High Impedance Ground Fault Detection Utilizing Communication Network Infrastructure

Mubarak Suliman
Distribution Protection Engineering Department, DPED
Saudi Electricity Company, SEC
Riyadh, KSA
MHSulaiman2@se.com.sa

Sarfaraz Musa Shaikh
Digital Solution Center-ELDS
ABB Industries LLC
Dubai , UAE
sarfaraz.shaikh@ae.abb.com

Zulfiqar A. Qureshi
Distribution Protection Engineering
Department, DPED
Saudi Electricity Company, SEC
Riyadh, KSA
ZAQureshi@se.com.sa

Ahmed Anwar
Digital Solution Center-ELDS
ABB Industries LLC
Dubai , UAE
ahmed.anwar@ae.abb.com

Ashraf K. Al-Maslamani
Distribution Protection Engineering
Department, DPED
Saudi Electricity Company, SEC
Riyadh, KSA
AKMaslamani@se.com.sa

***Abstract*— Detection of live downed conductors occurring with high fault resistance/impedance (reaching kilo-ohms) is always a challenge especially in countries like Saudi Arabia where ground resistivity is very high in general (reaching more than 1000 Ω-meter). Such faults continue to cause damage until the fault is reported and isolated manually from control center or the source substation.**

SEC Distribution Protection Engineering Department and ABB has partnered to develop a new cost-effective solution for HIF resulting from downed conductors by utilizing simple & effective technology that is suitable for large scale deployment.

The method used to detect High Impedance Faults in the MV Distribution Network is based on Three (3) phase voltage & unbalance voltage measurements at the LV side of distribution transformers (13.8/0.4kV (or) 33/0.4kV) connected at the branch end of the feeder and communicate the condition as an alarm to the Control Room with minimal delay for taking immediate preventive action.

The project has proven successful in detecting of open conductors and all types of live down conductor faults in medium voltage network, hence this solution will go a long way in protecting life and property from such incidents. Moreover, the solution is a building block towards a total smart grid on which the network is monitored, controlled, and operated remotely with a possibility to introduce automation.

Keywords*— *Ground Faults, Earth faults, distribution network, overhead lines, broken conductor, HIF/HIZ: High Impedance Faults, GSM: Global system for mobile communications

I. Introduction

Electric grids have posed many challenges since the inception in the late 19th century. The grids had to expand to reach its ever-increasing consumers situated in different geographical locations. Scientists and engineers have since worked relentlessly to develop protection solutions to safeguard the equipment and personals involved in the electric grid. With the technology on their side most of the protection and distribution challenges have been subdued by the grid engineers. However, one such untamed challenge remains viz. the detection of live downed conductors in high resistance ground environment.

When a live overhead power line fall on ground with high resistivity (like dry sand) they generate High impedance faults (HIFs). Such faults are a major public concern because the fault currents are generally too low for detection by protection relays at the feeding level (substation level).

Although many solutions have been introduced and tried, the problem seems to remain unresolved due to the different geographical topologies involved.

In the distribution network of the Middle-East region specially, HIF fault due to broken power system conductor is very hard to detect due to high value of soil resistivity. This type of faults remains undetected and remains a huge threat to human and animal lives of the region. There have been many reports of loss of animal & human life due to broken power conductor faults.

ABB with SEC has jointly worked on the pilot project on downed conductor detection by measurements at the LV side of the protection line and communicating the data to the central control center over mobile network and the results have been found satisfactory and encouraging.

The designed solution is also suitable for large scale implementation and with few alterations can also be implemented as Self Isolating and Healing network solution.

Even though this technique requires investment in additional equipment, it is justifiable as it aims to protect against faults that have potential to damage life and property yet remain undetectable.

II. High Impedance Fault and Traditional Detection Techniques

High Impedance Fault is a condition where a power system conductor (broken or unbroken) creates an unwanted electrical contact with a surface exhibiting a high impedance path to the substation source

HIF on distribution network is difficult to detect at the substation level due to various factors such as Unbalance Loads (Single phase loads) and multi path returns of unbalanced currents. As the distribution networks has huge number of single phases connected loads the distribution network can have very high unbalanced currents especially when a single-phase branch is out of service. Additionally, the transformer inrush & sudden picks in loads must be also considered while setting the conventional ground overcurrent protection devices. Thus, current based protection relays working on the basic principle of current threshold breach are ineffective in detecting HIF faults. The characteristics of HIF and LIF faults are depicted in Fig 2.

The below are few characteristics of the HIF faults [2].

Low-level currents (high impedance)

Discontinuous fault current flow (arcing)

HIF arcing patterns consistent in their inconsistency

Exhibits random

behavior Unstable

Wide fluctuations in current and harmonic levels

Low risk of power system equipment damage

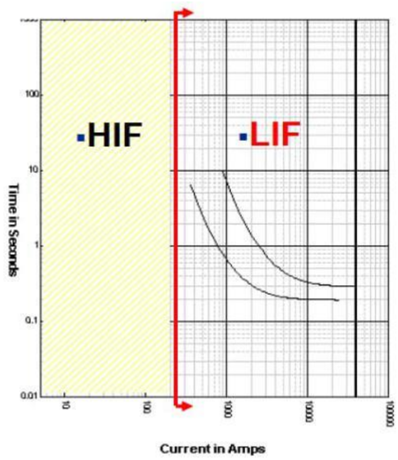

Fig. 1. HIF & LIF current ranges & Characteristics [5]

A. SEC Efforts in Detection of High Impedance Faults

Since the downed conductors pose serious safety concerns, SEC Distribution Protection Engineering Department has made rigorous efforts and coordination for reliable & secure solutions to detect & isolate HIF faults in distribution network.

Based on the manufacturers / companies response, probable HIF solutions were analyzed along with the implementation of certain pilot projects as under:

1) Solution from major protection relays manufacturers i.e. GE, SEL, ABB, Siemens.

2) Solution from smart sensor manufacturers i.e. SEL, ABB, Kries, Schneider Electric.

3) Mechanical solutions implemented internationally i.e. fault through switch, guard wire mesh.

4) Solution from primary equipment manufacturers like study moving towards arc suppression coil grounding.

5) Solution from international research organizations i.e. EPRI.

6) Communication based solution utilizing distribution transformer L.V. measurement.

B. HIF/HIZ & ABB

ABB has long studied HIF/HIZ faults and has dedicated HIZ functional block in its protection relays since 2005. ABB has developed innovative technology for high-impedance fault detection (PHIZ) with over ten years of research resulting in many successful field tests. It is a patented technology (US Patent 7,069,116 B2 June 27, 2006, US Patent 7,085,659 B2 August 1, 2006) to detect a high-impedance fault.

C. ABB HIF/HIZ protection Block Basic Operation Principle (PHIZ)

PHIZ uses a multi-algorithm approach. Each algorithm uses various features of earth currents to detect a high-impedance fault.

Although the PHIZ algorithm is very sophisticated, the setting required to operate the function is simple. The Security Level setting, with the setting range of 1 to 10, is set to strike a balance between the extremes of security and dependability which together constitute the reliability of any system. The setting value “10” is more secure than “1”” [2, p. 811]. Fig 2 shows an electrical power system equipped with PHIZ.

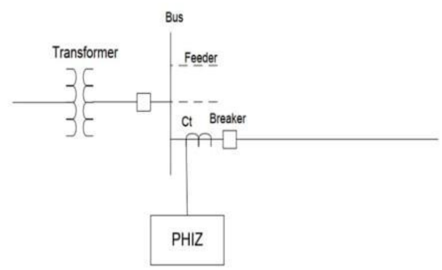

Fig. 2. Electrical power system equipped with PHIZ [2]

Power system signals are acquired, filtered, and then processed by individual high-impedance fault detection algorithm. The results of these individual algorithms are further processed by a decision logic to provide the detection decision. The decision logic can be modified depending on the application requirement. [2, p. 812]. Fig 3 depicts the block diagram of PHIZ.

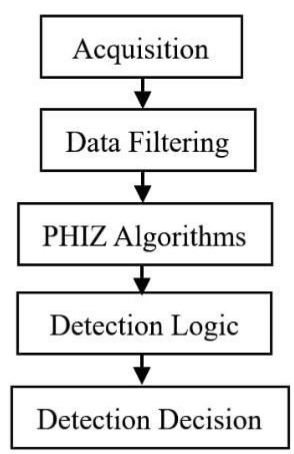

Fig. 3. Block diagram of PHIZ [1], [2]

PHIZ is based on algorithms that use earth current signatures which are considered non-stationary, temporally volatile and of various burst duration. All harmonic and non-harmonic components within the available data window can play a vital role in the high-impedance fault detection. A major challenge is to develop a data model that acknowledges that high-impedance faults could take place at any time within the observation window of the signal and could be delayed randomly and attenuated substantially. The model is motivated by extensive research, actual experimental observations in the laboratory, field testing and what traditionally represents an accurate depiction of a non-stationary signal with a time-dependent spectrum [2, p. 812].

ABB has done HIF tests with our protection relays in multiple locations affording great variety of performance evaluation, in a variety of

- Geographies
  - Geologies – mineral-deficient soils to mineral-rich soils
- Topologies – plains to mountains
  - Distribution voltages: 4 – 26 kV systems
  - Feeder circuit design, measuring CTs
- System grounding
  - Surfaces: Concrete (reinforced), sand, gravel, asphalt, grass, trees

Fig. 4, 5, 6 and 7 are the few pictures of the test results.

Fig. 4. PHIZ test on gravel [2], [3]

Fig 5: PHIZ test on Concrete [2]

Fig 6: PHIZ test on sand [2]

Fig 7: PHIZ test on grass [2]

D. *Conclusions of Historical Research*

It has been observed that, no two HIZ faults are alike, i.e., their ‘signatures’ are inconsistent hence, the fault detections are possible though some false detections may be experienced. The detection rate varies by the ground conditions and geography. Fig 8 depicts the PHIZ detection levels for different ground conditions.

HIZ detection are best applied in a protection scheme as an alarming element adding information to these dispatchers' already receiving calls on outages. They cannot be fully relied upon for detection.

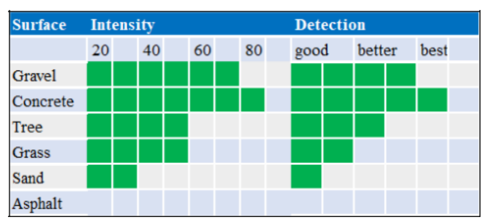

Fig. 8. PHIZ test on different geographical conditions [5]

To further improve the detection rate, monitoring feeder’s HIZ detections over several months will inform Protection Engineer on its reliability and offer slight setting adjustments to improve results. Staging HIZ events, studying HIZ detections and progressing the utilization of the HIZ detection will prove valuable when applying HIZ detection to your distribution feeder’s protection and control scheme.

Hence, we can surmise that high impedance earth fault detection algorithms are not able to conclusively detect all the faults and are especially weak when earth resistance is extremely high as is the case in the Gulf region.

III. HIF Fault detection via ABB "HIZ Grid Automation Solution"

A. System Architecture

The proposed concept for detection of downed conductor is based on installation of Measurement & Communication module at the end of each branch of distribution feeder to detect unbalanced / abnormal voltages (i.e., occurring due downed / open conductor) and communicate the condition to the control center through GSM Modems installed in HIZ Grid Automation (HIZ-GA) cabinets.

The solution is briefly described in the below diagram shown in Fig 9.

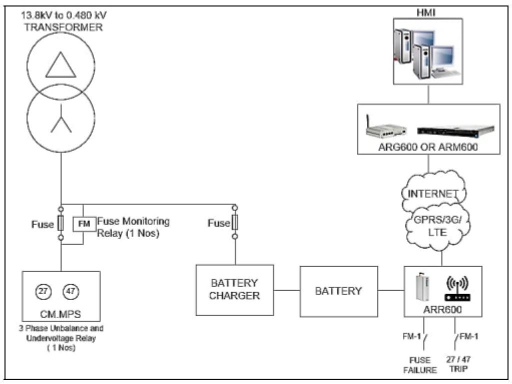

Fig. 9. Block diagram of downed conductor detection via measurements at LV side

The Project is based on the principle that a Downed Conductor in the HV Side have two (2) possible scenarios:

1) Under-Voltage in one of the phase: If one (1) of the phases is downed in the primary of the transformer, there might be undervoltage observed in the secondary as well. The voltage dip is related to the phase lost & the load at the transformer. the protection relay can be set for the undervoltage threshold value with the tripping delay.

2) Phase Unbalance: In case of a large transformer running on No/Low Load, undervoltage might not occur. In such scenario it is important that, the relay measure the phase angles and generates a fault signal for phase unbalance. The protection relay detects phase unbalance, phase sequence & phase loss by measuring the phase angles.

Additionally, voltage measurements on the secondary side of the transformers are measured and transmitted to the control center along with the Unbalance/Under Voltage Signals via GSM modems.

The system components are 3 Phase Undervoltage/Unbalance relay, Battery Charge, Battery, ABB industrial gateway and SIM Card for cellular communication with the control center.

B. Methodology in Selecting Nodes to install this solution

1) Two 33kV feeders (i.e. RM11 & RM13) from 8505 SS in Rimah are selected for the Implementation of the Pilot Project.

2) RM11 & RM13 are selected based on the List of Worst Performing Feeders.

3) (3) Feeder Monitoring Panels installed in branch ends of each feeder @ Distribution Transformer L.V. side.

4) Longest Locations are selected to increase Downed Conductor Coverage.

5) Actual Faults have been simulated by Opening One Fuse Link & Phase Unbalance has been successfully received @ the Control Center.

Fig. 10, 11 and 12 depict the step wise installing of the Feeder monitoring panel at the LV side of distribution transformer.

Fig. 10. Installing of feeder monitoring panel

Fig. 11. Feeder Monitoring Panel installed @ the L.V. side of Distribution Transformer

Fig. 12. Feeder Monitoring Panel

C. Simulation and Modelling

The solution was simulated in ABB laboratory with different scenarios as explained below. The details of the Transformer simulated as described in the Table 1.

TABLE I. TRANSFORMER DETAILS AS SIMULATED

Transformer Core Construction	Three Limb
MVA	100 MVA
Primary Voltage (Line to Line)	13.8kV
Secondary Voltage (Line to Line)	0.44kV
Frequency	50 Hz
Winding #1 Type	Delta
Winding #2 Type	Star
Delta Lags or Leads	Leads
Leakage Resistance	0.1[pu]
No Load Loss	0.0[pu]
Copper Loss	0.0[pu]
Model Saturation	No
Tap Changer Winding	None

Transducer is connected phase to phase. Relay is connected phase to earth. Simulations performed for both phases to phase and phase to neutral measurement.

a) Case 1: Healthy, full load

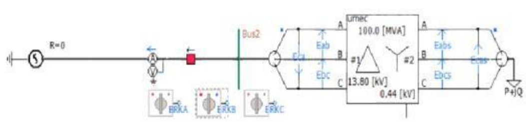

Fig. 13. Simulated Network

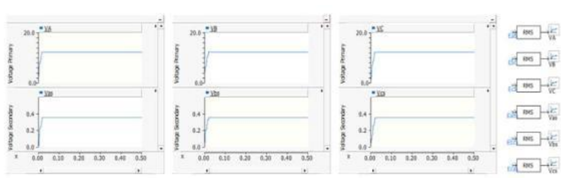

Fig. 14. Healthy, full load

b) Case 2: Phase A breaker open, full load

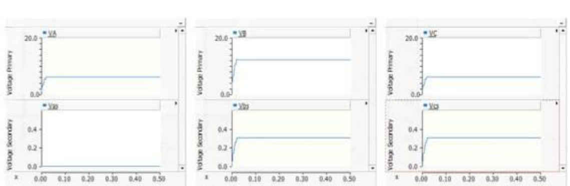

Fig. 15. Phase A breaker open, full load

c) Case 3: Phase A breaker open, half load

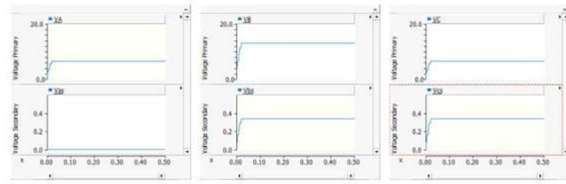

Fig. 16. Phase A breaker open, full load

d) Case 4: Phase A breaker open, no load

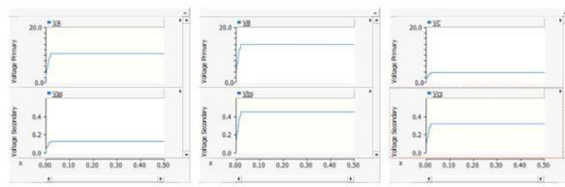

Fig. 17. Phase A breaker open, no load

e) Case 5: Phase B breaker open, full load

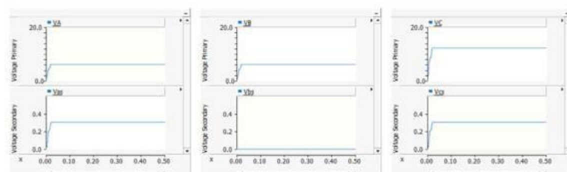

Fig. 18. Phase B breaker open, full load

f) Case 6: Phase B breaker open, half load

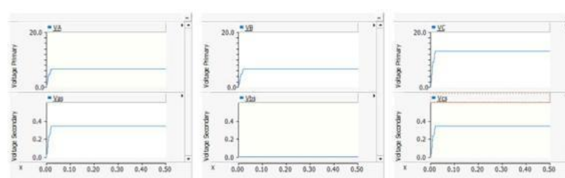

Fig. 19. Phase B breaker open, half load

g) Case 7: Phase B breaker open, no load

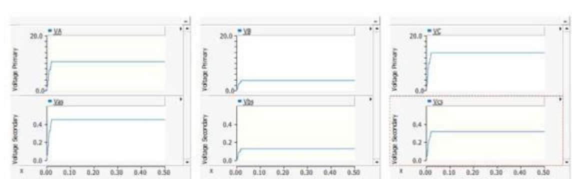

Fig. 20. Phase B breaker open, no load

h) Case 8: Phase C breaker open, full load

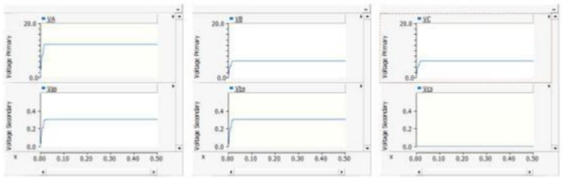

Fig. 21. Phase C breaker open, full load

i) Case 9: Phase C breaker open, half load

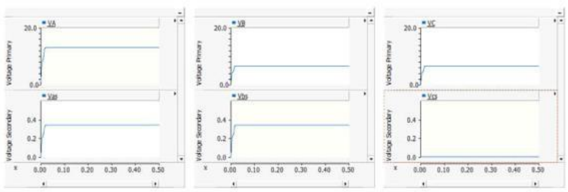

Fig. 22. Phase C breaker open, half load

j) Case 10: Phase C breaker open, no load

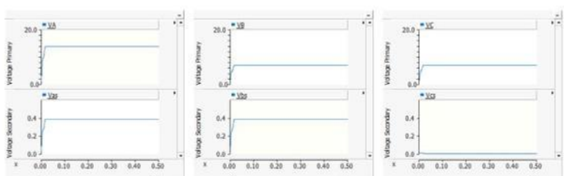

Fig. 23. Phase C breaker open, no load

As shown above the transformer primary Phase A was opened with different load conditions viz Full load, 50% load and No load and the secondary side voltage on all the three phases were recorded. The other phases were also tested similarly however not described in detail for simplicity.

D. Test Observations

1) It was observed that with primary side open the transformer secondary voltage dropped relatively with the load conditions effecting the voltage measured at the secondary

2) It was observed that if Phase A breaker was opened in full load & 50% load condition, the Transformer primary voltage VA(Prim) and VC(Prim) voltage dropped to approximately 0.6kV.

3) The same effect was observed at the secondary and the secondary voltage VA(S) recorded 0 Volts. The other two phases VB(S) & VC(S) showed no drop in the voltage readings.

4) If Phase A breaker was opened in no load condition the transformer primary voltage VA(Prim)dropped to approximately 0.6kV.

5) The same effect was observed at the secondary and the secondary voltage VA(S) recorded approximately 0.18kV. The other two phases VB(S) & VC(S) showed some voltage fluctuations.

E. Conclusions

It can hence be concluded from simulation and from actual test at site that this detection principle has a high success rate in a multitude of scenarios. This coupled with the ability to relay this information to central control system as described in following sections will lead to quick reaction from the utility to clear such faults.

IV. Communication System

Communication is an integral part of the solution. The detections made on the remote field locations are required to be transmitted reliably and promptly to operators in the control center who can take necessary actions based on the criticality of the feeders and dispatch maintenance teams to site.

Hence, it is imperative that the communication system is based on technology that is reliable, fast, futureproof and at the same time be economical from both CAPEX and OPEX perspective.

We chose to go with GSM technology. Mobile network penetration is close to a 100% in Saudi Arabia with reliable wireless data communication. No additional CAPEX is required and operational costs are minimal considering that our data requirements are not high for this solution.

A. Architecture

Fig 24 below shows the communication architecture for the overall solution.

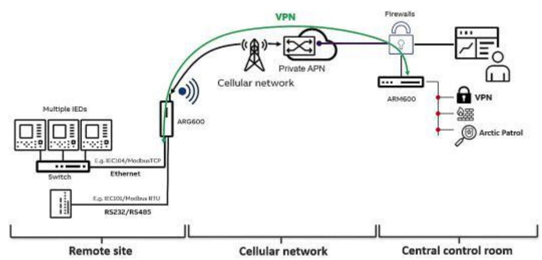

Fig. 24. Communication Architecture [6]

B. Cyber Security

ABB is involved in the standardization and definition of several cybersecurity standards, the most applicable and referred ones are ISO 2700x, IEC 62443, IEEE P1686 and IEC 62351. Besides standardization efforts there are also several governments initiated requirements and practices like NERC CIP and BDEW. ABB fully understands the importance of cyber security for substation automation systems and is committed to support users in efforts to achieve or maintain compliance to these [7, p. 8].

The solution provides a secure and reliable communication solution with support for secure VPN communication, static IP routing, an intelligent self-testing system, NAT, port forwarding and a firewall for monitoring IP traffic and blocking unwanted connections [4, p. 9].

V. Field Installation and Results from the Pilot

A. *Pilot Project Implementation - Downed Conductors Coverage in 33kV Feeder RM11:*

1) Total Feeder Length with Branches = 18 km

2) No. of Feeder Monitoring Panels = 3 Panels

3) Feeder Monitoring Panel Downed Conductors Coverage = 13km

4) Locations of the Feeder Monitoring Panels as shown in Fig 25 below:

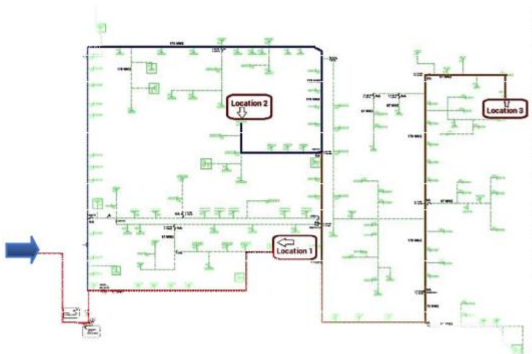

Fig. 25. Locations of Feeder Monitoring Panels

Percentage Covered Out of Total Length = 72%

B. *Pilot Project Implementation - Downed Conductors Coverage in 33kV Feeder RM13:*

1) Total Feeder Length with Branches = 60 km

2) No. of Feeder Monitoring Panels = 3 Panels

3) Feeder Monitoring Panel Downed Conductors Coverage = 57km

4) Locations of the Feeder Monitoring Panels as shown in Fig 26 below:

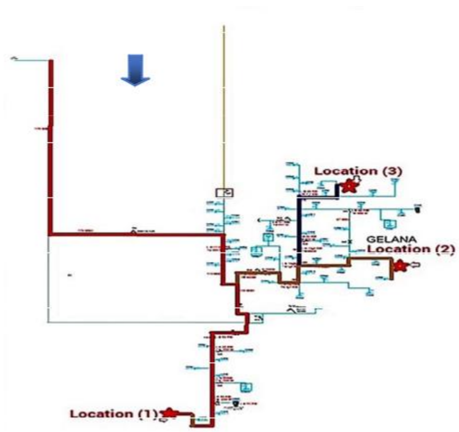

Fig. 26. Locations of Feeder monitoring Panels

Percentage Covered Out of Total Length = 95%

C. *Protection Functions and I/Os*

1) Protection Functions available in L.V. Relay installed in Feeder Monitoring Panel are as listed in Table II below:

TABLE II. Protection Functions

Function	Setting
Overvoltage U>	Disabled
Undervoltage U<	80% of Nominal Voltage
Phase Unbalance >	20% of Nominal Voltage
Phase Rotation	Built-in
Time Setting	5 seconds

2) (5) Binary Signals: (1) Signal Indicating Unbalanced Conditions & (4) Signals for Panel Monitoring (depicted in Fig 27.)

Description	Point type	State
Battery Ready	telemetered	NORMAL
Buffering	telemetered	NORMAL
Fuse Failure	telemetered	NORMAL
Replace Battery	telemetered	NORMAL
Unbalance Undervoltage	telemetered	NORMAL

Fig. 27. Binary Signals

3) Analog signals for L.V. Measurement

The same are depicted in Fig 28 shown below.

Name	Description			
RM11_1_V1-VOLTRMS	Phase Voltage (L1-L2)	telemetered	NORMAL	223.90
RM11_1_V2-VOLTRMS	Phase Voltage (L1-L3)	telemetered	NORMAL	228.95
RM11_2_V1-VOLTRMS	Phase Voltage (L1-L2)	telemetered	NORMAL	403.06
RM11_2_V2-VOLTRMS	Phase Voltage (L1-L3)	telemetered	NORMAL	403.42
RM11_3_V1-VOLTRMS	Phase Voltage (L1-L2)	telemetered	NORMAL	394.67
RM11_3_V2-VOLTRMS	Phase Voltage (L1-L3)	telemetered	NORMAL	403.89
RM13_1_V1-VOLTRMS	Phase Voltage (L1-L2)	telemetered	NORMAL	400.48
RM13_1_V2-VOLTRMS	Phase Voltage (L1-L3)	telemetered	NORMAL	399.95
RM13_2_V1-VOLTRMS	Phase Voltage (L1-L2)	telemetered	NORMAL	396.30
RM13_2_V2-VOLTRMS	Phase Voltage (L1-L3)	telemetered	NORMAL	396.83
RM13_3_V1-VOLTRMS	Phase Voltage (L1-L2)	telemetered	NORMAL	399.13
RM13_3_V2-VOLTRMS	Phase Voltage (L1-L3)	telemetered	NORMAL	397.33

D. *Future expansion*

For future improvement, the following steps & improvements shall be introduced:

1) Feeder should be modelled in SCADA Application as per GIS SLD.

2) Phase Unbalance Measurement should be Enabled in Smart Field ACR & Feeder Monitoring Panels.

3) Smart Field Auto-reclosers & Feeder Monitoring Panels are used to locate the Downed / Opened Conductor Faults.

4) Accordingly, Faults location can be identified (F1, F2, F3) as in Fig 29 below.

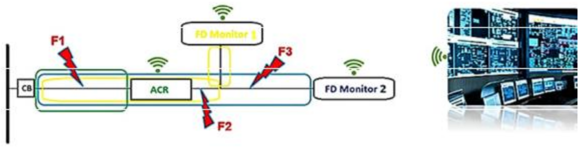

Fig. 29. Fault Location Identification

E. *Limitations:*

1) Feeder Monitoring Panel shall be installed in places where there are Cellular Communication Network Coverage.

F. *Future Research*

Research is on-going by Distribution Protection Engineering Department to study possibility of utilization of Smart Meters installed @ L.V. Transformer & Customers for detection of downed conductors.

VI. Solution Enhancements

A. *Large Scale implementation*

The current HIZ Grid Automation Solution with very minimal changes can be implemented on a large scale. The exact technical scope and requirements must be defined before such implementations. Few key factors before going for the large scape implementation are:

1) The number of sites/points to be monitored needs to be identified.

2) The monitoring data to be defined.

3) Communication protocols to be defined.

4) CAPEX/OPEX to be estimated.

5) Cybersecurity requirements to be defined.

The proposed solution is economically suitable and technically scalable to thousands of remote sites.

We propose a dedicated SCADA system for distribution fault management and downed conductor detection. The dedicated SCADA system should be capable to integrate the multiple HIZ Grid Automation cabinets performing downed conductor detection units. The SCADA system will monitor the measurement and alarm signals coming from all the HIZ-GA cabinets for downed conductor detection system and should be able to display all relevant information briefly across different locations, enabling the operator to make reliable, data-backed decisions.

The SCADA should have geographical map view to locate the alarmed downed conductor detection units which can be zoomed in to monitor the actual device.

The SCADA should have automated message control feature, which in case of an event for example a downed conductor detection should be able to automatically send the alarms and events via Email, SMS & Voice mail for immediate attention.

The SCADA system should have inbuilt standard communication protocol support to reduce the number of interface devices such as RTU's etc. to reduce the CAPEX cost. The large-scale implementation design is depicted in Fig 30 below:

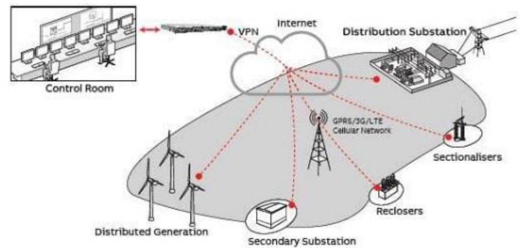

Fig. 30. Large Scale Implementation of the solution [6]

B. *Automatic Self Isolating and Healing Network*

The next solution enhancement would be the Automatic Self Isolation and Healing Network. The HIZ Grid Automation Solution and the SCADA control system with further system integration and additional logic can automatically self-isolate a network with downed conductor without operator intervention.

We created the below diagram in Fig 31, which explains the step involved in the detection of a downed conductor until the automatic self-isolation of the network.

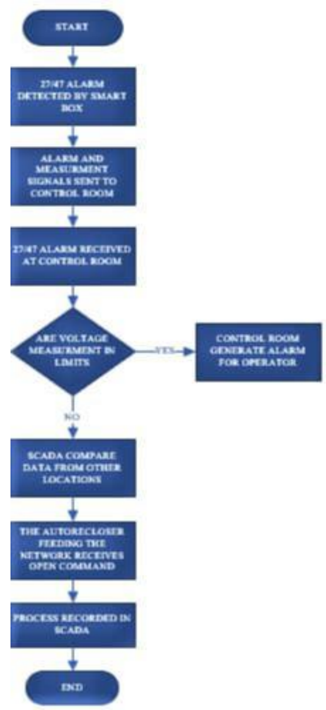

Fig 31: Steps involved in detectionof downed conductor

VII. Conclusion

It is well established that the traditional methods are not 100% accurate for detection of the HIF/ HIZ faults. Due to the high risks and human life at stake the problem cannot be further overlooked. This technique of detection of HIF/HIZ fault is more reliable and accurate.

The Pilot project has proved the following.

1) All HIF/HIZ faults can be detected with this solution with correct selection of monitoring location.

2) The solution can be enhanced further making the system more safe and secure

3) Additional benefits from this solution can be derived such as Load monitoring and management.

Important points to be considered before implementing this solution are:

1) OPEX & CAPEX Cost.

2) Cyber security requirements need to be defined and considered to secure the system.

3) HIZ Grid Automation cabinet should be reliable for outdoor installation.

Acknowledgment

The authors would like to acknowledge and express their gratitude to the following persons for their support and contribution to various aspects of this study, installation, and testing.

SEC Engineers: Mubarak Hassan Suliman, Zulfiqar A. Qureshi ,

ABB Engineers: Praful Chandarana, Simi Valsan, Faisal Khatri, Janak Panchal, Usman Haroon, Shiv Ganesh, Yashomitra Rath, Masood Butt.

References

[1] R. Das and D. Bayoumi, "System for detection of high impedance fault." *19th International Conference on Electricity Distribution, Vienna, Austria*, Paper – 0876, May, 2007. Available: http://citeseerx.ist.psu.edu/

[2] *Relion Protection and Control 615 Series Technical Manual,* Rev N., ABB, Finland, 2018, pp. 810-813. Available: https://library.e.abb.com/public.pdf

[3] C. Mark, R. F. Hoad, T. D. Bruton, R. Das, S. A. Kunsman and J. Peterson, “Staged-Fault Testing for High Impedance Fault Data Collection” presented to *31st Annual Western Protective Relay Conference*, Oct, 2004. Available: https://ieeexplore.ieee.org/abstract/document/1430417

[4] *Wireless I/O Gateway ARR600 Product Guide,* Rev E., ABB, Finland, May 2021. Available: https://library.e.abb.com/public/ARR600_pg_758464_ENe.pdf

[5] E. P. Flores (2016). High Impedance HIZ Faults Detection [Power Point slides].

[6] A. Anwar and SEC (2022). Downed Conductor Detection [Power Point slides].

[7] *Arctic Cyber Security Deployment Guideline,* Rev F., ABB, Finland, 2020, pp. 8-9. Available: https://search.abb.com/library/Download.aspx.