Towards Improved Reliability Indices using Waveform Distortions in Distribution System

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Abstract— **Reliable power supply to the consumers is the key goal for power utilities. The two key reliability indices for power utilities are SAIDI and SAIFI. These indices indicate the average duration and frequency of supply interruptions for the consumer. A low value on these indices reflects a reliable and mostly uninterrupted power supply. Reliability of the power supply is most threatened by events such as incipient failures that often go undetected by conventional protection schemes and can significantly increase average outage duration. However, such events initially manifest in terms of distortions in current and voltage waveforms. In this paper, waveform distortions are leveraged to detect and locate such events before they cascade to cause further damage. Early detection and localization will help in planning a swift response and mitigation of risk. Such a timely action will reduce the outage duration and interruption frequency, eventually leading to improvement in grid reliability indices. The paper further investigates these concepts by evaluating case studies on an IEEE-34 Node Distribution feeder test system in Real Time.**

Keywords—**Power system reliability, waveform distortion, situational awareness, SAIDI, SAIFI**

I. Introduction

System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are the two major indicators of reliable grid operations for power utility companies and Distribution System Operators (DSO's) [1]. SAIDI is measured as unit of time of the average duration of interruption for one consumer per year while SAIFI is measured as average number of interruptions for one consumer per year. Hence, the lower the value of SAIDI and SAIFI, the higher the quality and reliability of the power supply. DSO's spend significant amount of time and money on planning and resource allocation to achieve a fast and efficient response to any outage in the grid. Future capital expenditures are also governed by the need to have optimally designed feeders to reduce outage time in case of major disruptions. Several regulatory commissions determine reliability standards based on average values of reliability indices [2]. Hence, the idealistic reliable power supply scenario would have zero SAIDI and SAIFI values, which would be ideal for both power utilities and its consumers.

An estimate calculated by Eneco as part of their internal optimization study shows that reduction of even 1% in their supply recovery time would yield a saving of around €1.4 Million per year [3]. Council of European Energy Regulators (CEER) in their yearly benchmarking report on quality of energy and gas supply in Europe has also stated the need to have regulations on improving quality of energy supply to achieve optimum efficiency of implemented investments [4]. Hence, one can say that improvement of reliability indices is important, as it would translate into significant savings for utilities while guaranteeing reliable power supply to its consumers.

The two critical factors for improving reliability indices are early detection and accurate localization. The traditional approach of DSO's is to conduct periodic maintenance and inspection of distribution grid components with higher priority for expensive and critical equipment's like transformers, capacitor banks etc. [5]. A report compiled by Dutch DSO states that such an approach took very long time to fix a cascading blackout significantly pushing up its average outage duration [6]. Notably, such practice is inefficient in view of distribution systems that are spread over wide geographic areas with thousands of components. There is a need for a location specific input about an incipient failure for better situational awareness of the distribution grid.

Incipient failures ranging from equipment degrading over time to adverse weather effects often remain undetected by conventional protection schemes until they cascade into a blackout. However, for most of these incipient failures a *pre-failure period* exist that can be defined as the time interval between the normal working of grid and its subsequent collapse [5]. In this period, incipient failures manifest themselves in form of distortions in the otherwise pure sinusoid AC current and voltage waveforms of the grid. This pre-failure period provides an opportunity where waveform analytics can be used to detect incipient failures or similar events, eventually leading to improvement of reliability indices like SAIDI and SAIFI.

Waveform analytics has been already used for improvement of reliability indices in [7], while some other studies on improving reliability indices use logical relation and matrix operations in [8]. In this paper, we utilize the Distortion Detection Technique (DDT) devised by authors in [9]. Mathematically, DDT is based on the second-difference approach. This second-difference based approach leverages waveform distortions to differentiate between normal grid operation and incipient failures. In this paper, impact factor characterization of DDT results is used to better interpret and rate the damage potential of the event causing waveform distortions. The impact factor can be further utilized to localize the event, plan an efficient faster response and isolate the area of occurrence. In this paper, the improvement of SAIDI and SAIFI by DDT implementation is evaluated by simulating the effect of unplanned grid events like equipment failure and weather related outage on grid operations. The case studies are implemented on a standard IEEE-34 node test feeder in a real-time platform.

The paper has been structured as follows. Section II provides a brief overview of DDT principles and various implementation blocks including the features of impact factor and localization. Section III presents how the implementation of DDT will lead to improvement in reliability indices. Section IV presents the simulation cases and results. Section

V presents the interpretation of simulation results. Finally, Section VI presents the conclusions.

II. Distortion Detection Technique

This section is divided in two parts. The first subsection explains briefly the principle behind distortion detection technique and the second subsection explains the DDT implementation blocks.

A. Principle

The main principle of DDT is governed by the fact that pure sinusoids are complex exponential functions, which exhibit few unique characteristics like the rate of increase or decrease proportionally to the value of the function at that instant. In addition, complex exponentials are not infinitely increasing or decreasing exhibiting the property of periodicity. DDT calculates the second differentials of waveforms of grid measurements and observes when the above-discussed unique properties are violated. Any violation is an indication that at the specific instant, waveform is not sinusoidal in behavior. This is recorded as distortion in the DDT recorder. Distortion Detection block forms the heart of an overarching algorithm that helps to pre-empt failure. The algorithm flowchart can be seen in Fig 1.

B. DDT Implementation Blocks

1) Low-Pass Filter: The first step is passing the waveforms through a butterworth low pass filter with the cut-off frequency being the fundamental frequency to filter out harmonics. The objective is to avoid false flag reportings due to harmonics.

2) Distortion Detection: The main objective of this block is to implement the distortion detection technique. The input to this block is current or voltage waveform measurement from the grid. The output of the block is the reporting of distortions detected in real time.

3) Distortion Recorder: The objective of this block is to store the distortion occurrence data from Distortion Detection block in a data set of a specified length. This data set is called Memory Buffer. This Memory Buffer contains the instants of occurrence and non-occurrence of distortions in a fixed length of time interval.

4) Synchronizer: The grid recording devices may not have the same sampling rate. Hence, it is necessary to align all the distortion recordings as per their time-stamp such that a correct classification can be achieved. The synchronizer block helps in doing the same.

5) Classifier: The main objective of this block is to classify events and present the output to the operator. Occurrence of a disturbance at a certain point in the grid will not have the same impact over the entire section of the grid. For the same distortion, some measurement devices may report numerous and frequent distortion levels, some lower and some may not report any distortion at all. Hence, classification is achieved via two main data analyis procedures.

a) Impact Factor: The impact factor quantifies the damage potential of the event cauing waveform distortions. A severe event will cause numerous and sustained waveform distortions but a simple planned switching event will cause very few waveform distortions. Hence, the impact factor can be used to differentiate between normal grid events and

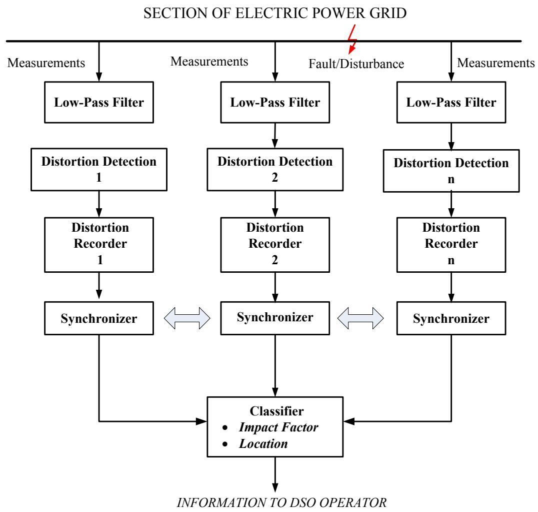

Fig 1. Distortion Detection Technique Flowchart

potentially harmful events. Impact factor classification is based on violation of thresholds. The thresholds are determined by running Monte-Carlo trials to record the average percentage of distorted samples in one cycle of the waveforms when normal grid events like load, capacitior switching are simulated. The waveforms serving as input to DDT are sampled at 128 samples/cycle. Table I presents a brief overview of thresholds. If the number of distorted samples is around 5% in one cycle (*7 distorted out of 128*), the impact factor rating would be 1.

Table I
Impact Factor Scale

Percentage of distorted samples in one cycle	Impact Factor
<3%	0 (normal event)
(3-6)%	1 (Possibly harmful event)
(6-9)%	2 (Harmful event)
>9%	3 (Full-scale fault)

b) Localization: Based on impact factor from different measurement devices in the grid, it is easy to locate the of event causing waveform distortions. Devices indicating higher impact factor will imply that they are closer to the point of disturbance and hence the maintenance teams can narrow down the location search to the area covered between those measurement devices.

III. DDT Implementation for SAIDI, SAIFI reduction

This section briefly explains how DDT can help to reduce SAIDI and SAIFI. SAIDI corresponds to average duration the electricity supply to consumer is interrupted and SAIFI corresponds to average number of times per year the electricity supply to customer is interrupted. They can be numerically expressed as:

$$SAIDI = \frac{\sum U_i N_i}{N_T} \qquad (1)$$

$$SAIFI = \frac{\sum N_i}{N_T} \qquad (2)$$

where N_T is the total number of customers, U_i is the annual outage time for location i, and N_i is the number of customers in location i [10].

Hence, as per equations (1) and (2), to achieve reduction in SAIDI and SAIFI, we need to reduce the average outage time per year, the average frequency of interruption per year and the number of customers being interrupted respectively.

DDT acts as an early warning system, which can be adapted to reduce SAIDI and SAIFI. In DDT, the operators at DSO level receive continuous real time information on the distortions and on the severity of their effect on the grid operations. The impact factor rating reduces search area for locating the event causing distortions. Armed with the valuable information, DSO's can choose from several possible responses. They can dispatch a quick response maintenance team to identify and fix the problem affecting the grid, which in turn will prevent a widespread outage reducing the average outage time per year and improving SAIDI. If fixing the problem in time is not possible, DSO's can prevent widespread outage by only isolating the customers near the location of the event until the problem is fixed. This will help in reducing the number of customers getting affected and improving SAIFI.

The most suitable action will be DSO dependent and based on host of factors like topology of the grid, ease of access to location, critical loads connected etc. Regular monitoring of the grid by DDT will also help in identification and timely replacement of damaged and ageing equipment.

IV. SIMULATION CASES & RESULTS

In this section, we look at the performance of DDT. In the following section (Section V), DDT performance is correlated with improvement of reliability indices. The simulation cases chosen to highlight the effectiveness of DDT is based on equipment failure and lightning surge. According to the report by Dutch DSO [6], equipment failure related outages were the source of approximately 50% of all reliability impacting outage events in 2018. Adverse weather effects like lightning surge can cause blackouts and severly damage expensive equipments like surge arrestors putting grid operations at danger. Hence, the chosen simulation cases are one of the most important cases for improving reliability.

A. Choice of Test System

The simulations are conducted on standard distribution system, the IEEE 34 node test feeder developed by IEEE PES Test Feeder Working Group [11] as seen in Fig. 2. The simulation has been conducted in RTDS power system simulator. The nodes of the placement of measurement devices are marked in blue. The event point location is marked in red (equipment failure) and green (lightning event). The placement of measurement devices is rudimentary in nature are evenly distributed throughout the grid for balanced data collection from all sections of the grid. Further studies would be required to devise an optimal placement of measurement devices.

B. Simulation Cases

1) Capacitor Switch Malfunction: This equipment failure based simulation case is based on a real life event as observed and recorded in [5]. Equiment failure events are characterized by slow degradation of electrical equipment over time which can last in a range of few weeks to few months. In the case from [5], the event stretches over two months where an initial equipment malfunction cascades into a full fledged failure. In our simulation, we model the real-world equipment degradation process in three simplified progressive sequences. The three event sequences and corresponding increase in transients are explained in Table II. The capacitor bank (node 834) starts switching abnormally at

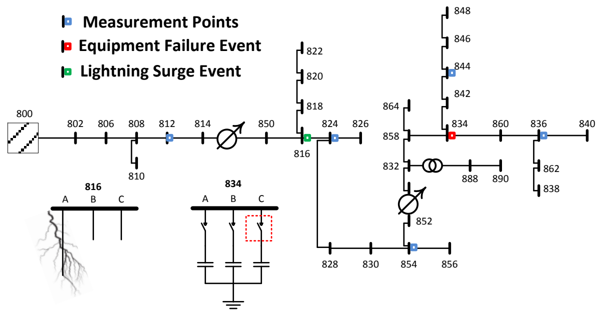

Fig. 2. IEEE-34 Node Feeder with Simulation Setup

first producing some transients. This doesn't raise any alarm. Unchecked, the abnormal switching frequency increases with time leading to gradual equipment failure and malfunctioning of the device. The capacitance is set to 1.9252μF per phase and connected to the grid through a vacuum switch. The vacuum switch is modeled as an ideal switch with a close resistance equal to 0.1Ω and open state of 1e6Ω. Phase C has been designed to malfunction. The resistance in that phase in open state changes to 250Ω. This results in a small current flowing to the switch even during open condition, leading to small transients. These transients gradually damage the equipment leading to eventual equipment failure.

Table II
Event Sequence Details

Event Sequence	Vacuum Switch Abnormal Operation Instances
Sequence 1 (Equipment Healthy)	Transients observed every 60 cycles
Sequence 2 (Equipment Slightly Damaged)	Transients observed every 30 cycles
Sequence 3 (Substantial Equipment Damage)	Transients observed every 15 cycles

The results presented in Table III are the interesting extracts of the real time recordings of the event sequences of the capacitor switch malfunction. The extracts represent DDT analysis of one second of recordings at the different measurement points after each of the three event sequences is initiated. Table III shows that after initiation of first event sequence, the grid operations are not that much affected with very few distortions reported except for the measurement points near to the event location. The impact factor rating of closest measurement points (844, 836 and 854) rise but for other measurement points it remains at zero indicating normal operations. After event sequence 2, it is quite clear that there is some issue in the grid with impact factor of devices at node 836 and node 844 rising to level 2. After sequence 3, the measurement devices at nodes 836, 844 and 854 shifts to impact factor 3 indicating a high risk event. In Fig. 4, we can see the event data recordings.

2) Lightning Surge: Around 20% of all lightning strikes lead to permanent faults and sustained outages as

Table III
DDT Implementation Results

EQUIPMENT DAMAGE

EVENT	Node 812		Node 824		Node 854		Node 844		Node 836		Major Conclusions
	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	
Sequence1	6	0	5	0	12	1	23	1	22	1	Potentially harmful event located between areas of nodes 854, 844 and 836. Search area reduction for the maintenance teams about 50%
Sequence2	12	1	17	1	19	1	45	2	47	2	
Sequence3	45	2	57	2	77	3	78	3	71	3	

LIGHTNING SURGE

Time-Period	Node 812		Node 824		Node 854		Node 844		Node 836		Major Conclusions
	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	Samples Distorted	Impact Factor	
(0.0-0.1)s	2	0	0	0	0	0	0	0	0	0	Very harmful event located between areas of nodes 812 and 824. Search area reduction for the maintenance teams about 75%
(0.1-0.2)s	182	3	203	3	70	2	40	2	11	1	
(0.2-03)s	157	3	124	3	67	2	14	1	13	1	

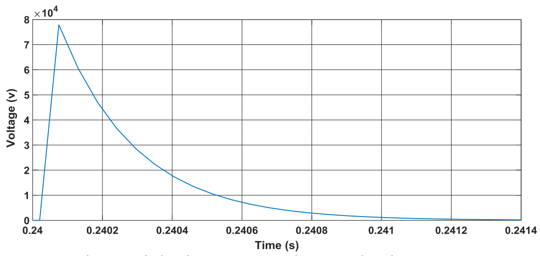

Fig. 3. Lightning Surge Voltage Behaviour

conventional protection systems fail to clear them. Lightning Surge can cause considerable damage in a very short time. Lightning surge has duration ranging from micro to milli-seconds and it can damage the insulation leading to a short-circuit. In this work the lightning surge is simulated by Equation (3) [12], with a rise of 1.2μs and decay of 50μs as seen in Fig. 3.

$$v(t) = V_o\left(e^{-t/t_b} - e^{-t/t_a}\right) \qquad (3)$$

where $v(t)$ is the voltage of the lightning strike, V_O is the initial voltage, ta is the decreasing exponential lightning enrgy and tb is the increasing exponential lightning energy. In our test case, we simulate the lightning event on node 816 at 0.1s.

As seen from the results in Table III, the measurement devices at nodes 812 and 824 show significant distortions after lightning strikes at 0.1s. The impact factor directly escalates to 3 and is sustained in the next time interval. The other measurement devices maintain impact factor levels of either 1 or 2. DDT implementation gives us clear indication that very harmful event has occurred in the areas covered between devices at nodes 812 and 816. The distorted waveforms can be seen in Fig. 5.

V. Result Interpretation in Context of Reliability Indices

A. *Capactior Switch Malfunction*

The DDT implementation along with the impact factor rating gives us an indication of a possibly harmful event (nodes 836, 844) during sequence 2 in a way predicting the eventual failure of equipment in sequence 3. Timely action could have prevented complete equipment failure reducing average outage time. Additionally, DDT helps to narrows down the location of the event between the areas covered by devices at nodes 836, 844 and 854. This translates to *search area reduction of about 50%* for the maintenance teams thereby reducing the time to locate the event and work towards faster restoration. Hence, DDT implementation can lead to reduction in outage time and event search area eventually helping to improve the reliability indices.

B. *Lightning Surge*

Since lightning strikes produce very fast traveling transients, it is almost impossible to predict them unlike equipment failure. However, DDT implementation can helps us to limit the damage extent. DDT implementation as seen in Table III gives us an indication that a very severe event has occurred in the area covered by nodes 812 and 824 leading to a *search area reduction by almost 75%.* The indication from DDT helps the maintenance teams to isolate the area of event so that the numbers of customers affected are minimized and further work can be done for quick restoration.

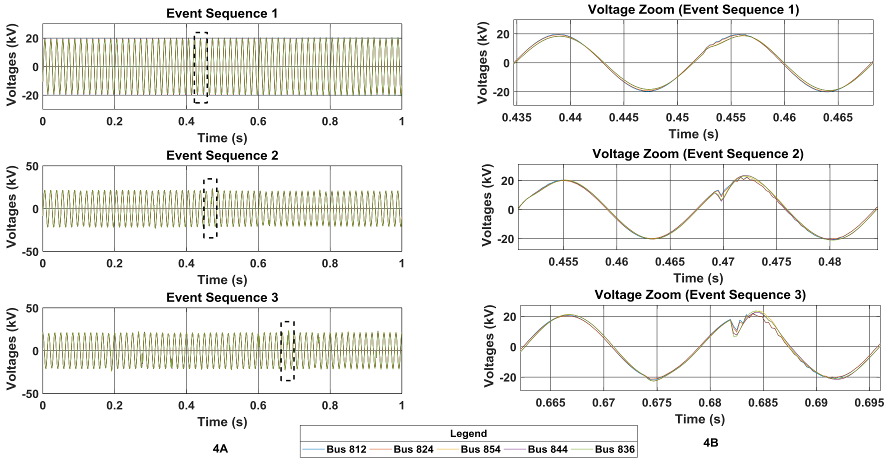

Fig. 4. Voltage Measurement from the different measurement points. 4A: Measurements recorded for 1sec simulation time after initiation of event sequences. 4B: Zoomed part of the sections to show in details the distortions encircled in black in 4A.

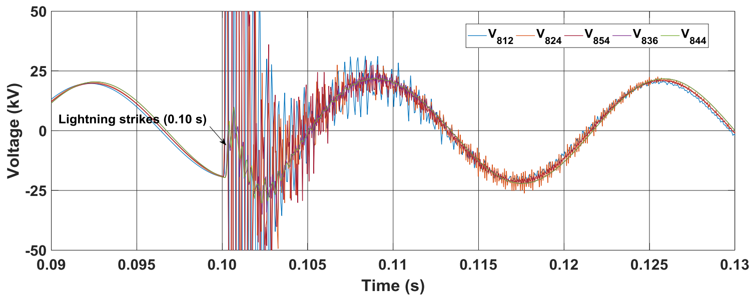

Fig. 5. Distorted voltage waveforms across different measurement points after lightning surge.

VI. Conclusion

The reliability indices like SAIDI and SAIFI can be improved with timely response and preventive maintenance. We show that timely identification of potential failures and their localization leads to a more insightful decision making by grid operators opening up opportunities for reliability index improvement. Such preemptive measures could be taken with the aid of DDT proposed in this paper. Subsequent work will involve evaluating DDT performance for different test cases and conditions to ascertain its average success rate and to assess the probabilistic improvement of reliability indices.

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