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Nodal Monitoring in Medium Voltage Distribution Grid using Smart Sensored Cable Termination

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Abstract

Tata Power-DDL worked in collaboration with 3M on a pilot project for making the medium voltage distribution network smart and efficient. This project aimed at enabling real-time monitoring of electrical parameters such as voltage, current and reactive-power-flow. While enabling these features, it was vital to make the solution compact and retrofit-to-existing-infrastructure for saving cost in terms of reduced equipment's footprint. In this pilot project, electrical parameters and direction of power flow were accurately captured using sensor-based technology. Captured parameters and corresponding benefits are analyzed in detail in this paper. Further, the availability of real-time captured data can be potentially used through analytical tools for enabling many features such as predictive maintenance and identifying faulted-segments in underground cabling networks. Power-flow-direction can potentially be used for advanced protection coordination in the looped distribution network. Thus, enabling reliable integration of existing grid with distributed energy generation source.

Keywords: Grid Automation, Grid Modernization, Smart Grid, MV Distribution Network, Sensored Cable Termination

1. Introduction

There is technology disruption going on in the power sector of India. The new technologies like solar generation plants, roof-top solar, EV charging stations, battery storage, LED lights, and other energy-efficient devices are penetrating in a big way. The load and generation have become very dynamic in nature. The utilities are exploring new technologies to meet or exceed the customer requirements to adapt to the changes. Indian distribution utilities are augmenting their existing equipment or installing new equipment for meeting changing demand and supply scenarios in the electrical network.

There are a few key contributing factors for change in power demand. First, there is an emphasis on increasing renewable energy. Renewable energy is expected to grow from 69GW in 2017 to 225GW in 2022. Second, the government of India has initiated a nationwide drive for the introduction of e-vehicles. 25% of vehicles in India will be all-electric by 2030. Charging stations are expected to be installed every 25 km across India. Growth in annual power consumption in India is close to 6%. Consumers expect access to an uninterrupted power supply.

These changes contribute to challenges such as bi-directional energy flow due to distributed generation, power quality issues due to rapid charging stations, and space constraints for installing new equipment to meet the ever-growing power demand. The dynamic demand and supply scenario call for deep network level automation and continuous monitoring of the nodes in the network.

The medium voltage distribution network needs to be upgraded to overcome the above challenges.

3M™ Sensored Cable Termination for MV network is identified as a potential solution to upgrade the distribution network by efficiently retrofitting into existing infrastructure. It includes a passive voltage sensor. The voltage sensor is a capacitive divider and provides output in both-voltage magnitude and phase angle. The current sensor is based on the Faraday principle (Rogowski coil), which provides the output in both– magnitude and phase angle. The compact form factor of Sensored Cable Termination can enable the utility to install the sensor

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inside the cable boxes of existing equipment; hence, eliminating the need for additional space. Furthermore, in combination with suitable intelligent electronic devices and analytics devices, these terminations can enable various applications in the MV network. Uses of data captured through 3M™ Sensored Cable Termination in combination with the 3M™ Underground Monitoring, Analytics, and Communication System (currently under development) are discussed in detail in this paper.

2. Overview of System Used in Pilot Project

2.1 Features of Sensored Cable Termination[4]

The 3M™ Sensored Cable Termination contains pre-calibrated, highly accurate, and passive voltage and current sensors. These sensors are designed to provide outputs in accordance with IEC 61869-10 and -11 and enable precise measurements without calibration on site. It is available both in skirted termination and screened T-body plug-in configurations. The sensing function is in addition to all the expected basic functionality of standard cable terminations, such as providing stress control, weather and tracking resistance, electrical insulation, etc. Safety, accuracy, and installation simplicity are the major features of this state-of-the-art technology, leading to many exciting grid modernization initiatives. Sensor terminations are fully type tested in 2018 at IEH, Germany, according to CENELEC HD 629.1, which is equivalent to IEC-60502-4 and IS 13573 part -II.

Some of the key technical parameters of the voltage sensors are as follows:

- Highest rated voltage for termination: 24 kV
- Rated primary insulation level: 125 kVp (1.2/50 µs)
- Rated frequency: 50 Hz
- Nominal voltage sensor transformation ratio: 10,000/1
- Accuracy class: 0.5
- Temperature category: -20° to +60°C
- Required voltage secondary circuit impedance (RTU input): 1 MΩ+2%

The key technical parameters of the current sensor are as follows:

- Rated frequency: 50 Hz
- Maximum current measurable: 100 KA
- Nominal current sensor converting ratio: Uncalibrated 30mV/kA @ 50 Hz
- Operating temp: -30 Deg C to 80 Deg C

2.2 3MTM Underground Monitoring, Analytics, and Communication System

The Electrical Analytics Unit processes the sensed data from Sensored Cable Termination and other installed sensors, analyzes the data based on programmed utility-specific parameters, and further transmits the data to the 3M™ hosted cloud through the 3M™ Communication Puck in packets. It can currently take inputs from 4 three-phase circuits (4 sets of 3 core cables) simultaneously.

Different system components of the analytical unit are illustrated here in the graphical format in Figure 1 along with features, advantages, and benefits.

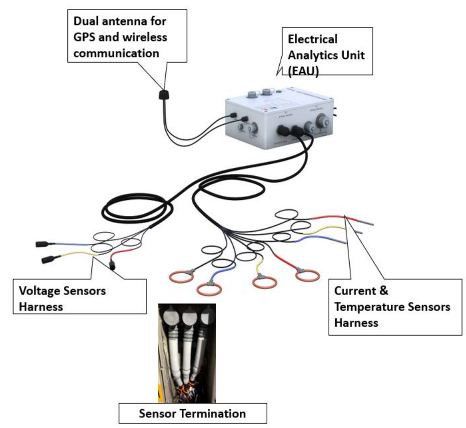

Figure 1. 3M system component installed for Pilot Project.

2.3 Block Diagram of Overall System

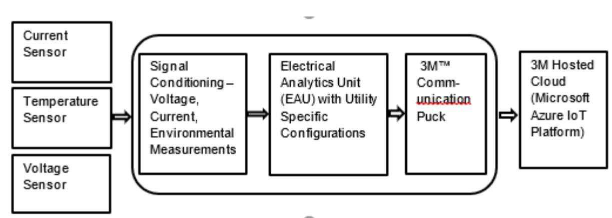

Figure 2. Block diagram of overall system used for the pilot project.

2.4 Site Layout of Pilot System Installation

Sensored Cable Termination along with the Electrical Analytics Unit are installed as a system for this pilot

Table 1. Features, advantages and benefits of Sensored Cable Termination and Underground Monitoring, Analytics, and Communication System

Feature	Advantage	Benefit
Wireless communications	Collected data can be transmitted (wirelessly) to a cloud platform	Helps spot maintenance opportunities, enables load planning
Integrated, modular solution	One-time hardware purchase, additional functionality can be added (firmware) as needs expand or capital is available.	Customizable; grows as your network needs evolve; "future-proof."
Highly accurate distributed sensing and analytics	Real-time electrical and environmental measurements taken at various underground nodes meets IEEE 386	Ability to accurately identify faults and magnitude of faults, as well as power quality (to be enabled in existing system) and temperature
Retrofits to existing hardware	It does not require new switching power, control, or protection equipment.	Lower installation cost
Environmentally robust	Meets IP68 requirements (immersion test of 15ft, 30 days), can be deployed long-term in harsh underground environments.	Durable, it produces reliable data with limited maintenance
Compact	Fits in constrained spaces, it requires limited existing real estate	Low equipment footprint

project. Site layout and field installation photographs for installation of complete system and Sensored Cable Termination are shown below in Figure 3.

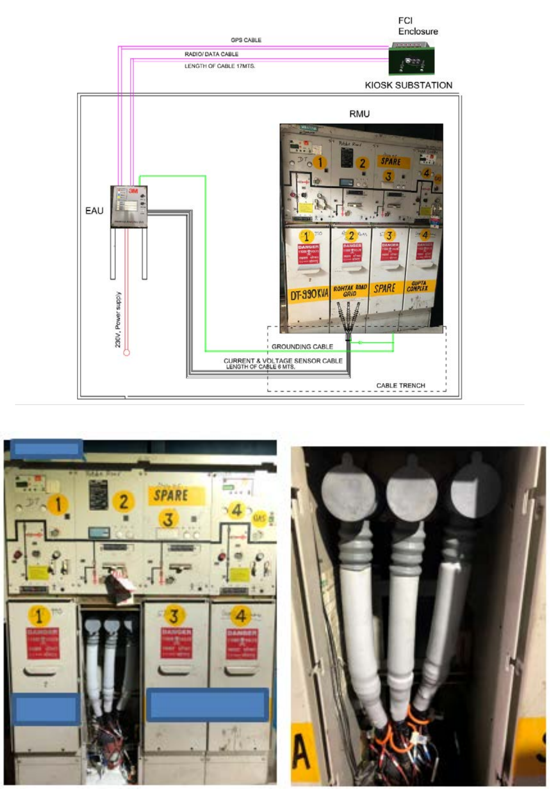

Figure 3. Field installation of cable terminations with voltage and current sensors.

2.5 Website Interface

3M™ Underground Monitoring, Analytics, and Communication System are capable of monitoring 4 number of 3 core cables simultaneously. A Sensored Cable Termination installed at TPDDL is connected to position 2 of the Electrical Analytics Unit. The attached screenshot of the website in Figure 4 confirms this. This dashboard shows voltage/current/phase angle and temperature with a timestamp. Data from the website can be exported to a .csv or .xls file.

3. Result of Pilot Study: Nodal Monitoring in Medium Voltage Distribution Network and Corresponding Benefits

3.1 Simultaneous Voltage and Current Monitoring and Corresponding Analysis

3M^{TM} Sensored Cable Terminations enable continuous and accurate monitoring of voltage and current with a timestamp. It can also capture voltage fluctuation. These voltage fluctuations can be plotted in graphical format. There are several instances of voltage fluctuation that have been captured during the monitoring cycle (refer Figure 5).

Voltage fluctuation or surges above the thresholds may reduce the lifespan of different equipment

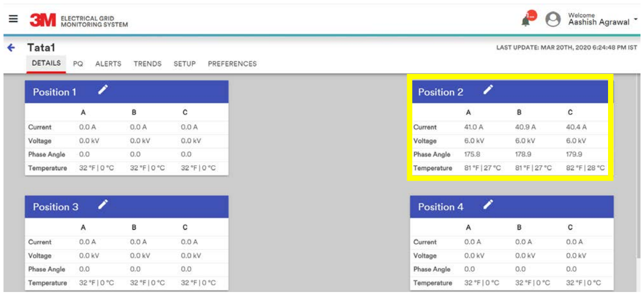

Figure 4. Screenshot of website.

connected to the network. The life of lighting equipment at the consumer end gets affected due to fluctuations. Monitoring voltage at different voltage levels in the network became very important due to the focus of utilities and consumers for the better quality of power. A few years back, utilities in India used to get low voltage complaints, but now consumers have started reporting high voltage complaints in urban areas. Technological changes like the use of capacitor bank for power factor correction at consumer ends, regular large-scale usages of insulated cables in distribution networks have decreased the reactive power requirement and hence contributed to elevated voltage levels at the end consumer. The significant penetration of roof-top solar and distributed generation has also contributed to elevated voltage levels.

CVR (Conservative Voltage Reduction) is the practice of actively lowering the distribution line voltage as low as possible while ensuring that the delivered voltage is still within required specifications. The practice is built on the principle that many devices (i.e., air conditioning, incandescent/fluorescent light bulbs, induction motors, etc.) function with higher energy efficiency at rated voltages. Implementation of CVR involves a combination of Volt/VAR optimization and switching capacitor banks to reduce line losses and maintain a more uniform voltage along distribution lines, in addition to voltage regulation at the substation to reduce the voltage purposefully.

Broad implementation of Sensored Cable Terminations in distribution networks can help identify those segments of the network that have high voltage fluctuation and need CVR implementation. As a result, it can improve the power quality and increase the lifespan of associated equipment.

Furthermore, due to simultaneous monitoring of voltage and current, captured data can be used during analysis for eliminating false alerts. E.g., If there is high current flow in the network for a short period, but voltage is stable; it may be attributed to in-rush current, and a fault trigger alarm will be disabled.

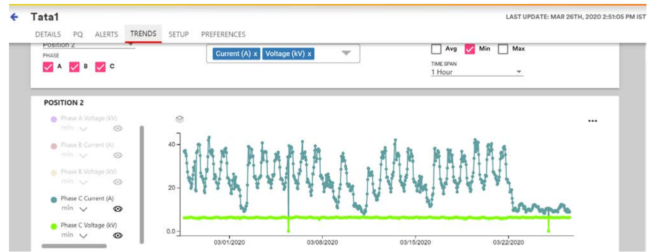

Figure 5. Source: Voltage and Current curve plotted using 3M Sensor Termination and 3M™ Underground Monitoring, Analytics and Communication System with hourly time installed in ring-main-unit at TPDDL.

3.2 Phase Angle Monitoring and Corresponding Analysis

Out of the total load in any utility, around 60 to 70% load constitutes induction motors. The phase sequence is very much important in any application involving the use of three-phase motors. In this pilot project with Sensored Cable Termination, phase angle monitoring is easy as it is plotted in graphical format. (refer Figure 6) The alerts can be set for any abnormal changes. Phase angle monitoring helps the utility to check whether the same phase sequence is maintained before switching the consumer load after any outage or shutdown, etc. Hence, consumer delight is ensured as no unforeseen events are recorded as when in earlier days process industries used to suffer a lot due to such instances. In such instances, the financial impact on consumers could lead to dissatisfaction. As India has embarked into the Open Access era wherein any customer can change his electricity supplier at any time, power quality and reliability became more critical. With the installation of a sensor termination at intermediate switching substations, any change in the phase sequence and phase angle gets detected easily.

Phase angle measurement is important for the implementation of VVO. This is enabled by Sensored Cable Termination through the concurrent measurements of voltage, current, and subsequent analysis of the time relationship between the two. Once measured, inductive loads can be compensated by switching in a capacitor bank to cancel out reactive loads or switching in a reactor to cancel out capacitive loads. This automation can significantly improve the operating efficiencies of the line.

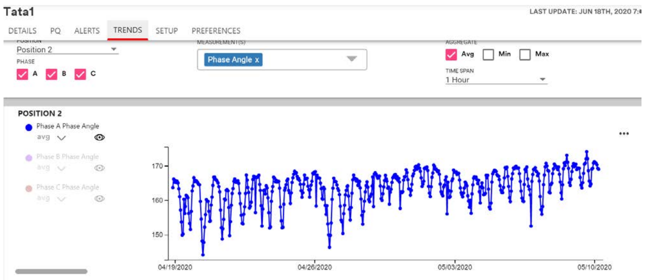

Figure 6. Source: Phase angle plotted using 3M™ Sensor Termination and 3M™ Underground Monitoring, Analytics and Communication System with hourly time installed in ring-main-unit at TPDDL.

3.3 Power Flow Alert

3M hosted cloud interface is equipped to generate power flow alerts and fault alerts to show when power direction is changed from forward to reverse (due to DER or ring typography) and whenever any fault is captured at the nodal point. (refer Figure 7).

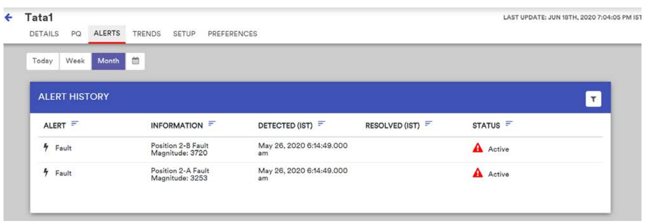

Figure 7. Source: Fault magnitude and alert captured using 3M™ Sensored Cable Termination and 3M™ Underground Monitoring, Analytics and Communication System installed in ring-main-unit at TPDDL.

3.4 Load Planning using 3MTM Sensored Cable Termination

Two important aspects of load planning are the availability of historic daily demand and peak load demand. The Sensored Cable Termination can enable continuous monitoring of load. Data can be plotted in graphical format for capturing average power demand and peak power demand for load planning (refer Figure 8).

In this case, it can be seen from the graph that generally, load demand is repeating a pattern on a daily basis except for one day when there is peak demand for few hours, which may be attributed to increased demand due to public neighborhood events. These data can help to predict area-wise load demand. With the availability of

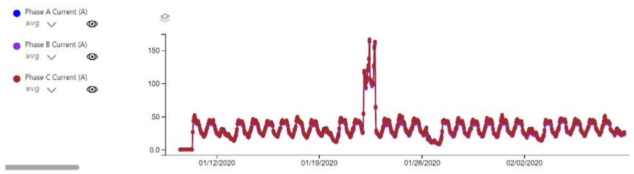

Figure 8. Source: Load curve plotted using 3MTM Sensored Cable Termination and Electrical Analytics Unit (EAU), a component of the 3M™ Underground Monitoring, Analytics and Communication System, with hourly time span for three core cable termination installed in ring-main-unit

historical and real-time data, the load growth rate can be predicted. Trend analysis, as shown above, can guide utilities about the suitability of distribution equipment capacity. It can potentially guide them about when to replace and install higher-capacity equipment in their network. Analysis of peak demand can guide them about the event's recurrence and can be accounted for in load planning purposes.

3.5 Outage Data Analytics

The system is also equipped to provide information on the duration of outage for nodal points. This information is helpful for the central unit monitoring the complete network to deploy resources for system restoration.

4. Potential Use Cases from Enabling Nodal Monitoring

4.1 Predictive Maintenance using Waveform Capture

4.1.1 Incipient Fault

Generally, incipient faults are self-clearing sub-cycle faults. Given their sub-cycle nature, capturing the waveform is essential. A common reason for the occurrence of an incipient fault is moisture ingress in the cable joint. For understanding purposes, we can provide an example. Typically, damage due to cable splice degradation allows moisture to enter the splice in the affected areas. Moisture content inside the cable joint causes an arc, which evaporates the moisture and extinguishes the fault. These faults are hard to capture with existing telemetry infrastructure since both current and voltage waveforms are needed to be captured. These types of arc faults, when they become more and more frequent, can lead to a full-blown fault.

Incipient faults are precursors to permanent faults in the same phase. The frequency of incipient fault occurrence increases over time. There might be one or two such events initially, but their frequency can increase before they are about to turn permanent. The picture below (refer Figure 9) illustrates the theoretical possibility of capturing the incipient fault. If maintenance activity had been planned based on the first two captured waveforms, the permanent fault of the network could have been avoided altogether.[6]

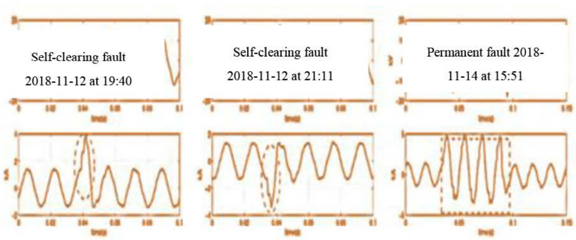

Figure 9. Source: Illustration of self-clearing fault.

4.1.2 Lifecycle of Fault

The lifecycle of an electrical fault in an underground cabling network can be understood with the help of a block diagram. (refer Figure 10) If there is any problem in installation, such as moisture or surface cut or contamination, etc., it leads to partial discharge. Partial discharge leads to treeing in the insulation, which further leads to an incipient fault and eventually a permanent fault. There are many options available for PD measurement which are capital intensive. Our objective is to capture incipient faults so that accessories can be planned to be replaced before the permanent fault.

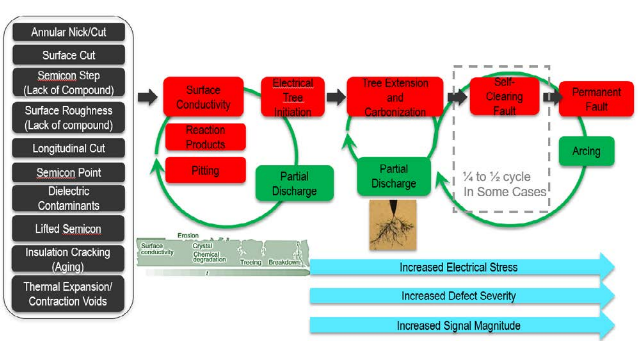

Figure 10. Life-cycle of Fault in Underground Cable Network[5]

4.1.3 Predictive Maintenance by Waveform Analysis

Precise voltage and current waveforms captured through 3M™ Sensored Cable Terminations and appropriate telemetry devices can be analyzed using a suitable tool for determining the distortion at the specific point in the waveform. In addition, the ability to monitor a corresponding increase in current could enable avoiding false positives due to harmonics.

4.2 Sensored based Protection System

The output of the 3M™ Sensored Cable Termination can be used by a relay for enhancing protection coordination in the MV network. Voltage and current sensors used in 3M™ Sensored Cable Termination are signal sensors with linear response and broad dynamic range compared to ferromagnetic based sensors (e.g., VT, CT, etc.). Given the accuracy and dynamic range, these sensors are well suited for protection, monitoring, and waveform analysis.

Overall, in terms of grid modernization, sensor-based protection, monitoring, and analysis can enhance safety and reliability. New IED/Relays are emerging for use with signal sensors such as 3M™ Sensored Cable Terminations.

5. Other Applications of 3M™ Sensored Cable Termination[4]

5.1 Fault Identification and Location

Full-scale deployment of Sensored Cable Terminations in the distribution network enables nodal point monitoring. The waveforms generated by a fault and measured by the device can be sampled at a high frequency and analyzed using signal locating methods, including Time-Domain Reflectometry (TDR) and time-domain Transmissometry (TDT). These analysis methods work on the basis that the captured waveforms are affected by the impedance of the conductor(s) the signal travels along. Coupling these measurements with time stamps and a network model including knowledge of cable lengths and impedance allows for fault locating via time of flight data. With Sensored Cable Terminations and appropriate IEDs placed optimally in the electrical grid, faults can be measured from multiple locations and triangulated for fault location.

5.2 Power Quality Monitoring

The Sensored Cable Termination can measure up to the 50th harmonic, which is generally considered most relevant and sufficient for power quality-related studies. Furthermore, with nodal point monitoring, the Sensored Cable Terminations in the network can help identify possible sources of harmonics and potentially help the distribution companies tackle the issues related to failures and premature ageing of assets in a more informed way.

6. Conclusion

This pilot study by 3M and TPDDL is a significant milestone in enabling nodal monitoring in a medium voltage distribution network using a retrofitted design. This project has successfully demonstrated accurate capturing of electrical & environmental (temperature) parameters and seamless wireless communication. Additional in-built functionality of automatic plotting of load curve, voltage curve, phase angle measurement is also demonstrated with this pilot. Analysis of available data on the website could be extremely valuable in establishing and planning various network activities such as load planning/ identification of power flow direction/ voltage fluctuation/phase sequence, etc. These data can provide insights into medium voltage distribution network monitoring. This pilot study has opened the avenue for modernizing the medium voltage distribution grid. A large-scale deployment may potentially help in faulted segment identification and even implementing predictive maintenance. This pilot study proved that all these features could be achieved in the retrofit design. The most exciting possibility is that with proper planning and deployment of Sensored Cable Terminations with an appropriate set of analytics, multiple functionalities can be achieved in the retrofitted design.

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