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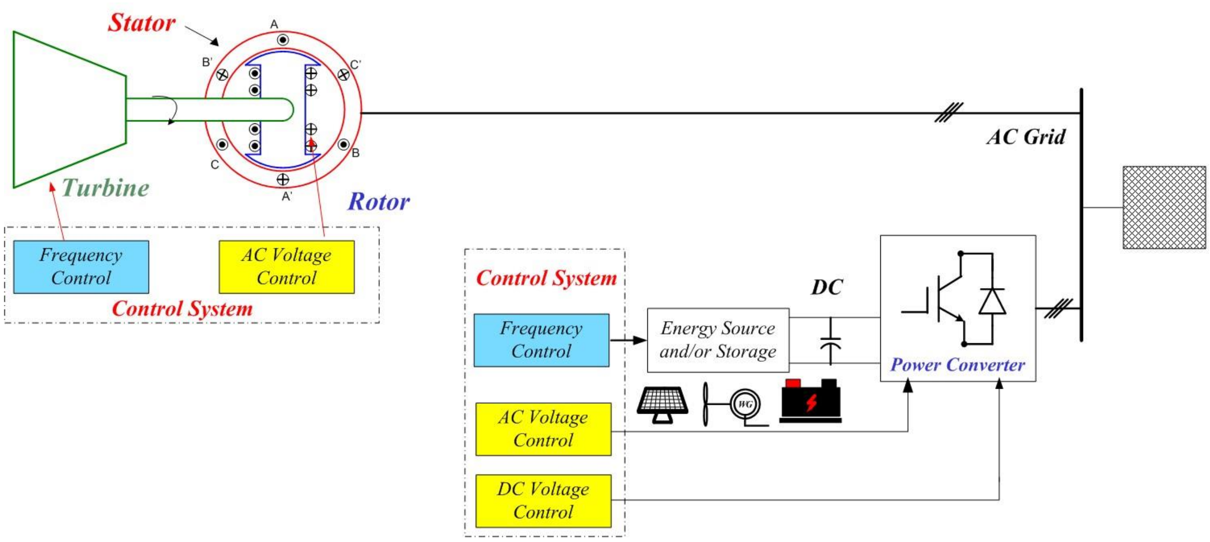

Line Protection Analysis on Faults in Networks with high penetration of Inverter-Base Generation. Recommendations For Future Improvements

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Keywords: Inverter-Based Resources (IBRs), Point of connection (POI), Weak infeed (WI).

Abstract

The increasing penetration of IBRs in power systems presents challenges for conventional protection schemes, particularly line distance protection. These challenges are pronounced in scenarios involving WI sources, where a transmission line connects a strong energy source at one end and a weak or renewable-based source at the other one. In contrast, differential protection schemes, used for generators, lines, and transformers, have demonstrated robust performance in grids with high IBR penetration. This paper analyses the performance of distance and line differential protection for lines in networks with high IBR penetration levels using the Electromagnetic Transient Program (EMT) ATPDraw and the IEEE 9-Bus model. Additionally, it examines the behaviour of other parameters, such as sequence voltages and currents, to explore their potential for enhancing protection schemes. Based on the findings, the paper proposes alternative and complementary solutions, including new protection schemes for both primary and backup systems, with examples of novel approaches to improve fault identification in IBR-dominated grids.

1 Introduction

To enhance the visualization and understanding of infeed effects, a grid model shown in Figure 1 was implemented using the classical EMT software ATPDraw. The model is based on the classical IEEE 9-BUS system, as described in references [1,2], with the addition of two extra buses: BUS10, connected via a 30 km transmission line, and BUS11, connected via another line of identical characteristics but connecting a renewable generation (wind type 3 - doubly-fed asynchronous generator - or solar PV) [3]. The model incorporates distance relays (phase and ground) [4] as well and a basic model for a line differential protection (87L) in line BUS11-BUS7.

The models used to represent power system components, such as generators and relays, have been simplified and may not fully reflect real-world operation in other network topologies or with specific technologies, such as inverters, wind turbines, or devices with incorporated limiters and protection features. Despite these limitations, the observed performance of the devices in this study is expected to closely align with realworld scenarios. For practical applications, it is always recommended to use manufacturer-provided models for more accurate results. All relays employed primary voltage and current inputs, and impedance values were expressed in primary ohms

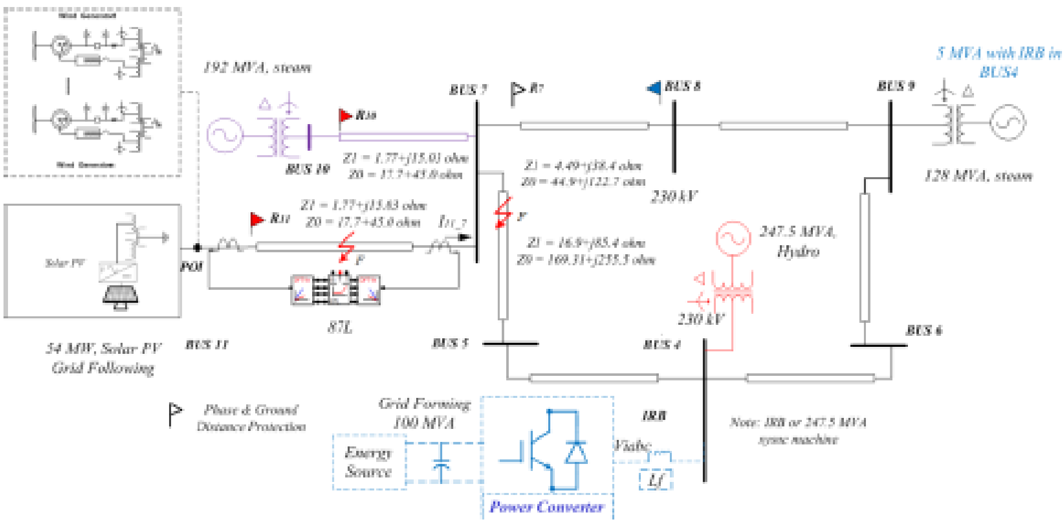

Figure 1 Grid Model used in fault simulations. Fault duration was 100 ms (relay+CB) on a 60 Hz network. Three scenarios were used: 1) Synchronous machines on Buses 4, 9 and 10 plus a PV on Bus 11, 2) Synchronous machines on buses 4 and 9 plus a PV on Bus 11 and 3) PV on Bus 11, IBR [5] on Bus 4 and a small size synchronous machine on Bus 9.

2 Line Protection performance During Internal and External Faults on BUS11-BUS7 line

2.1. Case study - Fault Simulation Results with Solar PV Connected to BUS11

The performance of the primary protection system, specifically the line differential relay, was evaluated under two fault conditions:

1. *Internal Single-Phase-to-Ground Fault*: Fault at 50% of the protected line with 10 ohms of fault resistance.

2. *External Three-Phase-to-Ground Fault:* Metallic fault at one end of the protected line.

These tests provide insight into the protection system's reliability and limitations when renewable solar PV is integrated into the network.

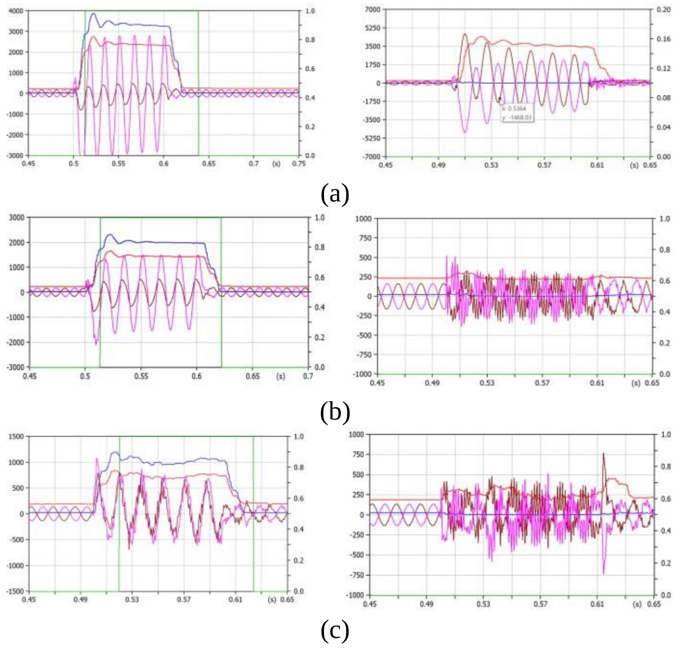

Figure 2 Performance of line differential protection during internal (left) and external (right) faults under different scenarios. (a) scenario 1, (b) scenario 2 and (c) scenario 3 from Fig. 1. Values in blue correspond to differential signals, in red to restrain signals and in brown and pink to current inputs to the relay. In green is show the trip action.

On Fig. 2 we can observe that line differential is very effective during internal faults and stable during external faults for all scenarios analysed. The external fault was simulated on the POI in scenario 1 and on Bus 7 in the other scenarios. The 87L model used is a basic phasor differential, where no filtering and other enhancements has been used. It is expected a better performance if filtering, error estimation and directional elements are being used. Section 3.1.1 describes some enhancements existing in today´s relays provided from some vendors [6] and some other proposals [7] for future develops.

In case of distance protection, as we can observe in Figure 3, the performance is not so good. Note that, even if the fault is in the middle of the circuit, the distance relay "sees" the impedance way outside the relay characteristics. This is a well-known problem reported in several studies. [8,9]

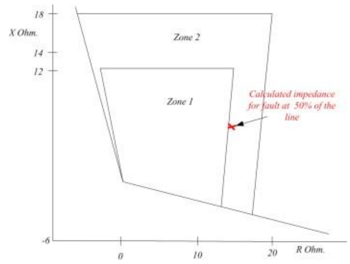

Figure 3 Performance of distance protection for single-phaseto-ground fault at the middle of the line on scenario 2.

2.1.1 Behaviour of other parameters:

Other parameters were also evaluated, to know if some of them could be utilized to support and improve fault detection.

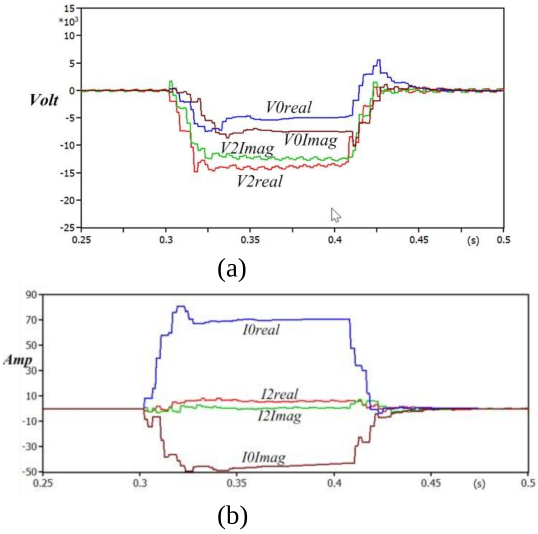

Figure 4 Real and imaginary sequence Voltages (a) and currents (b) in the relay R_{11} during a single-phase-to-ground fault on 100% of the BUS7-BUS5 (longest adjacent line) with 5 ohm of fault resistance on scenario 2.

During a fault, sequence voltages and current angles remain stable. Zero-sequence values offer distinct advantages over negative-sequence values due to their higher signal magnitudes during asymmetrical faults. Both parameters are highly reliable and can be effectively employed for both primary and backup protection with minimal restrictions.

3 Recommendations for future Improvements

3.1 Primary Protection

3.1.1 Differential Protection:

New algorithms enhance stability by employing a dynamic restraint mechanism that adapts to waveform errors, such as non-sinusoidal distortions, by automatically adjusting the restraint level. These algorithms often incorporate directional elements to strengthen restraint during external faults while minimizing or bypassing it during internal faults. By adding additional dimensions to the analysis, such as in the four-dimensional algorithm shown in Figure 5, the performance of differential protection is further optimized, with dynamic adjustments accounting for measurement errors.

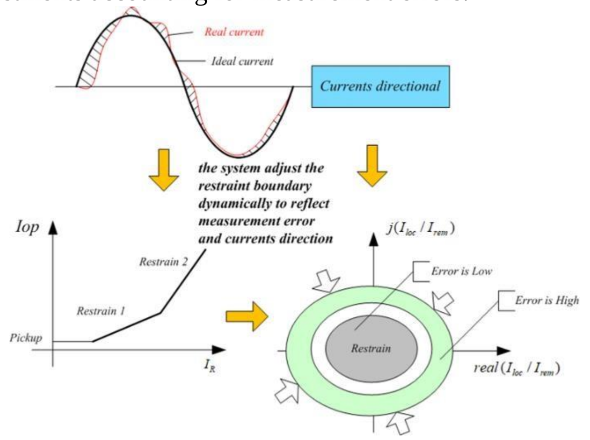

Figure 5 Enhancements to improve differential algorithms performance. [6]

The proposal, illustrated in Figure 6, addresses performance limitations of the algorithm from reference [6], which reportedly achieves operating times around 110 ms. However, it is unclear whether this measurement pertains solely to the algorithm or the total clearing time. Regardless, the state estimator imposes significant processing demands that exceed the capabilities of commercially available relays, leading to longer operating times. To mitigate this drawback, the proposal suggests integrating a conventional algorithm, activated by a supervisory unit (depicted in yellow), to enhance efficiency.

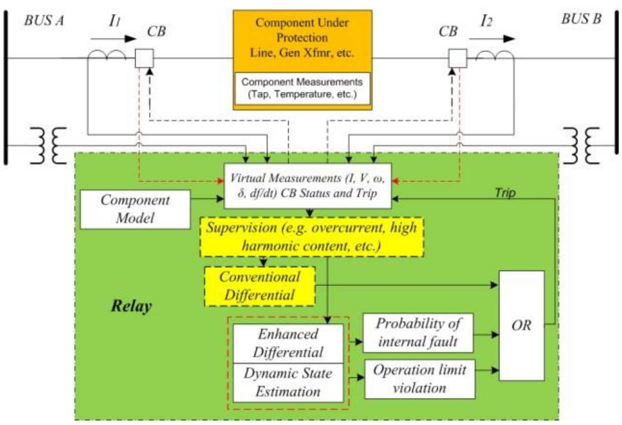

Figure 6 Enhanced differential algorithm incorporating Dynamic State Estimation. [7]

3.1.2 Distance Protection:

Several studies have addressed this challenge for primary protection systems using distance relays, suggesting improvements such as:

1. *Relay Characteristic Adjustments:* Modifying relay characteristics in the inductive region to account for frequency differences between local and remote ends caused by the dynamic response and differences of ROCOF on renewable sources versus conventional synchronous machines: [10]

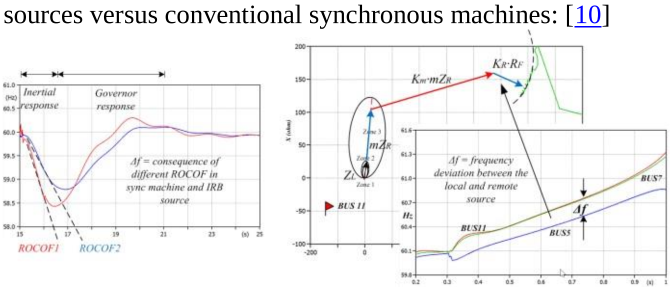

Figure 7 Effect of frequency in relay distance operation.

2. *Enhanced Directional Elements:* Employing IncrementalQuantity Directional Elements optimized for unconventional sources. [10]

3. *Overcurrent Supervision Logic:* Utilizing current magnitude differences to distinguish between forward and backward faults. [10]

4. *Time-Domain Algorithms:* Transitioning to new time-domain distance algorithms to mitigate frequency-related issues in traditional frequency-domain approaches. [10]

5. *Additional improvements by using voltages and currents from both ends:* The most common approach is to use voltage and current measurements from a single line terminal to estimate the fault impedance using various approaches that are referred to as impedance-based single-ended methods and are nowadays a standard built-in function of transmission line relays. All these methods are based on certain assumptions due to a lack of accurate information to solve equations. When the assumptions are not satisfied for a given fault situation, significant errors may occur. Impedance based methods are challenged by many factors, including but not limited to Parallel lines mutual coupling, Uncertainty in zero sequence compensation factor, Fault resistance and power flow, System homogeneity, WI applications, etc. [11]

Relay distance systems that utilize information from more than one line terminal are referred to as multi-ended relay distance. A multi-ended relay distance eliminates the key weakness of a single-ended approach but requires communication channels to relay data from geographically dispersed line terminals to a single location where the actual fault calculations are performed.

One important aspect of distance protection is the accuracy. Accuracy data provided by vendors is only the produced by the internal data collection and calculation of the internal algorithm. [12] We have not data from field operation available but for fault locators, that in essence operates very similar to distance protection. Table 1 shows some results for fault locators' operation during different type of faults on 220 kV transmission lines.

Table 1: Some field results of fault locators on 220 kV transmission lines. [13]

Line	Fault Type	Fault location. Real point (Km)	Error Two-ended fault locator (%)		Error Single-ended fault locator (%)	
			Specification	Real	Specification	Real
1	1PH-G	224	0.5	0.58	1.5	6.47
2	1PH-G	224	0.5	3.53	1.5	8.19
3	2PH-G	224	0.5	0.13	1.5	4.43
4	2PH-G	140	0.5	0.14	1.5	4.64

These results can be extrapolated to distance protection by observing the benefits by using multi-ended relays

3.1.3 Enhanced tripping schemes for primary protection

Some HVDC vendors use a triple protection scheme in their systems with a vote logic for tripping. This philosophy could be used to compensate the dependency from the communication system in new protection schemes.

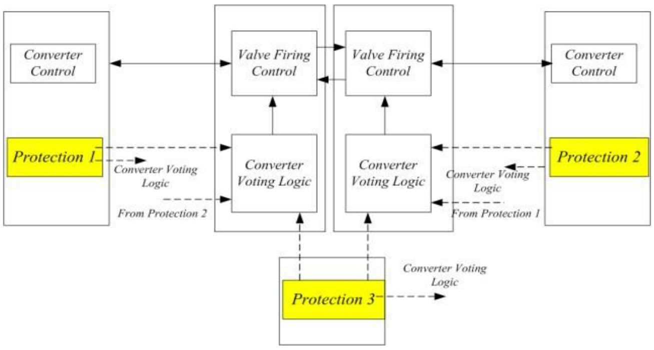

Figure 8 Protection scheme used for HVDC. [14]

Figure 9 depicts a protection scheme without major changes in the actual protection philosophy but incorporating enhanced algorithms with state estimation in some of them.

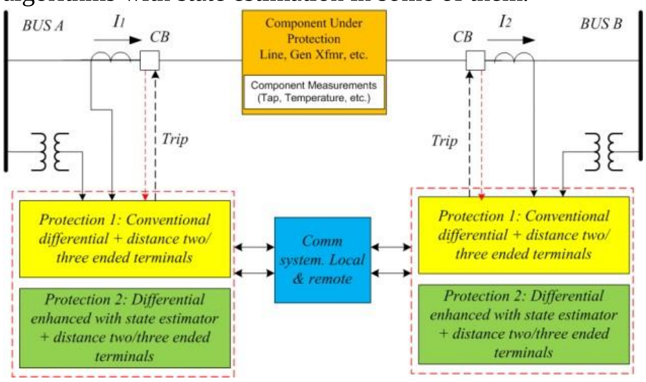

Figure 9 Conventional Protection scheme but modified with new algorithms in distance and differential protection.

3.2 Backup Protection

3.2.1 Remote Weak Infeed (RWI) Logic: [11]

A remote reverse blocking scheme using a routable GOOSE protection protocol is illustrated in Figure 10. In this setup, remote relays send blocking signals to the local relay at CB1 when their reverse directional ground overcurrent elements operate or if their phase overcurrent exceeds a specified pickup threshold. This threshold is set higher than the forward current but lower than the reverse current, leveraging a conditioned overcurrent function.

If the local relay at CB1 receives a blocking signal, it will refrain from tripping. Conversely, in the absence of a blocking signal, the relay will trip based on its forward directional overcurrent or conditioned overcurrent function after a specified time delay. This scheme ensures selective operation and enhances system reliability.

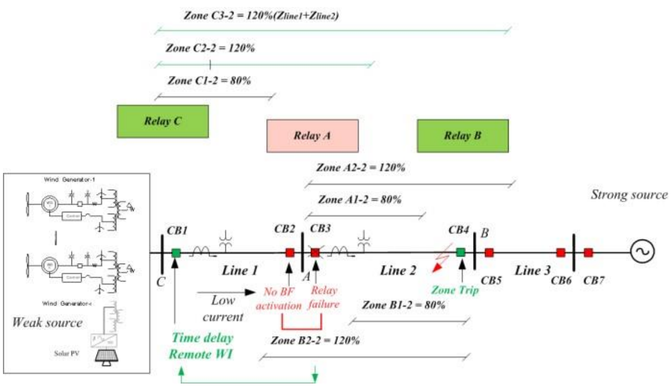

Figure 10 Remote WI logic.

3.2.2 Voltage backup:

Time delay Phase Undervoltage could be used as a backup for three-phase faults and Time delay Negative or zero sequence Overvoltage for phase-to-phase faults. Phase-to-ground faults provide sufficient zero-sequence current for a directional overcurrent function. Remote signals such as the ones described (remote WI logic) could be used to limit the reach to adjacent lines.

3.2.3 Selective Backup Protection for AC HV and EHV Transmission Lines: [15]

Distance protection faces significant challenges as a remote backup solution for high-voltage (HV) and extra-high-voltage (EHV) transmission lines, particularly in ensuring reliable operation across all fault scenarios. Traditional remote backup approaches, like Zone 3 with a time delay to cover adjacent lines, have limitations, including:

- *Unreliable Fault Coverage:* Variations in fault impedance due to resistance and source impedance mismatches can result in Zone 3 maloperations or failures to operate.

- *Overload Maloperation:* Severe contingencies can push load impedance into the Zone 3 region, leading to false tripping.

To address these issues, a novel approach proposes dividing the grid into *Super Nodes* with protective overlaps, similar to the existing concept of Bus Protection but applied to larger grid sections. Super Nodes are balanced during normal operations, enabling differential protection with phasor measurement units (PMUs) as sensors and a Phasor Data Concentrator (PDC), even though sources are geographically distributed. This method introduces a time-delayed operation suitable for backup protection.

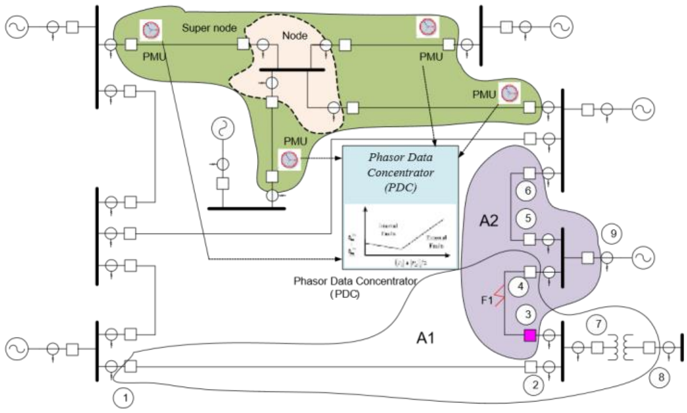

Figure 11 Selective Backup Protection. [15]

4 Final New Protection Scheme proposed

1. *Primary Protection:* distance and line differential protection serves as the first defence with the enhancements proposed.

2. *First Backup Selective Protection*: Time-delayed differential protection using PMUs, typically 200–300 ms. Active power-based criteria are preferred as they are unaffected by line charging or transformer inrush currents. This approach works well even with limited or no infeed from renewable sources like wind or solar, forming the second defence line.

3. *Second Backup Non-Selective Protection*: Conventional methods such as breaker failure (BF), Zone 3, or overcurrent protection act as a secondary backup. These are deactivated when the first backup is active and only enabled if the first backup fails.

In case of complex busbar arrangements, techniques as the mirror's strategies used in bus protection (e.g., double-bus arrangements) could be used.

A *third defence line* composed by a System Integrity Protection Scheme (SIPS) could be also included. [16]

5 Conclusions

- Communications systems are integral to modern protection systems, but they introduce additional dependency. The protection schemes proposed mitigate potential drawbacks.
- Remote inter-tripping schemes, like those proposed in reference [11], can also be used to clear faults on adjacent lines. These schemes apply similar criteria to conventional weak-infeed methods but are designed for remote backup protection.
- Selective backup protection is possible if we can rely on the communication systems as an integral part of any protection scheme.
- EMT software analysis is increasingly required to evaluate electrical phenomena in relays. However, due to limitations in modelling large grids, a new approach using "dynamic phasors" has been proposed to overcome these challenges. [17]

6 References

[1] Paul M. Anderson, A.A. Fouad. "Power System Control and Stability." IEEE Press.

[2] Perry Clements. "IEEE_9BUS_LF.ACP", 2016. [3] Francisco J. Peñaloza, "Demo case PV50MW_MPPT1." Aug. 26, 2015.

[4] Hans Kr. Høidalen. "Impedance element relay." Dec. 11, 2014.

[5] Rossano Musca, Gaetano Zizzo, Alessandro Manunza. "Grid-Following and Grid-Forming MODELS in ATPEMTP for Power Systems Simulation." University of Palermo, Italy, 978-88-87237-55-9 ©2022 AEIT.

[6] L90 Line current differential system, GE Vernova.

[7] A. P. Sakis Meliopoulos, Fellow, IEEE, George J. Cokkinides, Senior Member, IEEE, Zhenyu Tan, Student Member, IEEE, Sungyun Choi, Student Member, IEEE, Yonghee Lee, Student Member, IEEE, Paul Myrda, Senior Member, IEEE. "Setting-Less Protection: Feasibility Study." 013 46th Hawaii International Conference on System Sciences.

[8] Migrate Horizon 2020 project (https://www.h2020migrate.eu/).

[9] Jorge Cardenas. "Line Protection Performance during faults in networks with Solar PV and Wind renewable energy." www.adneli.com/downloads. 2022.

[10] Bogdan Kasztenny. "Distance Elements for Line Protection Applications Near Unconventional Sources." Schweitzer Engineering Laboratories, Inc.

[11] Carlos Aguilar. "Grid backup protection on renewables substation plants: zone 3, overcurrent and other options", GCC, 2020.

[12] M S Saha, J Izykowski, E Rosolowski. "Fault Location on Power Networks," Springer-Verlag London Limited, 2010.

[13] ATN. "Análisis de la función de localización de fallas." 16 nov. 2012.

[14] elumina™ PLATFORM. GE Vernova.

[15] Jorge Cardenas. "Selective Backup Protection for AC HV and EHV Transmission Lines." Actual Trends in Development of Power System Protection and Automation. 01 June – 05 June 2015, Sochi.

[16] Jorge Cardenas. "Impact of Network Protection in the prevention of Major Events in the Power System." CIGRÉ Russia, 2013.

[17] Mario Paolone, Trevor Gaunt, Xavier Guillaud, Xavier Guillaud, Sakis Meliopoulos, Antonello Monti, Thierry Van Cutsem, Vijay Vittal, Costas Vournas. "Fundamentals of Power Systems Modelling in the Presence of ConverterInterfaced Generation." Electric Power Systems Research. December 2020.