The Hidden Costs of Transition to Renewables

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Background

- Pacific nations have been heavily dependent on diesel generation in the past.
- Over time, there was a steady uptake of solar energy and other renewable generation, bringing tangible benefits to the communities and distribution networks
- That uptake is accelerating, and the electricity industry faces a serious transition period that will challenge traditional network concepts, including rising costs.
- Apart from project costs regarding planning, installing, and commissioning renewables, some hidden costs could become apparent only later when the integration is completed, and the system is fully operational.
- This Paper discusses the ‘hidden’ costs of the transition to renewables and suggests how to mitigate them with practical, cost-effective and affordable measures, as follows:

1. Protecting 'Blind spots' on distribution networks [1]

Traditional distribution networks are passive e.g. power flow is unidirectional. A high uptake of renewables creates a bi-directional power flow that can decrease fault levels, create 'blind spots' for protection, and cause false tripping [2].

Traditional protection relays often cannot cope with these networks' electrical parameter changes. They might fail to detect a real fault, resulting in decreased network reliability, increased SAIDI, and potential safety issues. It can also cause unsynchronised reclosing and loss of main power.

In other words - when a large-scale renewable is connected to a radial distribution feeder, the fuse-recloser coordination is lost:

- The fuse may 'see' more fault current than the recloser
- The fuse will then operate before the recloser operates
- It may result in false tripping on a transient (temporary) fault, instead of a permanent fault only
- Recloser will have no chance to clear a transient fault
- This will affect the overall reliability of the feeder
- This challenges how to detect and isolate potential faults.

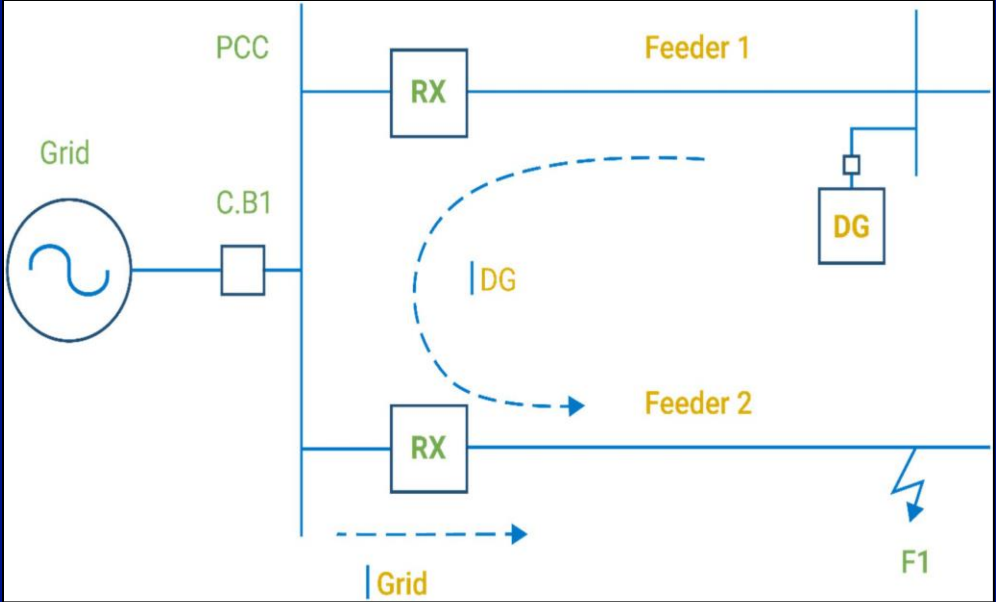


Fig.1 - Possible false tripping due to a fault on another feeder [4]

1.1 Potential solutions

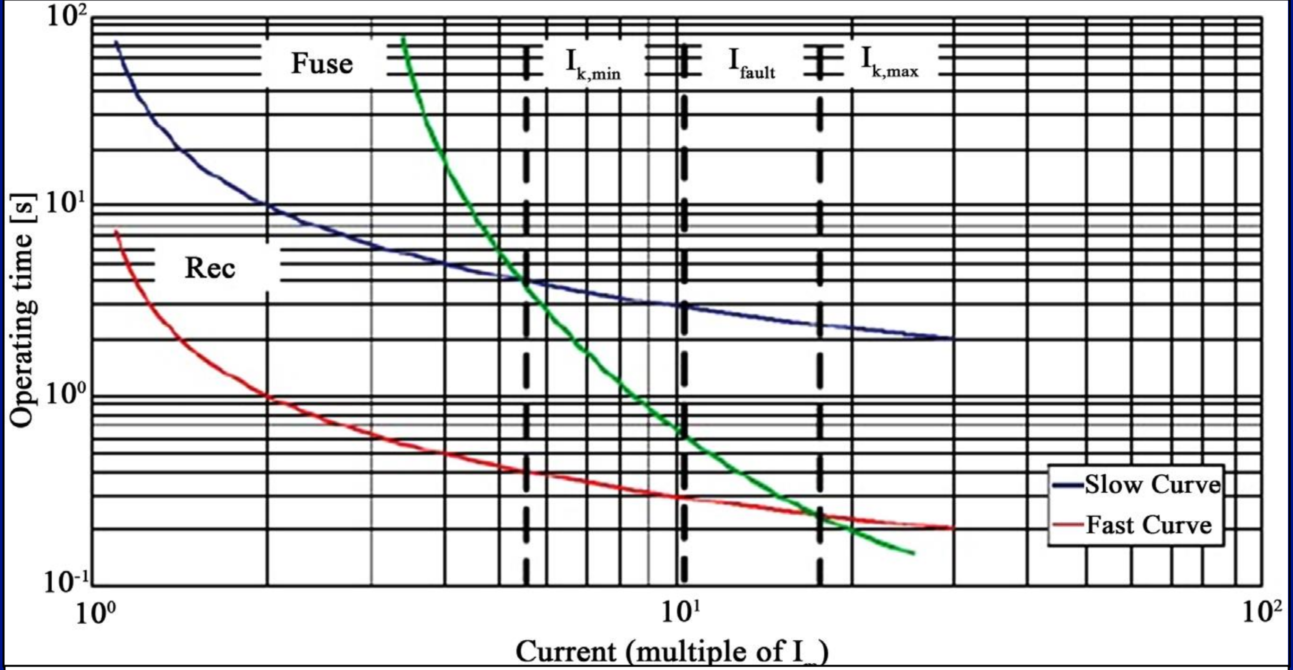


Fig.2 - Fuse-recloser coordination curves. At the instant of fault current - the fuse should operate after the recloser's "fast curve" and before the recloser's "slow curve" [3]

There are many potential solutions to this problem proposed [2] for example:

Adaptive protection schemes, increasing sensitivity of overcurrent relays, improving coordination, protection of inverter-interfaced DG units, differential protection using communication, a balanced combination of various types of DG sources, symmetrical and differential current components, fault current limiters, the central protection, rate of voltage change, AI, etc…

However, most of the above solutions are complex, expensive and difficult to implement. They require full study/analysis of network impedances and parameters, added equipment, and perfect coordination protection relays - reclosers.

Most of these techniques do not notably improve the problem, whilst they can compromise other critical parameters, making protection too sophisticated, oversensitive to further upgrades, and difficult to maintain.

1.2 Recommended solution

Reclosers provide overcurrent protection and reliability by detecting and breaking the fault current, thus eliminating temporary faults with their “trip & reclose” capability.

In a typical radial feeder, reclosers detect only the unidirectional flow of current. However, with the addition of DG, the fault point impedance changes and it is important to place a recloser in an optimal location and adjust its settings.

A comprehensive study has been conducted based on a real power system and simulating real-case scenarios in DIGSILENT [6], aiming to avoid blind areas and improve reliability.

The results of the study show that: [6]

- The operating time of the protective relay increases with the fault point impedance, which forces the OC relay to go into a blind area
- On the other hand - the recloser curve setting closes faster than the feeder OC relay curve, so the recloser operates faster than the OC relay
- Therefore, the recloser protects the blind areas that OC relays can’t see
- Thus, the recloser improves the feeder reliability by cutting the total outage by about 50%

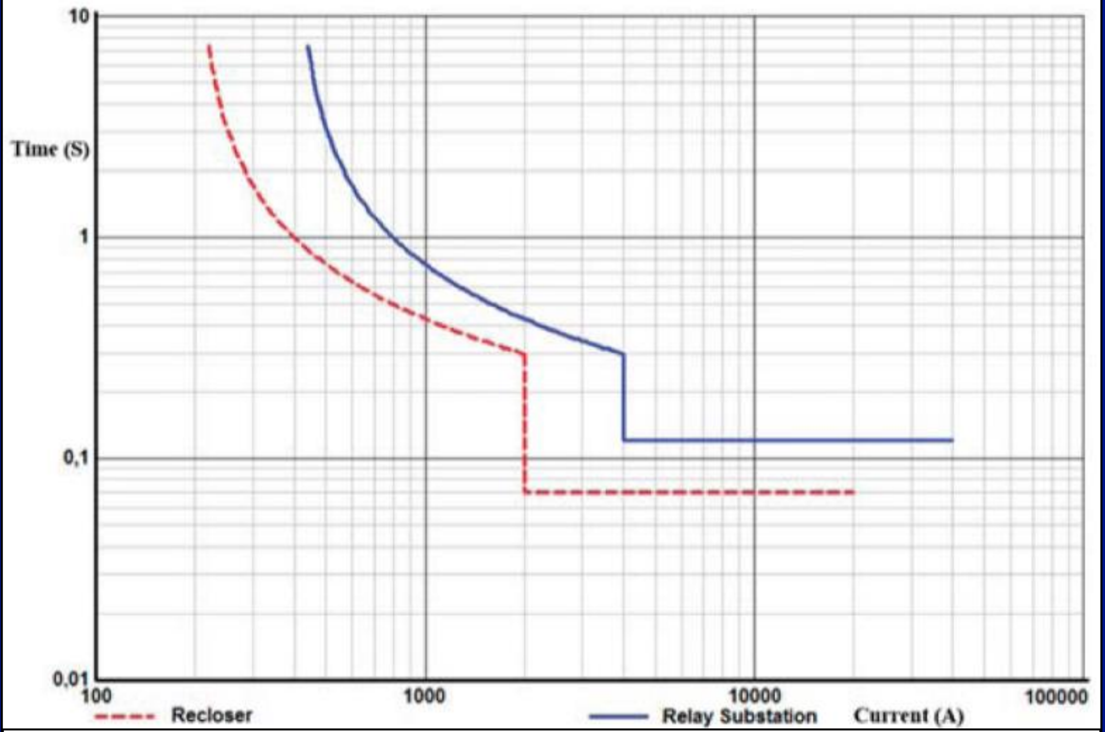


Fig. 3 - Comparison of overcurrent relay characteristic curves of substation 20 kV feeder and recloser relays. [6]

It has been shown that a recloser with proper settings and at an optimal location can cover the blind spots and improve protection. This solution is based on the simple fact that a modern recloser is faster than overcurrent relays.

1.3 Selecting the right recloser

There are many types of classical reclosers from different manufacturers. Most of them are good, but they are made for bigger and more complex distribution networks to be integrated with SCADA and higher automation schemes. Hence, they can be a technology overkill for radial feeders in the Pacific networks, for what is needed and their pricing.

A careful investigation and comparison between various reclosers revealed one of them that stands out. It fits key requirements for the Pacific distribution networks:

- Excellent technical characteristics and capability to mitigate the problem of blind spots
- Economic value (e.g. best value for money)

Fig. 4 – Teros is a relatively new Recloser that can mitigate the issue of blind spots. [7]

It is durable and maintenance-free, automation-ready with 6 integrated voltage sensors, the highest level of reliability at a minimum cost.

It has higher creepage modules, a sealed mechanism, an access control system, a clear cover for mechanism visibility, and modular controls.

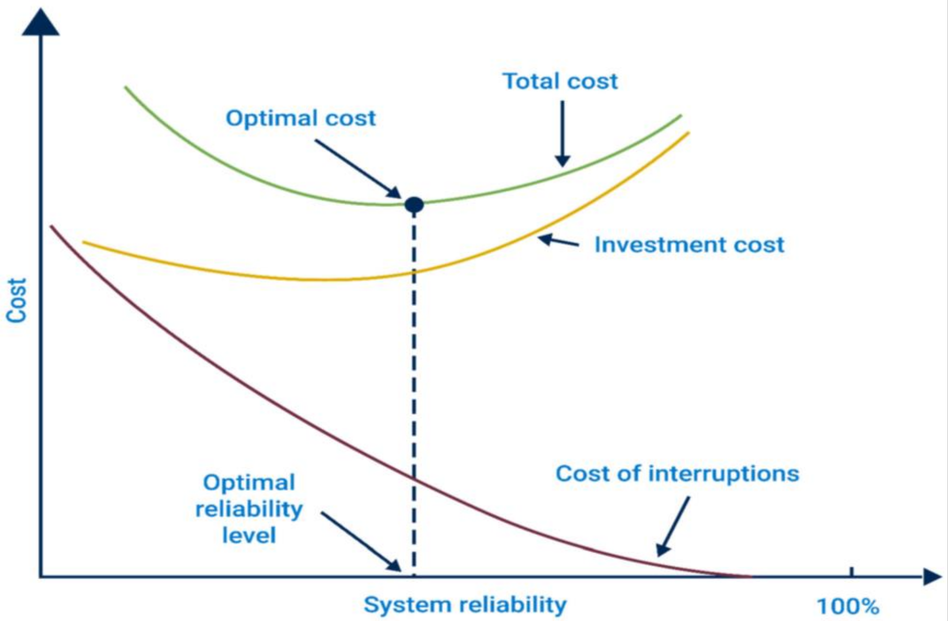


Fig. 5 - Cost versus system reliability [6]. If installed halfway of the feeder [5], this recloser would yield ~ 50% reliability improvement to upstream customers. If two reclosers are installed, they should be placed at 1/3 and 2/3 of the feeder length for the optimal investment.

2. Over-voltages

A bi-directional power flow can cause over-voltages, resulting in voltage-limit violations, safety issues, and damage to equipment.

2.1 Residential solar

Residential rooftop-mounted solar photovoltaic (PV) panels are typically connected at low voltage (LV). As per the earlier study in New Zealand in 2015 [8] - in most cases, the overvoltage would not be much higher than the statutory limits.

However, since then there has been a significant uptake in residential solar generation, and the instances of overvoltage have increased considerably [9].

- On the customer side, extended overvoltages can affect the life span of household electronic appliances.
- On the distribution side – they can shorten the service life of transformer on-load tap changers and line voltage regulators due to frequent operation [9].

To avoid or reduce overvoltage, PV inverters should be pre-set to reduce output power, however, if the overvoltage problem is not remedied it could lead to complete disconnection of solar generation. [9] It also reduces the efficiency of solar generation.

Over-voltages (continued)

2.2 Grid-connected solar

For grid-connected large solar farms, it becomes more complicated and expensive. Temporary overvoltages on distribution lines caused by faults or switching can be exacerbated by a high intake of solar, resulting in extensive damage to power lines and other equipment. [11]

A proposed method is "*a combination of virtual impedance and modified switching strategy for grid-connected CSI-based (current-source inverter) PV systems*" [11]. This method damps current and voltage oscillations and restricts power injection during fault conditions. However, although promising, this method still needs to pass rigorous tests in real-life applications.

2.3 Other potential solutions

The other methods to potentially solve the problem are BESS (battery energy storage system), DSTATCOM (Distribution static compensators), export limit, reconductoring (increasing the conductor size), reconfiguration of lines, and DVR (Dynamic Voltage Restorer). [9] Some solutions are more practical and cost-effective than others.

3. Harmonics

Harmonics are generated by inverters and non-linear loads, resulting in distortion of the sinusoidal waveform on power lines.

As per some studies [12], harmonics in systems can cause the following effects:

- Heating of cables, conductors, joints, transformers, switchgears, etc.
- Overvoltages due to the harmonic current flowing against impedance
- Resonance (series & parallel) in an inductive-capacitive-resistive circuit, resulting in high harmonic currents and voltages.
- Interference with comms, control & protection (by EM induction or by ground currents)
- Overstressing and heating of insulation, electronics failure, etc.
- It can also instigate fuse-blowing, relay maloperation, and circuit breaker tripping.

The most noticeable effect of high harmonics is overheating and deterioration of connections which are the weakest points of any circuit. It is caused by the 3rd harmonic, which increases the zero-sequence current, thus increasing the current in the line neutral conductor.

Potential solutions

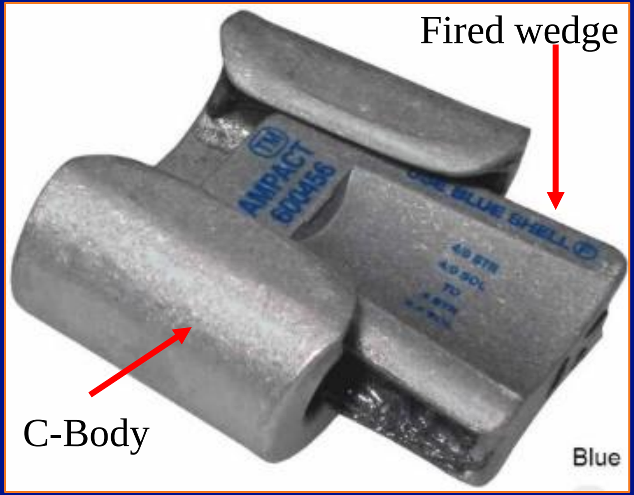
The connectors and joints are critical for all LV, MV & HV networks. The main purpose of any connector is to make a reliable and long-lasting connection by achieving a low contact resistance. It is even more important in circuits with high harmonic distortion.

A connector always has a much smaller real contact surface area than the cross-sectional area of the conductor it is used on. Therefore, to mitigate issues caused by harmonics, it is necessary to select and install the most suitable connectors, as follows:

3.1 The fired-wedge connector is the best connector for connections on bare conductors. It has been tested and proven internationally. It creates and maintains the largest real contact surface between connecting parts, with the lowest contact resistance for the current flow while helping mitigate the effects of the 3rd and other harmonics.

Fired wedge connectors have superior electrical conductance and thermal properties e.g. they have approx. 3 times lower contact resistance than other connectors.

They are currently the only non-tension connectors rated to Class AA (Extra Heavy Duty) as per ANSI C119.4 Standard for use between Aluminium to Aluminium or Copper, and Copper to Copper conductors[13][14].



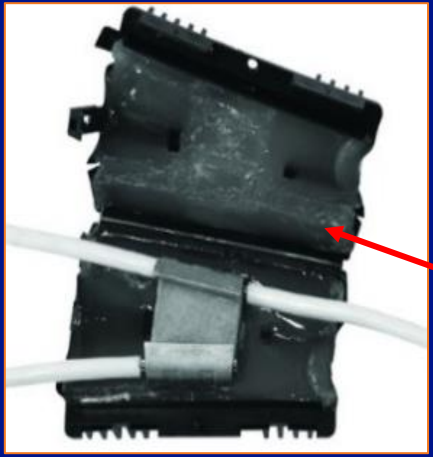


Fig. 6 – Fired wedge connectors have been around for over 50 years. This top-quality connector retains a constant contact pressure even under frequent temperature changes (ambient and load-related).

If fitted, the Gel Cover insulates, seals, and protects the connection in harsh environments

Potential solutions (continued)

3.2 IPC (Insulation Piercing Connectors) are suitable mostly for covered LV conductors and LV ABC. The key requirements are low contact resistance, reliability, and long service life. However, there is a major difference in IPC connector designs e.g. in relative geometry of teeth and conductors.

An IPC with teeth in line with the conductor has its teeth fully engaged with the conductor to achieve max contact surface and low contact resistance to lessen the effects of the 3rd harmonic. It also has a spring element that compensates for thermal changes.

Oppositely, an IPC with teeth perpendicular to the conductor has about 50% smaller contact area, causing about 30% higher contact resistance. It has no spring element but a weak spring effect of tinned copper clips. [15]

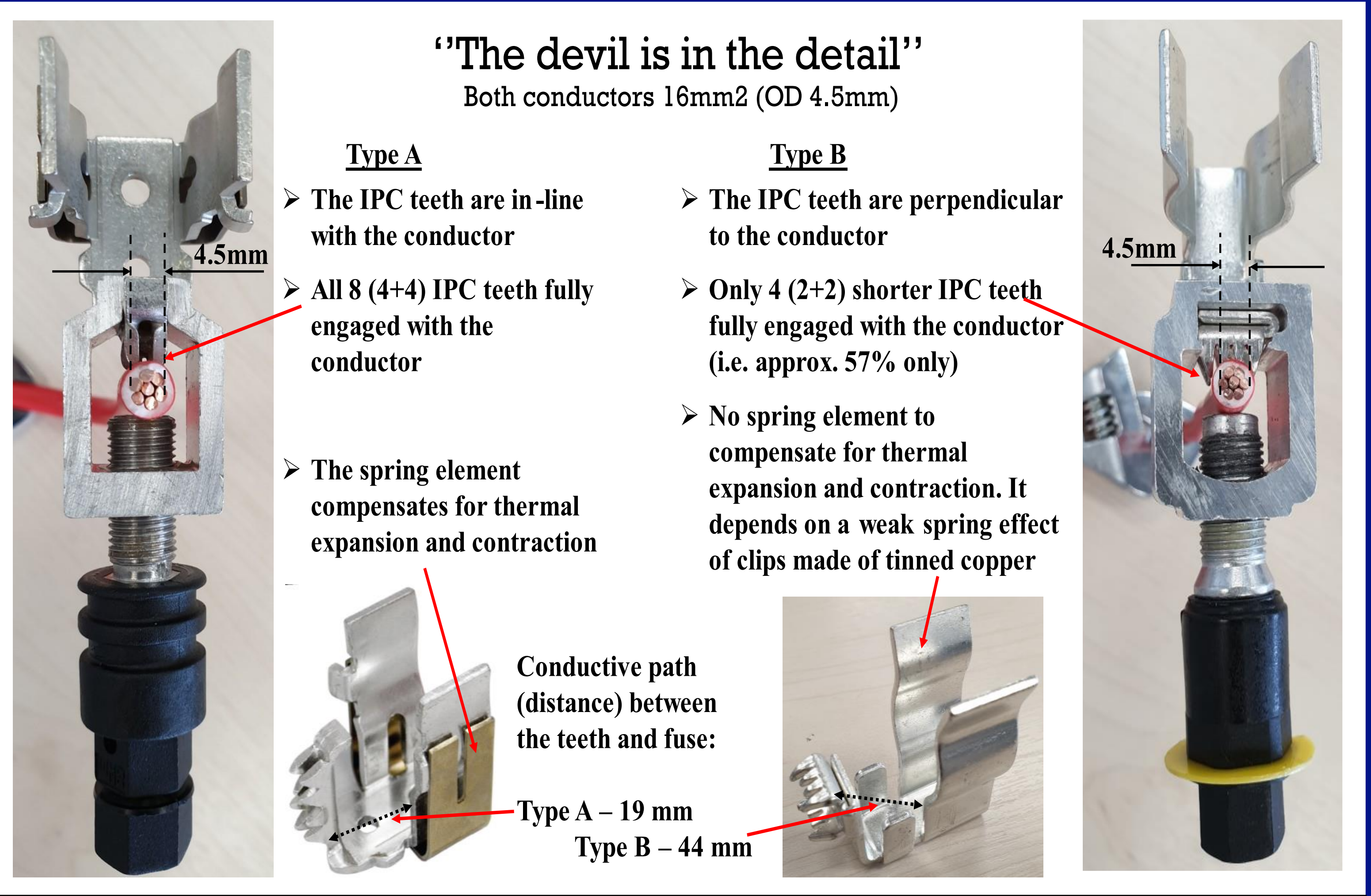


Fig. 7 – Comparison between two different IPC designs [15]

To further mitigate the effects of the 3rd harmonic on the LV service neutral, it is recommended to use the 2-bolt IPC connectors.

Potential solutions (cont.)

3.3 A new type of nut with anti-loosening screw threads [16][17]

Bolted connections use bolts & nuts to achieve good contacts. However, bolts & nuts over time get loose due to constant load and thermal cycling, vibrations, galvanic processes, bad tightening, etc. They then start overheating, especially in circuits with harmonic distortions.

The new type of nuts with anti-loosening screw threads will not get loose. Yet again, the difference is in geometry. The thread of the new nut has two parallel contact lines next to each other in the thread valley. They induce double contact locking lines between threads. It maximises the static friction force between the bolt and nut threads, thus preventing loosening. The new nut is used with the ordinary bolt. There is no need for spring washers, double nuts, nylon-type nuts, adhesives, coating process, etc. It is also very cost-effective.

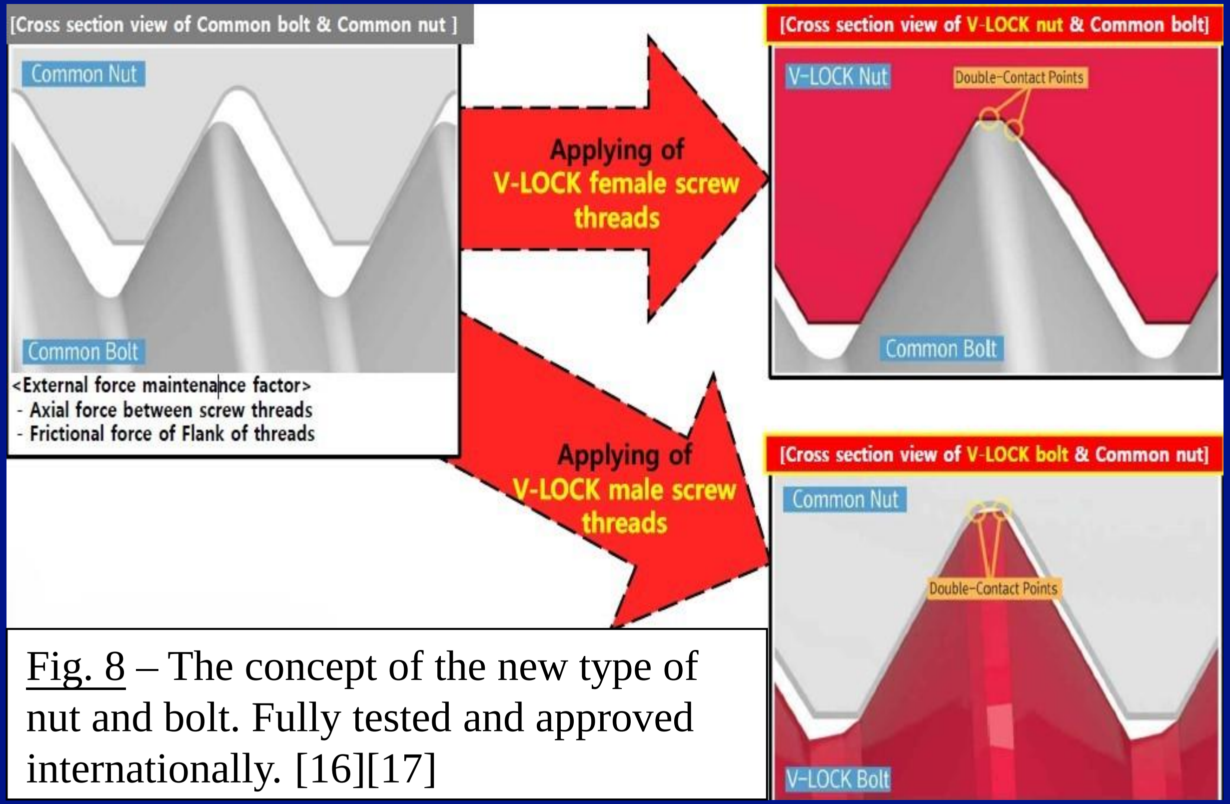


Fig. 8 – The concept of the new type of nut and bolt. Fully tested and approved internationally. [16][17]

Table 1 - Junker machine test report - Comparison of V-LOCK nut vs other methods [16] [17]. V-LOCK nut was the only one that remained tightened. Nut size/material: M8 (HEX) / SUS 304

No	Test sample	Initial load	End load
19-3-3	Common nut	3217.68 N	475.20 N
19-4-1	Common nut & Plain washer	3082.47 N	470.09 N
19-4-2	Common nut & Plain washer & Spring washer	3417.33 N	498.26 N
19-4-4	Common nylon nut	3110.32 N	902.15 N
19-4-5	V-LOCK nut	3138.45 N	2337.69 N

Note: The above cost-effective methods will help significantly mitigate the effects of the 3rd harmonics on connections and joints, but they will not eliminate harmonics. In addition, good contacts will over time notably reduce energy losses.

4. Lightning strikes

Generally, there is a small chance that lightning will strike a single-roof solar. However, a solar farm can attract lightning strikes due to a large metal supporting structure spread across a big field. Wind turbine blades also attract lightning. A single lightning strike, direct or indirect, can cripple solar generation and cause massive damage to the connections, solar panels, inverters, and communications. It can also create surges and induce overvoltages and transients on the DC and AC side, the connecting power lines, and other critical equipment.

Although there are fewer lightning strikes in the Pacific Islands than in the continental areas, the increased changes in weather patterns bring more frequent storms including lightning. There is a growing number of lightning strikes on solar farms worldwide, as follows:

In 2020, an 8MW solar farm in northern Thailand was struck by lightning at night, damaging 4,209 modules. They found that the lightning protection design was incomplete. [18]

Fig. 9 - Three bolts of lightning strike at Wandoan Solar Farm, west of Kingaroy, Queensland, 6 Dec 2020 [19]

Fig. 10 - A lightning strike hit the Shelby solar array in North Central Ohio, knocking out the system's transformer.
The estimated cost of replacement and repairs is US$100,000.
The restoration lead time: about 3 months (Credit: Katie Ellington Serrao, June 28, 2024) [20]

Recommended solutions

Solar (and wind) generating plants should be protected from lightning strikes and electrical faults, as follows:

4.1 Earthing and equipotential bonding system

- Must provide a low resistance and impedance path for high lightning and fault currents to the surrounding ground
- All electrically conductive components like metal structures must be bonded together e.g. equipotential bonding. It should also provide safety regarding step and touch voltage.

4.2 Lightning arresters (Surge diverters) should be installed on connected OH lines e.g. at transition points between overhead lines and underground cables, between bare conductors and covered conductors like CCT or ABC, and at the solar connection to the network.

4.3. A lightning protection system (e.g. 'air terminals' or 'strike termination devices') should be installed directly on the solar farm site. The simplest and most cost-effective is a system of lightning rods/conductors attached to dedicated poles that protrude above the solar panels and are directly connected to the earthing system. They attract and 'catch' a lightning strike first, then quickly and safely convey the high currents via the earthing system into the ground. Some more sophisticated but more expensive lightning strike termination devices are on the market.

Recommended solution (cont.)

4.4 Earthing rods and lightning rods

Galvanised rods have a limited lifetime. Zinc coating acts as a sacrificial metal, and it will gradually get depleted in the ground. Furthermore, if it is scratched on a rock during installation, it will last even shorter. Once zinc on a galvanised rod is damaged or gone, the exposed steel will corrode quickly. Therefore, it is recommended to use Copper-bonded earthing rods and lightning rods (instead of galvanised). "*A grounding system based on typical galvanised rods will have a lifetime of about **one-third** that of a system based on typical copper-bonded rods.*" I.e. 10-15 years vs 30-40 years respectively. [21]

Fig. 11 - Copper-bonded earth rods with a 254-micron electrolytic coating of copper ensure a long-lasting molecular bond between the strong copper layer and carbon steel core.
It will not slip or tear when driven, nor crack when bent.

4.5 Connections

Good earthing and lightning protection systems also depend on good connections. Lightning strikes produce very high overvoltages and currents in a very short period and are viewed as high-frequency events. The lightning currents create a so-called 'skin effect' in a conductor which is exacerbated at connections and joints. Therefore, running an uninterrupted lightning conductor (down-lead) directly to the earth is very important as installing the best connectors to mitigate the 'skin effect'. Recommended connections are:

4.5.1 For above-ground connections – two connector types:

- Fired-wedge connectors - the best, longest-lasting, and most reliable connectors [13][14].
- V-LOCK nuts for bolted connections - will not get loose [16][17]

Recommended solution (cont.)

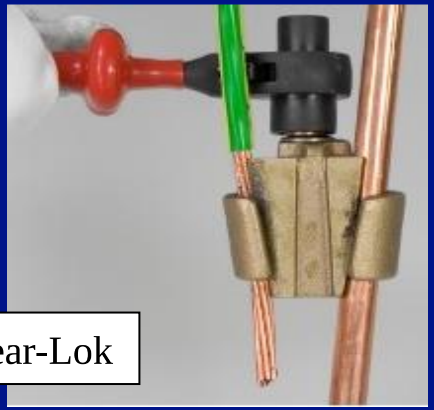
4.5.2 For the connection of the grounding conductor to the ground rod – two connector types:

- 'Hammerlock' connector - easy to install with a hammer only, makes a strong permanent connection; designed to withstand ground faults and lightning currents

Fig. 12 - Patented Eritech 'Hammerlock' connector

- Wedge-type connectors for mid-range magnitudes of fault currents.

Wrench-Lok



Shear-Lok

Fig. 13 – Wedge-type connector recommendations:

Wrench-Lok for substations (meets the IEEE 837 requirements)

Shear-Lok for Lightning Arresters, ABSs, and transformers.

Recommended solution (cont.)

4.5.3 For the underground connections - exothermically welded or fired-wedge connectors. Exothermically welded connections "*provide a molecular bond that will never loosen or corrode.*" [22] They can withstand repeated faults, surge currents, and localised arcing caused by lightning dissipation in the ground because copper melts at 1083 °C versus zinc at 419 °C.

Fig. 14 – Cadweld exothermically welded connections (meet the IEEE 837 Standards)

4.6 Ongoing regular maintenance

The saying "Out of sight, out of mind" also applies to earthing and lightning protection. After the installation, these systems are typically 'forgotten' or neglected, until they deteriorate or fail. These systems should be regularly inspected and maintained as follows:

- Inspect the system visually after each lightning storm or feeder fault
- Test the above-ground equipotential bonding connections for high-contact resistance
- Test earthing system resistivity regularly. It can be high due to volcanic soil. In addition:
    - In areas affected by recent eruptions the soil can contain chemicals and volcanic ash residues that are corrosive and can accelerate the deterioration of both systems
    - Circulating earth currents between the two earthing systems (network and solar) can accelerate galvanic processes and cause corrosion and premature deterioration.

In conclusion - for lightning protection, earthing systems, and equipotential bonding it is necessary to install the best quality, longer-lasting, and cost-effective components.

Recommended solution (cont.)

4.7 Continuous monitoring of lightning arresters

After lightning strikes, many lightning arresters fail internally but it cannot be detected visually. If faulty arresters are not replaced promptly, the subsequent lightning strikes or even transient overvoltages can damage the solar and connected network. Some cost-effective methods exist for remote monitoring and advanced analysis of surge arresters and concurrently getting other parameters of the OH line's health status. One of them stands out as follows:

Fig. 15 – RAM-1 measures a resistive component of the leakage current. It detects arrester destruction, power outages, pole tilt, operation of disconnecting devices, and excessive ambient temperature (fire warning).

It provides a lightning counter and navigation to a fault location.

Easy to install at the bottom of the arrester.

5. Fault detection and location

In a network with large solar generation and a bi-directional power flow, detecting, locating, and isolating faults on time is very important. It is especially critical in radial networks, where a fault could result in a loss of supply to many customers. A fault can also result in unintentional islanding on a radial feeder with dispersed solar generation. [23]

There are many methods for fault detection. Modern monitoring and fault detection technologies are safe (contactless), require fewer detection devices per feeder kilometres, and are cost-effective. One of the recommended systems is as follows:

Fig. 16 – ‘Grayhawk’ measures the magnetic field of the OH line.
No direct contact with OH lines.
Installed at 1.2-1.5 m below the line in~30 min.

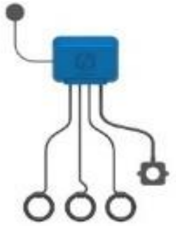
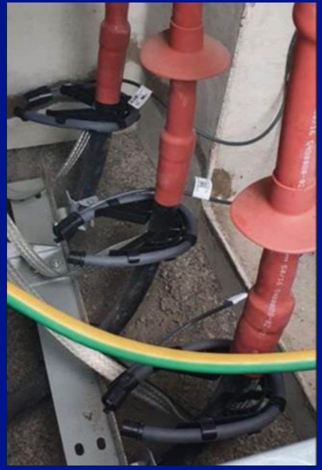


Fig. 17 – ‘Grayfox’ for the UG cable network has Rogowski sensors attached to cable screens.

Installed in ~30 min



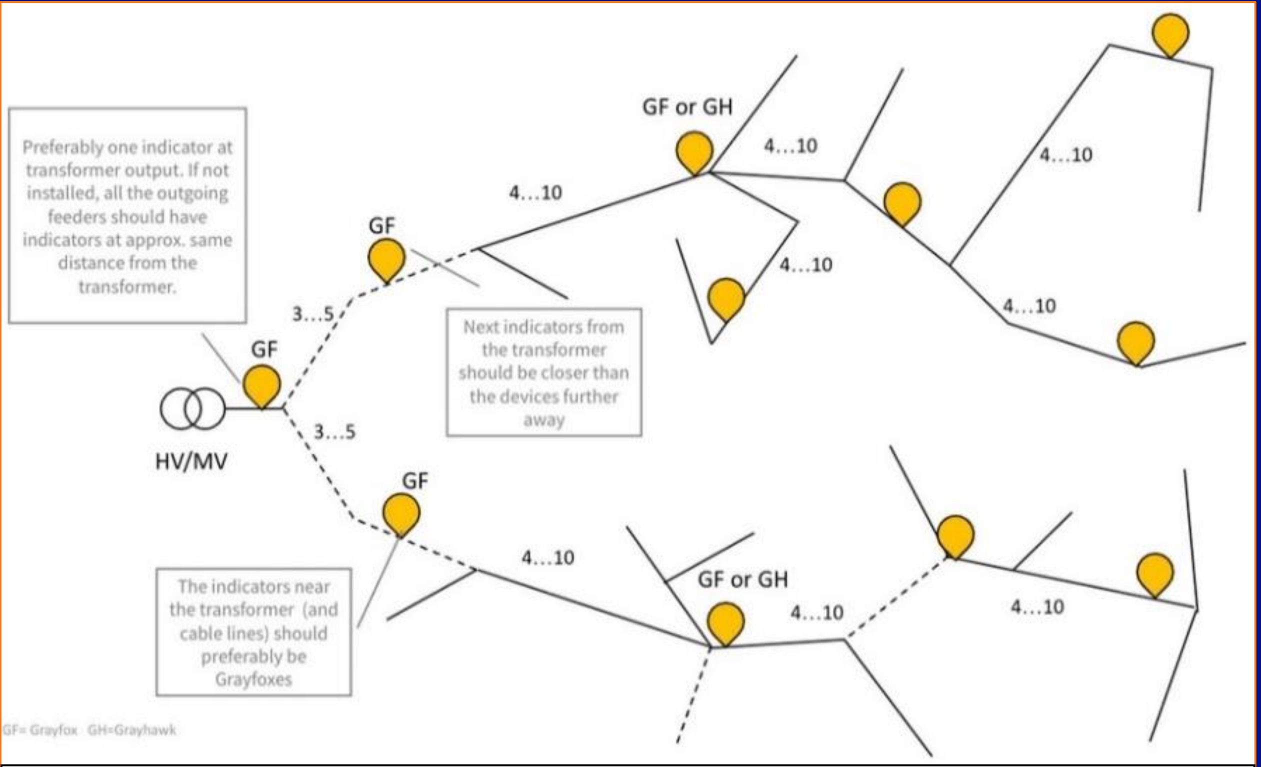


Fig. 18 – The integrated ‘Safegrid’ solution offers the precise location of faults, full network visibility, enables predictive maintenance, and improves SAIDI/SAIFI. Ideal distances between sensors in a rural area are 4 to 10km with a fault location accuracy of <200m.

Conclusions

In this paper, potentially multiple Hidden Costs of Transition to Renewables have been identified and explained.

- Several effective and efficient solutions have been proposed.
- They should also improve the system's reliability and resilience at a minimum or reasonable cost.

This approach is suitable for the Pacific distribution networks with mostly radial feeders. It is also highly relevant and can be applied in other countries to other types of distribution networks with high uptake of renewables. All distribution networks will eventually face the same or similar problem of Hidden Costs of Transition to Renewables.

Applying timely solutions to potential problems and hidden costs of transition to renewables will also significantly contribute to reliable, sustainable and future-proof smart networks, while reducing carbon emissions and bringing tangible benefits to the communities.

Thank you

References

1. Stojadinovic G., Protecting blind spots on distribution networks, *Article in PPA-Magazine-Vol.30-Issue-3-FINAL-1 (2022)*
2. Meskin M. at al., Impact of distributed generation on the protection systems of distribution networks: analysis and remedies – review paper, *IET Generation, Transmission & Distribution Journal (2020)*
3. Shahzad U. at al., Protection of Distributed Generation: Challenges and Solutions), *Scientific Research Publishing, Energy and Power Engineering (2017)*
4. El Naily N. at al., Mitigating The Impact of Distributed Generator on Medium Distribution Network by Adaptive Protection Scheme, *The 8th International Renewable Energy Congress (IREC 2017)*
5. Telukunta V. at al., Protection Challenges Under Bulk Penetration of Renewable Energy Resources in Power Systems: A Review, *CSEE Journal of Power and Energy Systems, VOL. 3, No. 4, December 2017*
6. Farkhani J.L. at al., Impact of Recloser on Protecting Blind Areas of Distribution Network in the Presence of Distributed Generation, *MDPI, Switzerland, Applied Sciences Article (2019)*
7. Teros Recloser, G&W Electric, https://www.gwelectric.com/webfoo/wp-content/uploads/gw-electric-teros-recloser-a-three-phase-gang-operated-15-and-27kv-recloser.pdf
8. Jeremy D. Watson, Neville R. Watson at al., Impact of solar photovoltaics on the low-voltage distribution network in New Zealand, *Article in IET Journals (2015)*
9. Sharma V., at al, Effects of high solar photovoltaic penetration on distribution feeders and the economic impact, *Article in Renewable and Sustainable Energy Reviews (2020)*
10. Mansouri N., at al, Photovoltaic power plants in electrical distribution networks: a review on their impact and solutions, *Article in IET Journals (2020)*

References (cont.)

11. Ali Azghandi M., at al. A Temporary Overvoltages Mitigation Strategy for Grid-Connected Photovoltaic Systems Based on Current-Source Inverters, *Article in Iranian Journal of Science and Technology, Transactions of Electrical Engineering (2020)*
12. Minal Matre, Harmonics in Photovoltaic Inverters & Mitigation Techniques, *Study by Sterling & Wilson Solar www.sterlingandwilsonsolar.com*
13. Stojadinovic G., The truth about wedge connectors, *White paper, TransNet NZ (2020)*
14. W. Holness, Engineering Test Report - Tyco Electronics Transverse Wedge Connector, *Test Laboratory Markham, Ontario (9/11/2009)*
15. Stojadinovic G., Choosing the right IPC fuse – can we see the forest for the trees?, *White paper, TransNet NZ (September 2020)*
16. Stojadinovic G., Little things that make a big difference - Introducing V-LOCK nuts with anti-loosening screw threads, *Article in PPA Magazine (August 2023)*
17. Stojadinovic G., “Solving the problem of cable system failures due to loosening connections”, *CIGRE NZ 2022 Conference, Whakatane*
18. Boonseng C., at al., Investigation and Diagnosis of Lightning Strikes Affects Solar Cell Damage in Solar Farm, *IEEE Conference, Thailand (December 2020)*
19. Weather report on 7NEWS Brisbane, Queensland, www.7NEWS.com.au/ #qldweather #7NEWS, Credit: Nick Doolan (6/12/2020)
20. Richland Source Newsletters Presumed lightning strike knocks out Shelby solar array (richlandsource.com) (*June 2024)*
21. F. D’Alessandro at al., Experimental Evaluation of the Corrosion Performance of Copper -Bonded and Galvanized Grounding Electrodes, *Article in IAEI (2008)*
22. Rempe C., Comparing Copper and Galvanized Ground Rods, *ERICO Inc. USA*
23. Khamis A. at al. Islanding detection and load shedding scheme for radial distribution systems integrated with dispersed generations, *Research Article, IET Generation, Transmission & Distribution (2015)*
24. *Safegrid Intelligent Grid System https://safegrid.io/*