). He is also a registered Professional Engineer (P. Eng.) with Board of Engineers Malaysia, The ASEAN Federation of Engineering Organization, The Asia–Pacific Economic Cooperation, and The International Engineer Register.