# Transmission line protection scheme selection for HV lines with IBRs: Utility example

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***Abstract*—This paper discusses the practical considerations for the selection of type of protection on a transmission line for inverter-based resources (IBRs) application. Phasor based differential (87), distance (21), overcurrent (51, 67), undervoltage (27) and multi-function (11) schemes are considered. Various aspects of protection such as ability to trip locally, reliability (dependability and security), selectivity, speed, simplicity, and economics are compared to select the line protection scheme. The results of cost-benefit analysis are presented in this paper for the project case study which is a 100 MW solar cut in on high voltage (HV) bulk electric system (BES) in southeast United States (USA). Vendor application guides and recent solutions are considered in this paper to shortlist existing issues with relay protection for transmission lines, both at in-and-out station and bulk power stations. The paper also discusses the evolution of philosophy and standards for the particular utility to add perspective to the chosen solution. A decision ladder is proposed which can be applied to select the protection scheme for transmission lines with similar challenges.**

***Keywords— Transmission line relay protection; Inverter based resources; Solar interconnection; Cost-benefit analysis; Protection scheme section decision ladder.***

## I. INTRODUCTION

Several research and planning models including Electric Power Research Institute's (EPRI) technical report [1] and Midcontinent Independent System Operator (MISO) Transmission Expansion Plan (MTEP) show rapid capacity growth, led by solar, through 2030. MTEP23 [2] is also reporting 476 projects in active queue totaling to 86.69GW in south region which is within Entergy's territory. Entergy's illustrative pathway [3] shows generation mix going from 2% renewables in 2022 to 24% (solar 19%, wind 4% and hydro 1%) in 2030 and 77% by 2050 with 33% coming from solar. While there is a lot of focus and research in this area, significant and rapid deployment of renewable resources, bulk of which will be non-synchronous, inverter based resources (IBRs), it also seems fair to say industry is still learning how to integrate these resources into existing systems. In this paper, we will discuss transmission line protection scheme selection for HV lines with IBRs.

Every project flows through different stages such as initiation, planning, execution, monitoring, and closure. Front End Loading documents (FELs) such as Project Execution Plan (PEP) and estimates are baselined at the scoping/planning stage. Funding and project alternatives are also discussed at this stage. There is an expectation to provide risk vs benefit type solutions for every project at this stage. Decision ladder presented in this paper is expected to help stakeholders with project scope selection and project definition prior to detailed engineering or execution.

Vendors, industry forums, researchers are actively supporting utilities in integrating these emerging technologies, however, with the lack of perfect solution, it often is up to every utility (execution) to determine the project scope and execution plan that best achieves business goals. There is also not enough time within the MTEP project schedule to deep dive with a project specific impact analysis and come up with best solution for the given project. Volume is also putting a resource constraint and thus driving design basis as opposed to per project decision. Transmission line protection challenges are well discussed within literature [4]-[9]. Several solutions have also been discussed [8]-[11], some interim, some a better compromise and some through lessons learned over the recent years of operations.

Section II of this paper provides an overview of Entergy's line protection philosophy and a comparison of various line protection functions for IBR applications. Section III discusses the different decision points for alternate protection schemes. Section IV presents the decision ladder on the different points built in section III. This section also shows how it was applied in a specific project and discusses the benefits of the decision ladder. Section V is a conclusion tying it all together showcasing how the decision ladder can help all stakeholders- project sponsors, project leaders, engineers, customers with scope, schedule and cost certainties driving project deliverables.

## II. PROTECTION FUNCTIONS COMPARISION

### *A. Overview of Entergy's line protection philosophy*

With 16,100 circuit miles of transmission lines spanning across 4 states, Entergy's line protection has different permutations to accommodate needs of different interconnecting customers-

**(i) Dual primary** protection with microprocessor distance, directional overcurrent and/or differential relays with POTT and

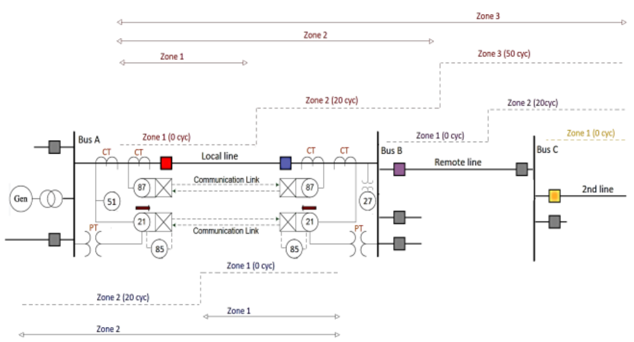


Fig. 1. Schematic summary of different line protection schemes.

DTT using Fiber, Digital Microwave, or Multiplexer for communications. These options are used on lines with critical clearing, system constraints demanding redundancies or critical customers.

**(ii) Single primary and back up** protection with microprocessor distance and directional overcurrent protection with POTT/DCB and/or DTT using PLC, Fiber, Digital Microwave, or Multiplexer for communications. This is common and most used protection scheme on HV lines.

**(iii) No-pilot** protection with microprocessor distance and directional overcurrent protection. This scheme is used for radial lines and on transfer breaker panels.

Entergy also has a sizable percentage of legacy electromechanical and obsolete relays such as solid state relays and early generations of microprocessor relays that are scheduled to be replaced with modern relays as part of multi-year asset renewal program.

### B. *Timeline summary of solar relay challenges at Entergy*

- In 2017, Entergy got its first set of solar interconnect projects. Engineering gets involved with writing scopes on the first batch of facility studies. Protection on these were based off of exiting line protection standards with microprocessor-based communication aided distance protection schemes.
- In 2019 handful of projects move to construction. Engineering group documents lessons learned for future projects. Relay teams learn more on limitations of existing models and distance relay schemes.
- In 2020 Engineering was made aware of the waves of MISO Definitive Planning Phases (DPP) projects in the next 3 years. Based on lessons learned and volume, relay teams stack hands to switch to differential protection as a standard for IBRs.
- In 2021 planning group receives 144 MISO DPP studies- 3x from 2020 cycle and 4x from 2019. Relay team standardizes and streamlines protection philosophy for interconnects.
- In 2022 company shifts to a customer centric business model with a focus in market competitiveness. Revised business goals meant finding creative ways to accomplish project deliverables while reducing spend. The same year Schweitzer Engineering Laboratories (SEL) releases application guide (AG) for line protection (with a focus on distance elements) with advanced logic to improve relay performance in IBR applications.
- In 2023, MISO DPP list grows to 369. 2.5x from 2021 and 10x from 2019. Relay team pilots implementing recommendations from SEL's AG. Evaluates scaling up the solution with impact studies. Comes up with a decision ladder to help determine the right protection scheme and justify project scope

### C. *Protection challenges on lines with IBRs*

Several challenges with IBR response to faults and relay protection has been well documented in literature [4]-[9]. IBR response could be managed by using fast switching of power electronics devices dependent upon manufacturer specific and often proprietary control system design; depends on pre-fault operating conditions, which in turn depends on variable factors such as weather. Relationship between residual voltage and inverter current is nonlinear resulting in oscillating impedance due to the controls within IBR. Short circuit current characteristics are non-universal and highly controlled jeopardizing the use of fault detectors for supervision. IBRs do not produce sufficient negative sequence. Negative sequence polarization has been used as it is immune to load and mutual coupling from parallel lines, this is now challenged. Negative sequence components have been used for phase angle and directionality too which is uncertain with the lack of codes and compliance standards. Mho expansion threatens the reliability of protection. Short line between collector station and utility point of interconnect, high SIR, challenge impedance relay application.

Most interconnects on transmission are built as a cut in on a network line or are connected directly to a network bus. Distance protection schemes are most challenged when IBRs are the sole source to the fault. Not isolating the fault could be a safety concern and relying on the generators to isolate themselves without transmission protection tripping for a fault on transmission system could be a liability. Various schemes are compared using protection principles in two metrics in Fig. 2- (a) if the objective of that principle is achieved ("✓") or not ("X") and (b) if introducing IBR made it better ("▲") or worse ("▼") off.

| Protection function | Local tripping | | Dependability | | Security | | Selectivity | | Speed | | Simplicity | | Economics | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Differential (87) | ✓ | — | ✓ | — | ✓ | — | ✓ | — | ✓ | — | ✓ | — | X | ▼ |
| Distance (21) + Dual pilot (85) + Advanced logic | ✓ | ▼ | ✓ | ▼ | ✓ | — | ✓ | — | ✓ | — | X | ▼ | X | ▼ |
| Distance (21) + Pilot (85) | X | ▼ | X | ▼ | X | ▼ | ✓ | — | ✓ | — | ✓ | — | ✓ | — |
| Overcurrent (51 and 67) | X | ▼ | X | ▼ | X | ▼ | X | ▼ | X | ▼ | X | ▼ | ✓ | — |
| Undervoltage (27) | ✓ | — | ✓ | — | ✓ | — | X | — | X | — | ✓ | ▼ | ✓ | ▼ |

Favorable Acceptable Unfavorable

Fig. 2. Protection functions comparison against protection principles.

| Relay type | N-1 conditions | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Loss of 1 relay | | Loss of 1 comm channel | | Loss of 1 relay function | | Loss of 1 PT | | Loss of 1 DC set | | Loss of 1 line source | |
| | Contingency | Backup | Contingency | Backup | Contingency | Backup | Contingency | Backup | Contingency | Backup# | Contingency | Backup |
| SEL 411L/411L (P1/P2) - DIFF/POTT/DTT, Fiber/Mux, | 411L | 411L | Comm on diff | Comm on pilot and P2 | Differential | Step distance | Loss of line PT | Differential will still work | Loss of station DC | Remote step distance | Solar only source to the fault | Differential trip |
| SEL-421/311C (P1/P2) POTT/DTT, Fiber/Mux | 421 | 311C | Comm on P1 | Comm on P2 | Step distance | Remote step distance | Loss of line PT | Remote step distance | Loss of station DC | Remote step distance | Solar only source to the fault | Echo conversion to trip |
| SEL-421/311C (P1/BU) POTT/DTT, Fiber/Mux | 421 | 311C | Comm on P1 | No Back up | Step distance | Remote step distance | Loss of line PT | Remote step distance | Loss of station DC | Remote step distance | Solar only source to the fault | Echo conversion to trip |
| SEL-421/311C | 421 | 311C | NA | NA | Step distance | Remote step distance | Loss of line PT | Remote step distance | Loss of station DC | Remote step distance | Solar only source to the fault | Non directional under voltage |

*- Schemes using DCB or schemes not using 4xx relays are at additional risk for N-1 conditions.
# - Assuming most stations only have 1 DC battery set.

Favorable Acceptable Unfavorable

Fig. 3. Protection scheme comparison for different contingencies

Differential protection is the most favorable protection scheme but is not always economically viable because of the redundant communication channel it needs. Multifunction microprocessor relays give us the flexibility to program logic and modify schemes without the need for panel replacements which has been explored. Vendors too have come up with versions of application guides [10] to help engineers better balance protection principles. These solutions [11] are only applicable when favorable conditions are present and often reduce dependability to increase security. Solutions may also only apply to certain relays and may not be applicable to relays from previous generation or firmware.

### D. *Line protection performance under contingencies*

NERC TPL standards and good protection practice requires contingencies to be considered. Several factors such as standards, system operating conditions and customer requirements may drive the evaluation for redundancy within the protection system. With existing protection challenges for systems with IBRs, it is important to account for N-1 conditions before selecting the scheme. Fig. 3 above helps understand the adequacy of different panel options under contingencies.

It is noteworthy that dual primary communication assisted distance protection schemes in a multifunction microprocessor relay maybe acceptable in some cases.

At the project planning stage, scope of the project should not be limited to point of interconnect and the immediate remote ends. N-1 loss of line source contingency applies to all buses until the next bulk electric station with three or more sources.

## III. Decision Points for Alternate Protection Schemes

Like with other business decisions, one must strongly consider economic feasibility and weigh the benefits against cost of panel replacements. Even more so when there could be multiple stations impacted between the point of interconnection (POI) and the next bulk station with three or more sources. There is significant value in understanding the “favorable” conditions and evaluating the associated contingencies to determine if a subset of the portfolio could benefit from capital investments made recently as part of other projects or through asset renewal programs. It is clear from Fig. 2 and Fig. 3 that communication assisted multifunction relays (21, 85, 67, 51, 27) are needed with redundancy to sufficiently protect transmission lines with IBR interconnects. We will build the decision ladder to find economical solution by reducing the need for differential panels.

### A. *Building the decision ladder*

1) *No existing protection deficiencies:* It is recommended to start by evaluating if the current application of the scheme is adequate with overlapping zones of protection for different operating conditions. This will also include checking for the relay range, compatibility, protection holes, fault detection etc.

2) *No known long term system constraints*: Long line followed by a short line, looped networks, lines with multiple tap stations, series compensated lines, lines prone to high fault resistance, multi terminal lines with normally open points are some examples of system constraints. Lines with critical clearing times is another prime example

3) *No mutual lines impacting apparent ground impedance*: With the lack of sufficient negative sequence components, ground impedance is now critical in determining the directionality and polarization. When there are mutuals or other factors impacting apparent impedance, zero sequence voltage polarized ground reach elements are vulnerable to overtripping for the most probable fault on the system- 1LG [9].

4) *Electrically long lines*: For a distance element, the higher the SIR (shorter the line), the lower the restraining voltage at the relay for an out-of-zone fault. Distance relays are typically set to accommodate the accumulation of errors from different sources which could be as high as 26 to 31% [9].

5) *Strong grid*: Instrument transformer errors, line impedance data, relay accuracy issues are all exacerbated in application to weak system. It is important to consider N-1 contingencies and the corresponding relay performance to determine the application of schemes [9].

6) *At least one end of either remotes is connected to the grid providing "favorable" conditions*: The distance elements are permitted to operate in the following conditions [10]:

- $I_1$ current is higher than $I_{MAX}$, with margin, for 3P faults.
- $3I_2$ current is higher than $I_{MAX}$, with margin, for line-to-ground, line-to-line, and double line-to-ground faults.
- $3I_2$ current is lower than $I_{MAX}$, and voltage-based fault identification and selection (FIDS) is enabled, for line-to-ground faults.

While these conditions could be difficult at the point of interconnect or at immediate remote ends, we could expect these "favorable" conditions at the remote bulk station with 3 or more sources.

7) *Ability to leverage vendor recommended advanced logic for IBRs*: Vendors have proposed advanced logic to improve the performance of relays when challenged with IBRs. These recommendations come with limitations as these can often only be applied to certain types of relays [10]. These recommendations de-sensitize elements and reduce dependability to increase security. While generally resulting in a better scheme, most advanced logic solutions are still up to engineering judgement. Existing panel type might not be suitable to apply vendor solutions and might be vulnerable to performance issues.

8) *IBR GSU with a strong ground source*: Interconnecting generator step ups (GSU) are not always set up as a strong zero sequence source. Not having a strong ground source affects the zero sequence response and all the elements that depend on that quantity including polarization and reclosing permissive logic. Declaration of ILOP also arms a zero-sequence time-overcurrent element.

9) *Dual differential protection on remote lines closer to IBRs*: Zone 2 and forward looking Zone 3 elements are back up line protection schemes and come into play during contingencies. Having sufficient redundancy locally reduces the reliance on time delayed, less dependable back up protection elements.

| Order of confidence to rely on distance panel for IBRs |
|---|
| Ability to not lose a strong source for the loss of one breaker or for a single contingency |
| Dual POTT scheme without SPOF |
| Dual differential protection on remote lines closer to IBRs |
| IBR GSU with a strong ground source |
| Ability to leverage vendor recommended advanced logic for IBRs |
| At least one end of either remotes is connected to the grid providing "favorable" conditions |
| Strong grid |
| Electrically long lines |
| No mutual lines impacting apparent ground impedance |
| No known long term system constraints |
| No existing protection deficiencies |

Fig. 4. Decision ladder for protection scheme selection in IBR application

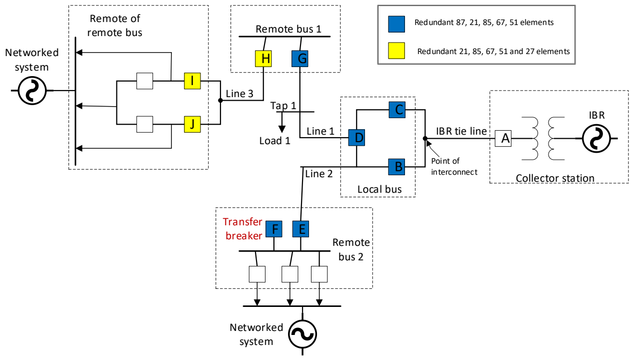


Fig. 5. Schematic outline of project system.

10) *Dual POTT scheme without single point of failure (SPOF)*: At remote and remote of remote stations where protection schemes rely on communication assisted trip schemes, it is important to have redundant communication channels since local trip could be dependent on that transfer trip or echo key. 21G logic is not available for faults fed by IBR because voltage-based FIDS is not available with DCB schemes. For this reason, POTT schemes are preferred.

11) *Ability to not lose a strong source for the loss of one breaker or single contingency*: Some station configurations such ring bus and double bus allow to retain source for single contingency events. Some single bus configurations have transfer breakers through which the source can be picked up for loss of line breaker. In strong networks, these configurations reduce the probability of being single sourced from IBRs and the negative effects of weak source on relays. Such strategic planning plays to the advantage of system protection even possibly mitigating the need for differential relay panels.

## B. *Applying the decision ladder: Utility example*

As part of generator interconnection agreement (GIA), Entergy Mississippi LLC (EML) entered into an agreement with MISO and a customer who was seeking to interconnect 100MW of solar photovoltaic generator to Entergy's 115kV transmission line. The interconnection of the customer resulted in the need of a new three breaker switch station (local bus in Fig. 5), to be owned and operated by EML. The facility study at the time only included the point of interconnect station and the immediate remote ends. Facility study process failed to identify the need to expand the scope of study beyond immediate remote station (remote bus 1), which is an in-and-out station, to the next bulk station (station with 3 or more sources). As part of PEP, relay impact on line 3 was analyzed. Facility study process also failed to include transfer breaker at remote end (remote bus 2) and the impact of interconnection while fed through transfer/bypass breaker. As part of PEP, relay impact for transfer breaker (at remote bus 2) was also analyzed.

Relays at transfer breaker F did not have any comm schemes reducing our confidence to use existing panel without hardware upgrades. Grid management's preference was to operate any line, including line 2 on transfer breaker when needed without any protection limitations for different system configurations. This will avoid radial conditions and reliability risks to customers. This flexibility will also not jeopardize the reliability of co-op's interconnection points tapped on the line. Bypass panel mirroring the protection scheme of the line panel was the most preferred solution for maintenance. Benefits of panel upgrade to standard option outweighed the cost of major hardware upgrades on existing panel. Line 3 has SEL-421 (Primary 1) 311C (Primary 2) POTT/DTT over multiplexer (MUX). This checked all the boxes of the decision ladder for the team to retain the existing panel and apply settings revisions to provide acceptable protection. Relays at breaker H on line 3 will rely on echo conversion to trip logic on weak infeed for ("unfavorable") conditions where it cannot detect and trip for a fault locally. It will also have to rely on undervoltage trip as a backup function. This was a risk utility was willing to accept for the cost benefit presented. Engineering, procurement, construction combined helped save $500,000 for this one project which was really two panels.

## IV. Conclusion

Scope, cost and schedule certainty forms the basis of successful project management. Decision ladder helps communicate uniformly across different customers interconnecting at different points in the system. MTEP facility studies are fast paced, high volume which demands clear strategy for engineering scoping that the proposed decision ladder can provide. Relay protection is both an art and a science. There is a design basis which varies from one utility to another, but there is always an engineering judgement at a project level. Having a consistent approach across the team helps all stakeholders and that is what is proposed in this paper. Industry is changing, our utility's culture is changing and so is our operating model which is becoming more customer centric. More options will be presented and teams must have the ability- tools and resources- to execute on it. Rapid acceleration of emerging technologies is not allowing for standard approach for a process and a solution to mature its way one by one though research, engineering and execution, rather, industry is working in parallel through these processes to meet project demands. Engineering decisions are challenged by project sponsors asking for cost benefit analysis of the scopes. Engineering organizations are also being asked to present the risks and benefits of alternate solutions to win in a market that is becoming more competitive. Decision ladder lays the decision points in front of all stakeholders to give the consistency and confidence in decision making empowering leaders to ensure scope of work and execution plan meets business goals. With over 300 projects in queue the potential for saving with this approach is expected to be in the millions which is promising.

Industry is at the cusp of energy transition. As renewables are embraced, engineering and protection challenges evolve as well. This paper focused on the application of solutions at a scoping stage rather than at the execution or detailed engineering stage. Problems associated with IBRs were packaged to give the big picture view of the risks that could expose protection scheme vulnerabilities and tied it to how it affects project deliverables. This paper also broke down the issues as it applies to utility's network system to determine if the chosen protection scheme would work. Different protection schemes were compared against the protection principles. Decision ladder was proposed also as a tool to justify the tradeoffs in protection principles to the business goals as it applies to projects. Through a project example, it was also shown how a decision ladder can help improve project deliverables and bring value in cost savings with the potential to scale up for several projects in queue.

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## Biography

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