International Journal on Advanced Science Engineering Information Technology

Vol.8 (2018) No. 5
ISSN: 2088-5334

Covered Conductor Burn-Down Phenomena in Indonesia without Protection Relay Operation

Putu Agus Aditya Pramana[#], Aristo Adi Kusuma[#], Nur Widi Priambodo[#], Buyung Sofiarto Munir[#]

[#] *Transmission and Distribution Research Department, PLN Research Institute, South Jakarta, 12760, Indonesia*
E-mail: putu.pramana@pln.co.id, aristo.kusuma@pln.co.id, nur.priambodo@pln.co.id, buyungsm@pln.co.id

***Abstract*— All Aluminium Alloy Conductor-Shielded (AAAC-S) which is covered conductor is widely used as the temporary solution to mitigate the earth fault problem during application of bare conductor in Indonesia distribution system. However, the burn-down phenomenon of AAAC-S is often found in some cases, and the protection schemes that have been installed on the distribution line is unable to detect any fault during the phenomenon. Due to no tripping order from protection relay, this phenomenon will lead some part of the conductor to remain hanging in the air and still in energized condition. This condition may cause a potential hazard to the surrounding environment. Therefore, this study was performed to determine the cause of AAAC-S burn-down, and the reason of protective equipment cannot work properly. Field investigation, modeling and simulation, and laboratory testing have been performed in this study to represent the condition in the field. The results show that the burn-down phenomenon of AAAC-S occurred due to many sequences of events. It started with insulation material breakdown that creates pinhole; then during overvoltage phenomenon, there will be an earth fault condition through the pinhole. Finally, if the short circuit energy at a specific mechanical tensile exceeds the critical energy of AAAC-S, then the burn-down phenomenon occurred. In this condition, the protection relay is unable to detect the fault due to the working time of protection relay is greater than the critical burn-down time of AAAC-S, where it is being influenced by the location of an earth fault, the cross-sectional area of AAAC-S, and grounding resistance of the pole.**

***Keywords*— AAAC-S; burn-down; protection relay; insulation breakdown; pinhole.**

I. Introduction

The covered conductor is a conductor that coated by insulating materials such as Cross-Linked Polyethylene (XLPE), High-Density Polyethylene (HDPE), and semiconductor. In Indonesia, covered conductor consisted of All Aluminium Alloy Conductor (AAAC) and shielded only by XLPE as the insulating material, which called as AAAC-S that intended to anticipate a temporary phase to ground fault. In order to preserve the electricity service to the customer, the protection relay is not expected to trip when the temporary fault occurred. However, there are many issues during utilization of covered conductor such as partial discharge problem, temperature aging, treeing, and burn-down conductor. Partial discharge phenomena of a covered conductor binding are given in [1] - [5]. Those papers provide an overview of partial discharge condition that occurred on a covered conductor, which potentially break the insulation capability of the XLPE. The temperature effects on XLPE aging are given in [6], [7], which showed that the temperature would reduce the lifetime of XLPE. The treeing process caused by the air cavities in XLPE is given in [8], [9], while the treeing caused by water seepage that enters the XLPE material are given in [10], [11]. The breakdown of XLPE material due to impulse voltage is given in [12], [13]. In addition to these issues, at some locations in Indonesia, it was found that the protection relay did not detect the burn-down of AAAC-S. The conductor burn-down without protection relay operation will cause the conductor to remain hanging in the air and still energized. This condition may cause a potential hazard to the surrounding environment. Therefore, to understand the phenomenon, this study examines the cause of the AAAC-S burn-down, the cause relay cannot detect the burn-down and a review of relay technology that has been developed to detect the covered conductor burn-down.

II. Material and Method

The research method that used in this paper consists of a literature study, field survey to find the real case data, laboratory testing, simulation, and analysis.

The literature study begins with a discussion of the electric field theory that associated with voltage stress on the conductors. It was performed to determine the effect of voltage stress on partial discharge that was experienced by AAAC-S. Furthermore, a literature study was conducted to determine the melting process of metal due to arcing. This information is used to determine the relationship between the cross-sectional area of the AAAC-S and its melting energy when AAAC-S experienced arcing during short circuit conditions. Also, a literature study was also conducted to determine the characteristics of the protection relay on the distribution system and the development of protection technology to detect High Impedance Fault (HIF).

Field data were collected to determine the AAAC-S physical condition after burn-down and the performance of protective equipment. These data were used as a basis for simulation and voltage stress testing, impulse voltage testing, short circuit current testing, and simulation of protection relay performance. Then, based on the literature study, field data, simulation results, and testing, analysis to determine the cause of the AAAC-S burn-down that cannot be detected by the relay protection were performed.

III. Results and Discussion

A. Field Survey

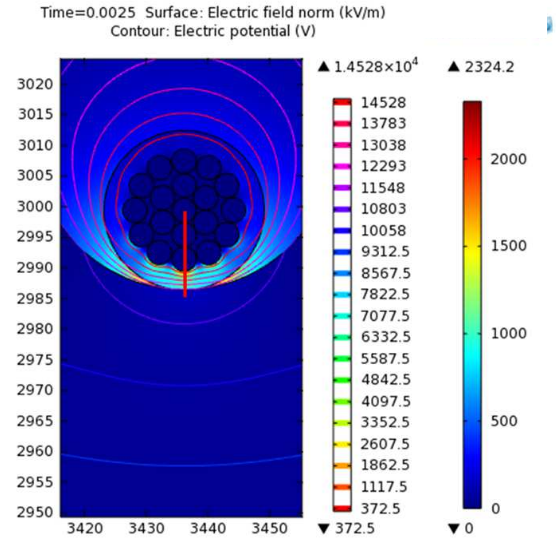
A survey in the distribution network that uses AAAC-S (size 70mm^2 to 240mm^2) has been performed to find out the further information of the AAAC-S burn-down cases. The survey results show that 34% of the distribution feeders have experienced the AAAC-S burn-down and more than 60% of the burn-down cases occurred near the isolators. The other 40% of burn-down cases happened in the middle of span caused by the trees that hit the AAAC-S. For the burn-down case near the isolator, the conditions is shown in Fig. 1, which shows a burning trace on the insulator and a neat cross-section cut of AAAC-S with a melting trace.

Fig. 1 AAAC-S burn-down and burning a trace on the isolator

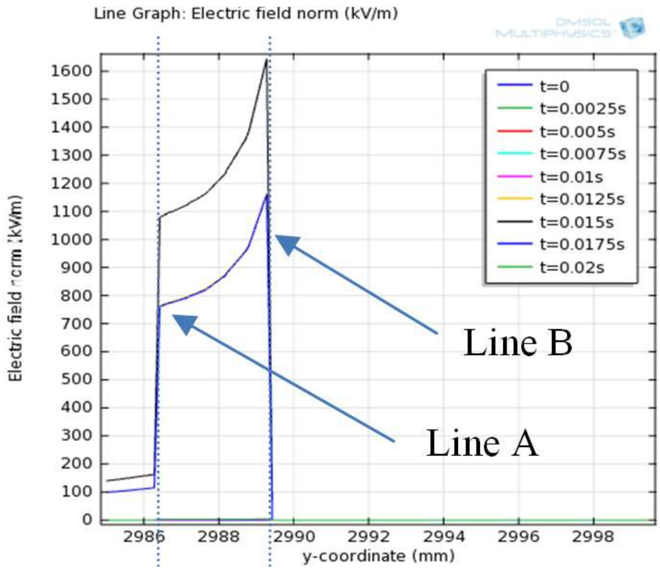
Based on the survey data that are given in Fig. 1, a presumption appears that the AAAC-S were broken due to the heating condition that exceeds the melting point of aluminum (about 600°C) that possibly occurred due to the arcing process on the AAAC-S. On the other hand, it was found that the protection relay does not work when the AAAC-S burn-down. To ensure the cause of the AAAC-S burn-down and undetected by the protection relay, the modeling and testing steps have been performed as given in the next section.

B. Voltage stress simulation and testing

The modeling process has been performed using finite element analysis software. The process was started by making a geometric model of an AAAC-S cross-section that located above the ceramic insulator as given in Fig. 2(a). In this condition, an operating voltage of 20kV$_{rms}$ addressed in the AAAC conductors. Then, the voltage value was varied according to the sinusoidal condition by taking a sampling time every 2.5ms during a full cycle. The simulation then continued by applying the governing equation, meshing, and post-processing of the result as given in Fig. 2(b). The vertical line in Fig. 2(a) represents the horizontal axis of Fig. 2(b). "Line A" is the boundary plane between XLPE and the isolator, while "Line B" represents the boundary plane between AAAC and XLPE.



(a)



(b)

Fig. 2 Voltage stress simulation of the cross-section area of AAAC-S

Fig. 2(b). Shows the voltage stress that occurs for each simulation time by using a sinusoidal voltage wave with a frequency of 50Hz and an amplitude of 16.329kV (representing a phase-neutral peak voltage value on a 20kV distribution network). Time t = 0 showed the voltage stress value when the voltage condition had a value of 0, time t = 0.0025s shows the voltage stress value when the voltage reaches the peak value, and so on for the other t values.

According to the Fig. 2(b), it can be seen that the maximum voltage stress value occurs on XLPE material especially at “Line B” (with a maximum value of 1600kV/m). Then, the voltage stress value reduced to reach a value of 1100kV/m at “Line A.” Based on the result of voltage stress value, the partial discharge will occur at “Line A” and “Line B” with the maximum partial discharge will occur at “Line B.” In addition to finite element simulation, a laboratory test was also performed to validate the appearance of partial discharges in AAAC-S. This test was performed by providing an AC voltage of 30kV/50Hz on the AAAC-S conductor and then recorded by the corona camera, which the result is given in Fig. 3.

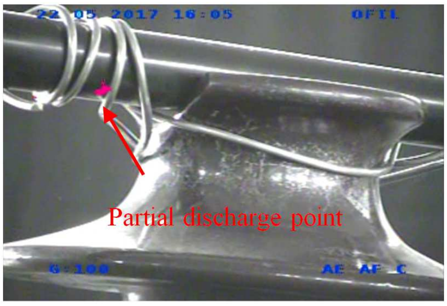


Fig. 3 Partial discharge appear on the lower side of AAAC-S

Fig. 3. shows that the partial discharges appear on the lower side of the AAAC-S (as given by the magenta color). These results indicate conformity to the simulation results that obtained in Fig. 2. Based on [1]-[5], the occurrence of partial discharges for long periods will lead the breakdown process of insulation material. Also, a breakdown in the insulating material may also occur due to friction between AAAC-S and its binding material when the AAAC-S swung because of mechanical force. This breakdown is marked by the appearance of the pinhole on AAAC-S. The pinhole is a small hole that occurs on the XLPE insulation that makes the AAAC conductor exposed directly into the air.

C. Voltage impulse testing

To understand the effect of pinhole when lightning struck AAAC-S, the voltage impulse test has been performed. The test scheme is given in Fig. 4. The pinhole that tested on this scheme is an artificial pinhole that obtained by an incision on XLPE material so that the AAAC material is exposed into the air. The artificial pinhole is used to speed up the testing process because the natural pinhole will be formed for an extended period.

Fig. 4 Voltage impulse testing

Based on the test results, when lightning impulses stroke the AAAC-S and the voltage that generated by the lightning impulse exceeded the basic insulation level (BIL) of the insulator, then an arc current will arise from the pinhole towards the grounding part of the insulator. It happened because the closest path that connects the conductor to the ground is only from the pinhole point to the insulator ground, while the XLPE material [5] isolates the other paths.

D. Short circuit current testing

When the arc current flow from the pinhole to the insulator grounding, it causes a phase to ground short-circuit condition. The magnitude of the short circuit current is equal to the short circuit current of the network. In this study, a short circuit current test was performed to determine the amount of energy required to break the AAAC-S. The short circuit test was performed by the testing scheme as given in Fig. 5.

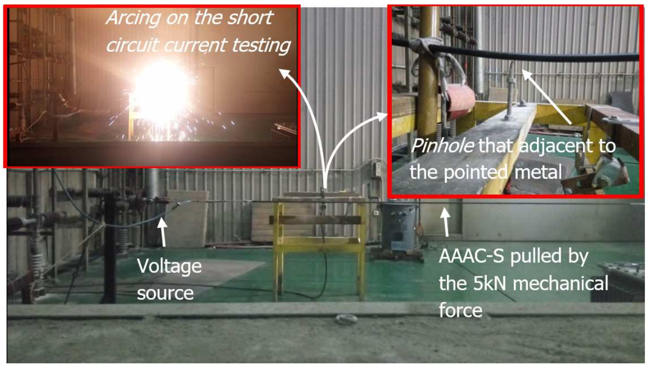


Fig. 5 Short circuit current testing

Fig. 5 explains that the mechanical force of 5kN pulls the conductor, and then the other endpoint of the conductor is connected to a voltage source. In the middle span of the conductor, an artificial pinhole placed adjacent to a pointed metal material. This fine metal material is connected to the ground, and it serves to trigger the occurrence of arc from the pinhole when the system voltage exceeded the breakdown voltage of the air (between the pinhole and the pointed metal). When the arc occurred, the current from the system will flow from the pinhole to the pointed metal and create a phase to a ground fault condition, with the voltage and current waveform as given in Fig. 6.

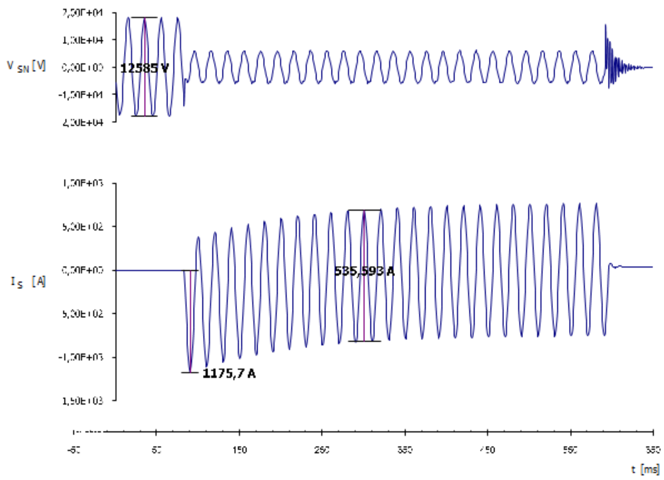


Fig. 6 Current and voltage waveform when short circuit testing

Fig. 6 shows that the short circuit current value is about 535A peak to peak and short-circuits voltage is about 2970Vrms, with the short circuit duration of 500ms. Besides the electrical parameters such as voltage and current, AAAC-S is also pulled by the mechanical tension of 5kN during the test. The tension value represents the real mechanical force that applied on the AAAC-S in the field, which is about 30% of the ultimate tensile strength owned by AAAC-S. In this case, the AAAC-S that used in the test is 70mm^2 with the ultimate tensile strength of 18kN. Measurement of AAAC-S tension during the test is carried out by a load cell.

During short circuit test, the result shows that AAAC-S is burn-down after two times short-circuit current injection. One short-circuits injection yields 0.56MJ of energy so that the accumulated energy supplied through the pinhole during two times short-circuits injections is about 1.13MJ. Thus, it can be found that the AAAC-S size of 70mm^2 will burn-down with the energy of 1.13MJ for the tensile force of 5kN. This energy is assumed as minimum energy that capable to break the 70mm^2 AAAC-S. This minimum energy is then called as critical energy, and it will be used as basic data to determine the critical duration required to break the AAAC-S. As the result of the burn-down on the short-circuit test, the cross-sectional shape of AAAC-S is given in Fig. 7.

Fig. 7 AAAC-S cross section after the short circuit test

To find the critical energy of the other cross section of AAAC-S, the equation given by [15] is used. It states that the energy required to melt the conductor is proportional to the cross section area of the conductor. Therefore, it can be determined that the critical energy for AAAC-S of 150mm^2 and 240mm^2 are 2.26MJ and 3.39MJ, respectively.

E. Performance of protection relay

In the real conditions, many AAAC-S conductors are burn-down and undetected by the protection relay. Based on the data obtained, it is known that the type of the protection relay that used in the field are Over Current Relay (OCR) and Ground Fault Relay (GFR). The Time Multiplier Setting (TMS) used for OCR relay is 0.15, and the current setting for pick up starting (Is) is equal to 480A. Meanwhile, the setting values of GFR are TMS = 0.3 and Is = 200A. The equation for determining the working time of the OCR / GFR relay is given in [14].

Based on field data, it is known that the specification of the transformer used to supply the distribution feeder is 150/20kV 60MVA. Also, it was found that the closest distance of AAAC-S burn-down case is about 0.25km from the transformer and the longest distance is about 19.35km. To observe the performance of the protection relay that used to handle the phase to ground fault condition, then some simulations were performed. The simulation purpose is to find the effect of short circuit location, grounding resistance of the pole, and the size of AAAC-S. The simulation was performed using the transient program analysis with a model as given in Fig. 8.

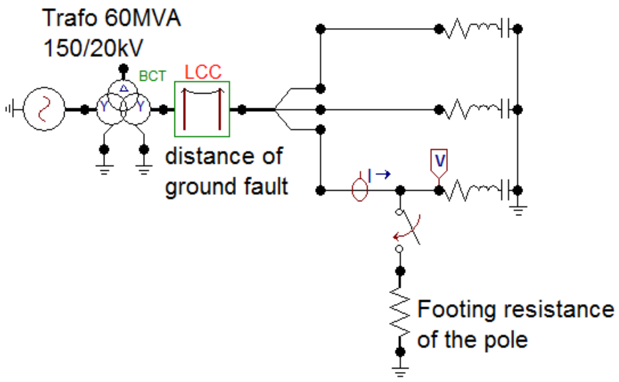


Fig. 8 Short circuit model

After the simulated ground fault current was obtained, then the relay working time is calculated according to the previously mentioned GFR setting (TMS = 0.3 and Is = 200A). Then, the critical time for AAAC-S to get burn-down was calculated by dividing the AAAC-S critical energy to the power occurring under the ground fault simulation. By using the calculation, the performance of protection relays can be obtained as shown in Fig. 9 to Fig. 12.

Fig. 9. shows the comparison of AAAC-S critical time and relay working time when the fault (short circuit via pinhole by lightning impulse) occurred 0.5km away from 150/20kV, 60MVA transformer. Under this condition, for each grounding resistance value, the relay will not be able to initiate the signal to trip the circuit breaker because the AAAC-S critical time is faster than the GFR working time. Therefore, AAAC-S will burn-down before the relay works.

Fig. 10. shows the comparison of AAAC-S critical time and relay working time when the fault (short circuit via pinhole by lightning impulse) occurred 2km away from 150/20kV, 60MVA transformer. In this condition, the relay can only send a tripping signal to the circuit breaker for the 240mm^2 AAAC-S with the ground resistance less than 0.1Ω, beyond that condition the relay will not work and AAAC-S will burn-down first.

Fig. 11. shows the comparison of AAAC-S critical time and relay working time when the fault (short circuit via pinhole by lightning impulse) occurred 5km away from 150/20kV, 60MVA transformer. In this condition, the relay can send a tripping signal to the circuit breaker for AAAC-S with the size of 240mm^2, 150mm^2, and 70mm^2 when the ground resistance is about 0.1Ω to the 0.5Ω, about 0.1Ω to the 0.3Ω, and less than 0.1Ω, respectively.

Fig. 12. shows the comparison of AAAC-S critical time and relay working time when the fault (short circuit via pinhole by lightning impulse) occurred 20km away from 150/20kV, 60MVA transformer. In this condition, the relay can send a tripping signal to the circuit breaker for AAAC-S with the size of 240mm^2, 150mm^2, and 70mm^2 when the

ground resistance is about 0.1Ω to the 5Ω, about 0.1Ω to the 3Ω, and less than 1Ω, respectively.

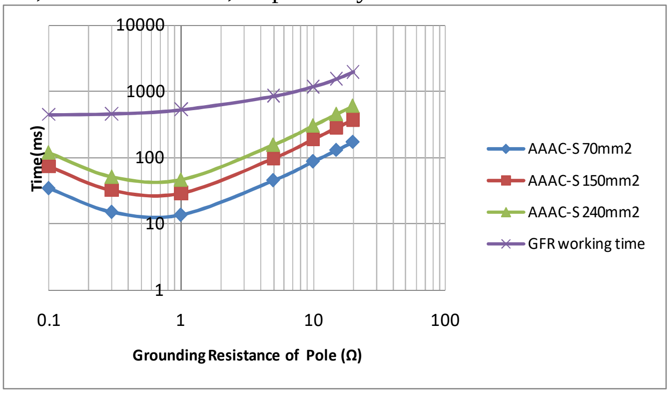


Fig. 9 The comparison of the critical time of AAAC-S and the working time of GFR when the fault distance s=0.5km

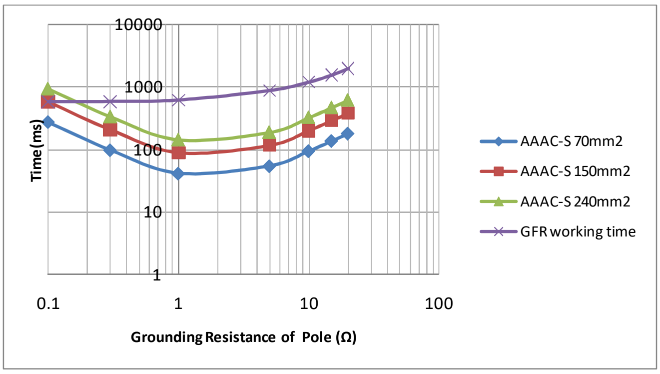


Fig. 10 The comparison of the critical time of AAAC-S and the working time of GFR when the fault distance s=2km

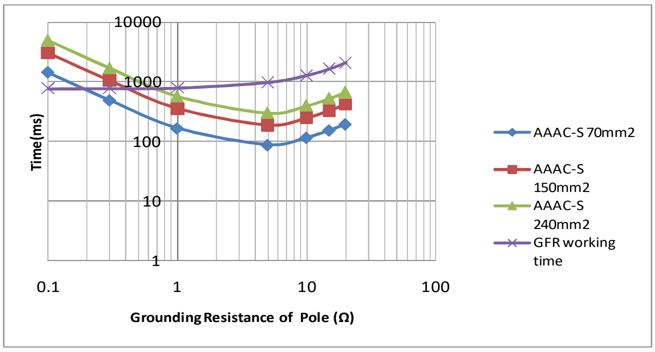


Fig. 11 The comparison of the critical time of AAAC-S and the working time of GFR when the fault distance s=5km

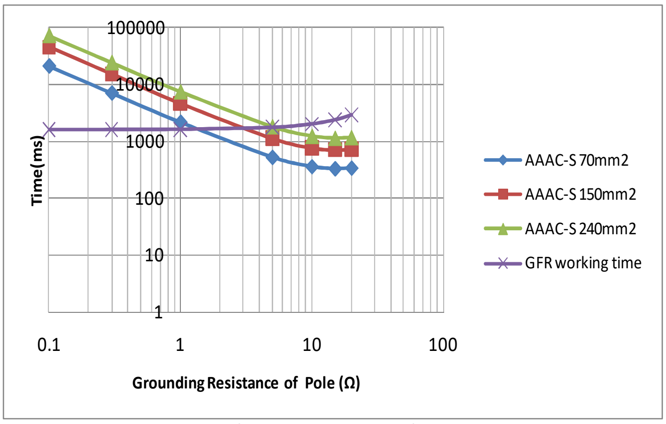


Fig. 12 The comparison of the critical time of AAAC-S and the working time of GFR when the fault distance s=20km

F. Discussion

By the result of voltage stress simulation and laboratory test, it can be found that the maximum voltage stress value occurs in the lower side of XLPE and it will initiate a pinhole. The pinhole is one kind of insulation breakdown, and it will be a path of phase to ground arcing. It happened when the lightning struck the AAAC-S, and the voltage that occurred exceeded the breakdown voltage of the air (between the pinhole and ground). These arcing will create a phase to ground short circuit condition.

Based on the results of the short circuit test, it can be seen that the energy required to burn AAAC-S at a specific mechanical tension value is called as critical energy. If the energy of the arcing that flowing from the pinhole to ground exceeds the value of the critical energy, then AAAC-S will experience heating, melting and breaking. This critical energy is the product of the multiplication of voltage, current and the duration of the short circuit condition.

By the simulation results, it can be found that the required short-circuit duration to burn the AAAC-S conductor varies with the magnitude of the grounding resistance of the pole where the short circuit occurs, the short-circuit distance to the source (transformer 150kV/20kV), and the AAAC-S cross-section area. If the short circuit close to the source, then the critical time to burn the AAAC-S will be shorter. Therefore, the GFR will not detect the fault, since the working time of the GFR is higher than the critical time of AAAC-S. Also, by the simulation results, it can be observed that the GFR is more comfortable to detect a ground fault for the bigger AAAC-S cross-section. Also, it found out that if the value of the grounding resistance is high, then the relay will be unable to detect the occurrence of the fault.

If AAAC-S is broken and dropped to the ground, it will cause a high impedance fault (HIF). Based on [19], the short circuit current value of HIF for some materials is given in TABLE 1.

TABLE I
TYPICAL SHORT CIRCUIT CURRENT ON THE VARIOUS MATERIALS

Surface	HIF current value (A)
Asphalt	0
Dry sand	0
Concrete without reinforcement	0
Wet Sand	15
Dry soil	20
Dry grass	25
Wet soil	40
Wet grass	50
Concrete with reinforcement	75

Table 1 shows that the short circuit current in the HIF condition has a minimal value, even it can reach zero when the AAAC-S touched the asphalt, sand and non-reinforced concrete. Based on these HIF data, the existing GFR that used in the field will face a problem to detect and clear the fault. Currently, there are two classification methods to detect HIF, which are a mechanical method and electrical method. The mechanical method uses the concept of converting the HIF into a low impedance fault by installing equipment that can capture the part of broken AAAC-S and connect it to ground. With the low impedance fault, it creates a high short-circuit current that enough to be detected by the existing GFR. Meanwhile, the electrical method utilizes current and voltage measurement values. Then, the waveforms of voltage and current are analyzed using a specific algorithm. These algorithms include sensitive earth fault method, artificial neural networks, fuzzy logic, and genetic algorithm. However, in order to achieve high success in detecting HIF, high costs are required for the investment of the original detection equipment and the installation of mechanical detection equipment at each feeder. Therefore, recently, the standard recommendation on HIF detection methods is still not available [14] - [19].

IV. CONCLUSION

The study of AAAC-S burn-down without protection relay operation has been performed. The results show that the AAAC-S burn-down consists of many sequences of events, started by the insulation material breakdown, which creates pinhole, overvoltage with arcing which caused a phase to ground fault through the pinhole, and finally short-circuit energy that exceeds the critical energy of AAAC-S in a specific mechanical tensile. In these conditions, the protection relay unable to detect the fault due to the working time of protection relay is greater than the critical burn-down time of AAAC-S that affected by the ground fault location, cross section size of AAAC-S, and grounding resistance of the pole. The further research would be conducted to find a method for reducing the partial discharge on XLPE that will avoid the pinhole formation.

REFERENCES

[1] Ronaldo E. de Souza, Rafael M. Gomes, Guilherme S. Lima, Fernando H. Silveira, Alberto De Conti, and Silvério Visacro, "Preliminary analysis of the impulse breakdown characteristics of XLPE-covered cables used in compact distribution lines" *International Conference on Lightning Protection*, Estoril, Portugal, 2016.

[2] K. Nakamura, P.J. McKenny, and M.S.A.A. Hammam, G. Adams, R. Fernandes, and F. Rushden, "Impulse Breakdown Characteristics Of 13.2kV Covered Conductor Insulator/Tie Configurations", *IEEE Transactions on Power Delivery*, Vol. PWRD-1, No. 4, October 1986.

[3] Narong Mungkung, Tanes Tanitteerapan, Werachai Chaokumnerd, Karun Morasilp, Panumat Limsuwan, Warawut Poolperm and Toshifumi Yuji, "Problem Solving of Partial Discharge on The Distribution Line," *WSEAS Transactions on Power Systems*, Issue 1, Volume 4, January 2009.

[4] George Eduful, Member, IAENG and Kivlyn N. Asante, "In Search of Electric Power Reliability in Forested Terrain with Covered Conductors: The ECG Experience," *Proceedings of the World Congress on Engineering and Computer Science 2012 Vol II WCECS 2012,* San Francisco, USA, October 24-26, 2012.

[5] Shigeru Yokoyama, Tomoyuki Sato, Sekioka Shozo, dan Yosuke Hashimoto, "Lightning Performance of Insulated Wires on Overhead Power Distribution Lines," *30th International Conference on Lightning Protection – ICLP*, Cagliari, Italy - September 13th -17th, 2010.

[6] S. R. Krishnamurthy and P Selvan, "Use of AAAC in a Distribution Network – A Strategy For Energy and Cost Reduction," *POWER ENGINEERING JOURNAL*, June 1995.

[7] Ya Wang, Zepeng LV, Xia Wang, Kai Wu, Chong Zhang, Wenpeng Li, and L. A. Dissado, "Estimating the Inverse Power Law Aging Exponent for The DC Ageing of XLPE and Its Nanocomposites at Different Temperatures", *IEEE Transaction on Dielectrics and Electrical Insulation*, Vol. 23, No.6, December 2016.

[8] Siti Norasmah Mohtar, Md Noah Jamal, and Marizan Sulaiman, "Analysis of All Aluminum Conductor (AAC) and All Aluminum Alloy Conductor (AAAC)," *IEEE Region 10 Conference*, Chiang Mai, 2004.

[9] Junxiang Zeng, Jiancheng Song, Zhipeng Lei, Yanwen Li, Muqin Tian, Lingyan Lin, "The Effects of Cavity on the Growth of Electrical Trees in XLPE," *IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, Chengdu, 2016.

[10] M. Hao, A. Fazal, G. Chen, A. S. Vaughan, dan J. Cao, H. Wang, "The Impacts of The Temperature and Electric Field on The Electrical Characteristics in Semicon-Bonded XLPE Insulation," *IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, Chengdu, 2016.

[11] Wenbiao Tao, Zhenguo Ma, Wenquan Wang, Jie Liu, Kai Zhou, Tianhua Li, dan Ming Huang, "The Mechanism of Water-Tree Growth in XLPE Cables based on the Finite Element Method," *IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, Chengdu, 2016.

[12] Wenbiao Tao, Shuyong Song, Yue Zhang, Wei Hao, Kai Zhou, Tianhua Li, dan Ming Huang, "Study on the Electric-field Characteristics of Water Tree Region on the Dry or Wet Condition in XLPE Cables," *IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, Chengdu, 2016.

[13] Roberto J. Cabral, Daniel S. Gazzana, Roberto C. Leborgne, Arturo S. Bretas, Guilherme A. D. Dias, Marcos Tello, "Improvement of an Overhead Distribution Feeder Performance Against Lightning Considering the Wire-Guard Protection," *International Conference on Lightning Protection (ICLP)*, Vienna, Austria, 2012.

[14] *Network Protection & Automation Guide: Protective Reles, Measurement, and Control*, Alstom.

[15] A. A. Ostsemin, "Melting Rate of Electrode Wire in Arc Welding," *Russian Engineering Research*, 2010, Vol. 30, No. 7, pp. 677–679. Allerton Press, Inc., 2010.

[16] Eloi Junior Rufato dan Carlos C.B. De Oliveira, "Short Circuit Tests for Detection of High Impedance Faults," *18th International Conference on Electricity Distribution*, Turin, 6-9 June 2005.

[17] Amin Ghaderia, Herbert L. Ginn III, Hossein Ali Mohammadpour, "High impedance fault detection: A review," *Electric Power Systems Research 143*, 376–388, 2017.

[18] B. Michael Aucoin dan Robert H. Jones, "High Impedance Fault Detection Implementation Issues," *IEEE Transactions on Power Delivery*, Vol. 11, No. 1, January 1996.

[19] Mohd Syukri Ali, Ab Halim Abu Bakar, Hazlie Mokhlis, Hamzah Arof, dan Hazlee Azil Illias, "High-Impedance Fault Location Using Matching Technique and Wavelet Transform for Underground Cable Distribution Network," *IEEJ Transactions on Electrical and Electronic Engineering, IEEJ Trans*; 9: 176–182, 2014.