Inverter-Based Generation Integration Protection Challenges: Real-life Experiences

Monir Hossain, Ph.D.
Electrical Engineer
Entergy Services, Inc.
New Orleans, LA
mhoss93@entergy.com

Sean M Boyer
Electrical Engineer
Entergy Services, Inc.
New Orleans, LA
sboyer@entergy.com

Scott C Brown
Electrical Engineer
Entergy Services, Inc.
New Orleans, LA
sbrow16@entergy.com

Tu H Nguyen
Electrical Engineer
Entergy Services, Inc.
New Orleans, LA
tnguyen@entergy.com

***Abstract*—This paper shares the real-life engineering experiences and the relay protection challenges when integrating inverter-based generation into the transmission grid. This article covers the relay impact study, the proposed protection scheme design, and the protection scheme implementation. The relay impact study reveals the impacts of transmission network sparsity and inverter-based generation on traditional protective relaying. The article concludes by describing the two years of post-implementation performance.**

***Index Terms*—Keywords:**

Inverter-Based Resources(IBR): Resources that are asynchronously connected to the electric grid and are either completely or partially interfaced with the bulk power system through power electronics.

Bulk Electric System (BES): The electricity power generation facilities combined with the high-voltage transmission system, which together create and transport electricity.

Source Impedance Ratio (SIR): the ratio of the source impedance behind the relay location, ZS to the line impedance protected by the distance relay, ZL.

I. Introduction

In recent years, the introduction of inverter-based resources (IBR) has dramatically increased. Large-scale (greater than 1MW) solar resources have drawn favor over traditional fossil fuel-based generation. This can be attributed to environmental, political, engineering, and other factors. Electric utilities generally have large fleets of traditional generation that are being supplemented or replaced by IBRs. Historically, relay protection schemes assumed the presence of three-phase synchronous generation when determining the presence of faults or other abnormal conditions on the bulk electric system (BES). With the increased presence of asynchronous IBRs, there are new relay protection challenges. This paper shares the real-life engineering experiences and the relay protection challenges when integrating inverter-based generation into the transmission grid.

Section II of this paper describes the project summary. Section III presents the relay impact study and its findings. The solutions and implementation including testing are illustrated in Section IV. The concluding remarks are presented in Section V.

II. Project Summary

In 2019, there was an interconnection customer, Iris Solar, who requested approval from Entergy Services, Inc. to pursue the construction and interconnection of 58.8MW of solar-based generation to the BES. Due to the location of the customer's solar arrays, the 115kV utility line from Amite 115kV substation to Bogalusa 115kV substation was identified as the interconnection location (Fig.1). Specifically, a location between Holton 115kV tap station and Franklin 115kV tap station was chosen as the construction site for a new substation, Par. The new substation would be constructed as a three-breaker ring bus as recommended for IBR interconnection [1]. Two nodes of the ring would be connected to the existing Amite 115kV and Bogalusa 115kV substations, while the last node would be connected to Iris Solar 115kV.

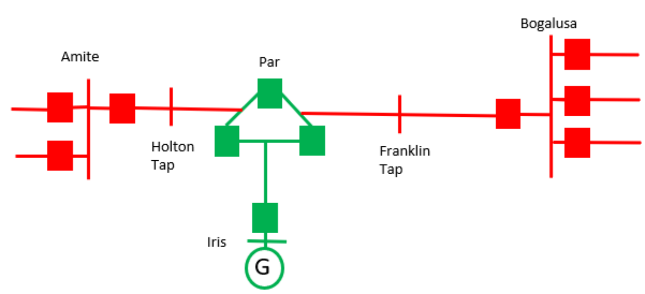

Fig. 1. Iris Solar Interconnection Scope (Green)

III. Relay Impact Study

The study included the re-evaluation of the existing protection scheme for the adjacent network with the new solar generation, identifying the proper protection for new interconnection, and the required protection enhancement for the adjacent network. The relay impact study started with the modeling of solar generation in fault analysis software. To simulate this source, the solar generation was modeled as a voltage-controlled current source [2] in short circuit software.

During the relay impact study, multiple issues were identified related to the cut-in of Par and the presence of the new solar generation:

- Short transmission line (1000ft) between Par 115kV substation and Iris Solar 115kV substation.
- Weak feed from Iris Solar 115kV substation during fault scenarios.
- Lack of negative sequence current contribution from Iris Solar 115kV substation during fault scenarios.

Issue 1: Short transmission line

Since the transmission line from Par 115kV to Iris Solar 115kV was only 1000ft long, the source impedance ratio (SIR) as seen from the Par terminal was found to be 500. This value far exceeds the IEEE definition of a "short" line [3], [4]. Impedance-based relaying has difficulty securely locating and tripping for faults on short lines. Specifically, short transmission lines generally have relatively small impedance which results in little resistive coverage from mho circle-based impedance zones.

Issue 2: Weak feed from solar

The solar generation at Iris Solar 115kV was to be comprised of 14 inverters at 4.2MW each connected at 34.5kV; the total aggregate is 58.8MW. Thus, the max aggregate load of the solar at 34.5kV is 984 amps derived from Equation (1).

To simulate this source, the solar generation was modeled as a voltage-controlled current source in short circuit software. Once the voltage at the 34.5kV bus dropped below 0.7pu, the solar was modeled to produce 1082A (1.1pu). After stepping through a 115kV-34.5kV transformer, only around 300A would be seen on the 115kV transmission system. Specifically, in the case of a fault on the Par 115kV to Iris Solar 115kV transmission line, the Iris Solar terminal would have a weak feed condition (325A) as shown in Fig. 2. The weak feed conditions demand to reduce the current transformer ratio (CTR) so the relay impedance elements can see the faults. However, the same current transformer (CT) experiences much higher current (8035A) from transmission system when faults are on the solar side (Fig. 3). These situations create the dilemma of selecting the proper CTR because tapped CTs are prone to saturate during high-fault current scenarios.

$$I_{max\ load} = \frac{58.8MW}{sqrt(3) * 34.5kV} = 984A \tag{1}$$

Issue 3: Lack of negative sequence current from solar

Traditional IBRs only produce positive sequence current during faults; thus, there is an absence of negative sequence and zero sequence current contributions. To correct for the lack of zero sequence current, transformers which connect the inverters to the BES are generally configured with a delta-connected tertiary winding to act as a source of zero sequence current; Iris Solar was designed as such. Additionally, the requirement for IBRs to provide negative sequence current is stated in IEEE P2800. However, the Iris Solar project occurred prior to IEEE P2800 being published. Therefore, there is no source of negative sequence current from Iris Solar (Fig. 4). This poses a serious issue to relay systems which require negative sequence to determine the directionality of protective elements. Furthermore, a lack of directionality can result in undesired operations and non-operations.

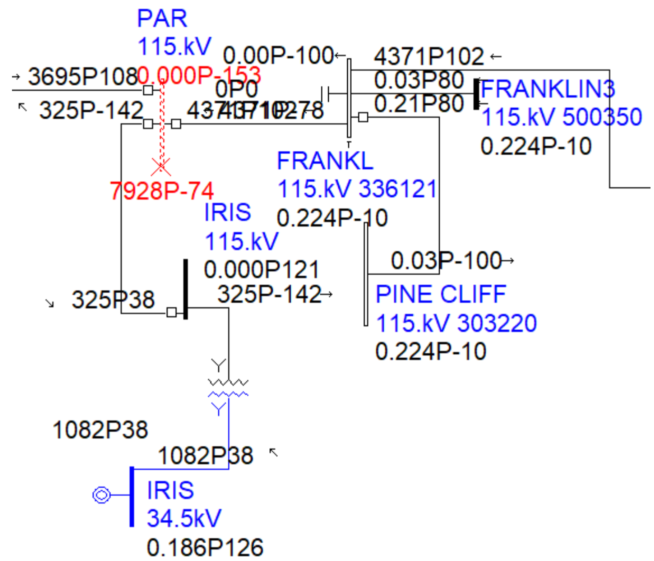

Fig. 2. Weak feed from Solar

Issue 4: Network Sparsity

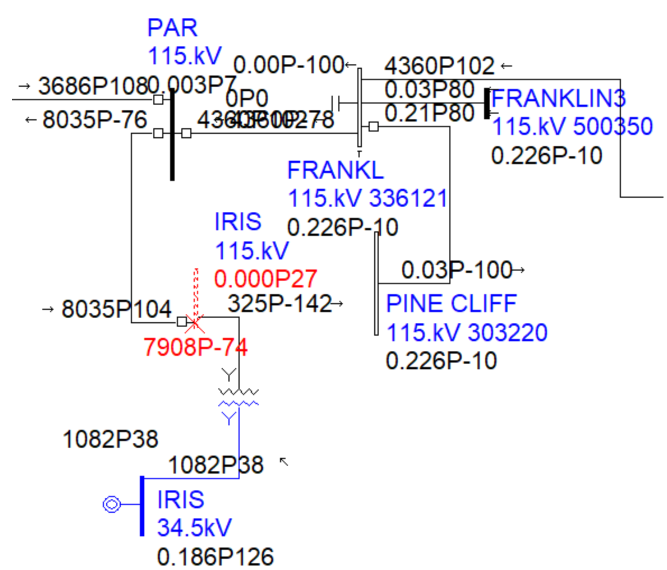

Fig. 3. High fault current from transmission side

The relay impact study also included contingency conditions. The study identified that both PAR-Amite and PAR-Bogalusa lines can be radially connected to the solar as shown in Fig. 5 and Fig. 6 during N-1 contingency condition. During that radial configuration both of the above-mentioned lines have the issues of weak feed and lack of negative sequence current. These issues will continue to spread in the adjacent network until a station has more than two active sources.

A. Relay Scope Identification

The study identified the required protection for the new system components as well as the enhancement of the existing protection schemes as mentioned below.

- Par-Iris Solar line:- New line protection panel for both ends.
- Par-Amite line:- New line protection panel at Par and replacing the existing Amite end panel.
- Par-Bogalusa line:- New line protection panel at Par and replacing the existing Bogalusa end panel.
- Par breaker control:- Three new breaker control panel for Par.

Iris bus and unit transformer protections were included in the solar plant scope.

IV. Implementation

A. Implemented Solutions

Since traditional distance relaying has issues with “short” lines as defined in [3], differential relaying was identified as the solution for all three lines. Not only are the deficiencies of impedance-based relaying hidden by differential relaying, but so is the weak feed condition. Furthermore, the weak feed condition has no impact on differential relaying because of the increased sensitivity of differential elements and the differential scheme’s security. Specifically, since the differential scheme is comparing current flow at each terminal of the line, internal faults will see high current at the Par 115kV end and low current at the Iris Solar 115kV end triggering the differential relay to pick up (Fig. 4). Conversely, faults into the Iris Solar 115kV system will result in high current on both ends of the transmission line in opposite directions, and there will be no operation of the differential relaying (Fig. 3).

The line panels on the three lines identified were designed to incorporate dual SEL-411L relays with two redundant fiber channels. Additionally, each line protection scheme was designed with one additional fiber channel per relay to be used for the SEL Mirror Bit Protocol. Furthermore, the SEL Mirror Bit communications were designed to perform direct transfer trip (DTT) in the case of a breaker failure and to communicate breaker and line switch statuses. Once the design was implemented, each line would have two redundant differential relays on each terminal to make a total of four

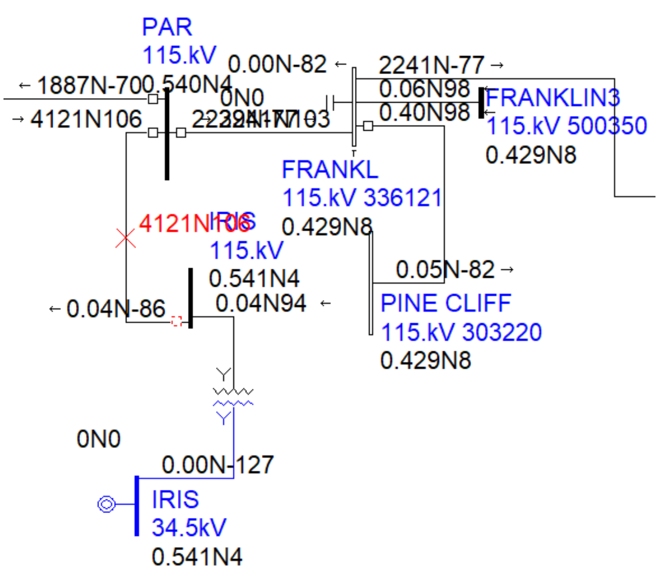

Fig. 4. Phase-phase fault on Par - Iris Solar 115kV line.

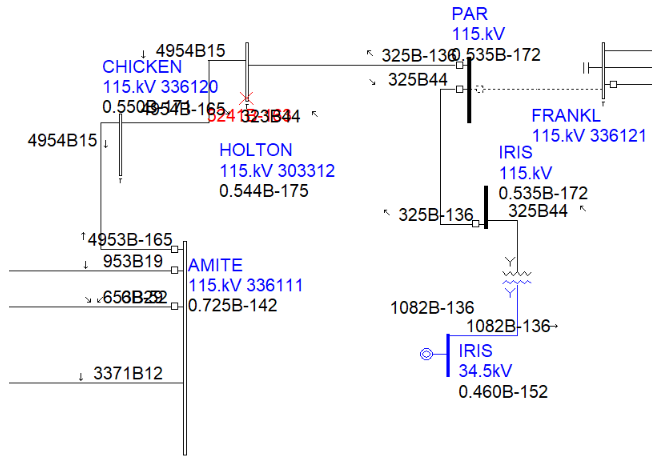

Fig. 5. Fault on Par-Amite line with Par-Bogalusa line out in N-1

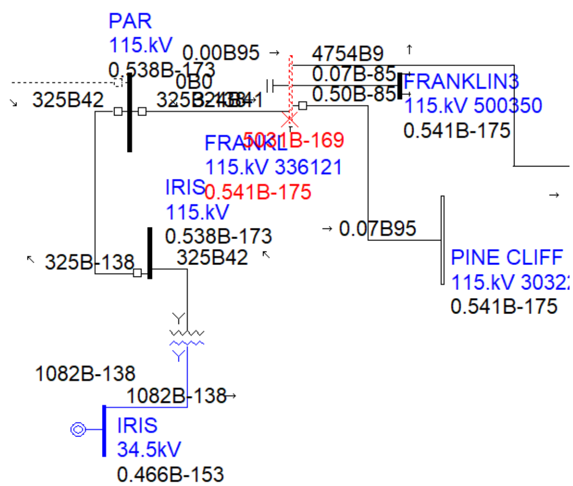

Fig. 6. Fault on Par-Bogalusa line with Par-Amite line out in N-1.

redundant differential channels.

In addition to the implementation of differential relaying, there were other standard relay functions that needed to be disabled or modified to account for the protection issues caused by the solar cut-in. Due to the ineffectiveness of impedance-based relaying when applied to "short" lines or lines with weak feed scenarios and the reliance of traditional communication-based protection schemes on negative sequence-based directionality, the permissive overreach transfer trip (POTT) scheme was disabled or delayed. Breaker failure functions were unable to be current supervised due to scenarios where weak feed could occur. Thus, breaker statuses (52a) were used to supervise breaker failure tripping where weak feed conditions were possible.

1) Summary of Par-Iris Solar line protection:

- Dual line differential with redundant channel
- Time-delayed step distance at both Par and Iris Solar supervised by communication scheme failure (Backup)
- Directional polarizing quantity: V
- No POTT scheme
- DTT scheme for breaker failure

2) Summary of Par-Amite line protection:

- Dual line differential with redundant channel
- Time-delayed POTT scheme
- Time-delayed step distance at both Par and Amite supervised by communication scheme failure (Backup)
- Directional polarizing quantity: V
- DTT scheme for breaker failure

3) Summary of Par-Bogalusa line protection:

- Dual line differential with redundant channel
- Time-delayed POTT scheme
- Time-delayed step distance at both Par and Bogalusa supervised by communication scheme failure (Backup)
- Directional polarizing quantity: V
- DTT scheme for breaker failure

B. Testing

All the above mentioned line and breaker control protection schemes were tested during commissioning to ensure the expected functionality. For each line panel two separate methodologies were applied as mentioned below.

- Relay element calibration testing: Each function of the relay including protection alarm were tested to ensure pick-up values. The calculated currents and voltages were simulated from power system simulator to inject to the relay [5].
- End-to-End Testing: End-to-End test was conducted to check the functionality of the communication aided schemes (line differential, POTT, and DTT). Various faults (internal and external) were simulated in the customized test system based on fault analysis software, power system simulator, and GPS.

V. Conclusions

As solar-based generation continues to penetrate the power grid, relay protection solutions are continuously evolving. Unfortunately, many protection challenges are still present, including weak feed scenarios and lack of negative sequence current contributions from solar resources. The Iris project facilitated the opportunity to explore the challenges in the implementation level. In Iris Solar project, redundant differential relays were used to compensate for the ineffectiveness of traditional impedance-based relaying and adjust for weak feed scenarios and the lack of negative sequence necessary for directionality. The protection schemes have performed as intended during hurricane IDA and some other fault events since 2020. The solutions implemented in the project in addition with smart inverter and time-domain based protection schemes [6], [7] may pave the way for future protection standards.

References

[1] "IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," in IEEE Std 2800-2022 , vol., no., pp.1-180, 22 April 2022, doi: 10.1109/IEEESTD.2022.9762253.

[2] Type-4 Wind Plant and Solar Plants, ASPEN modeling instruction.

[3] IEEE Standard C37.113, IEEE Guide for Protective Relay Applications to Transmission Lines.

[4] M. J. Thompson and A. Somani, "A tutorial on calculating source impedance ratios for determining line length," 2015 68th Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2015, pp. 833-841, doi: 10.1109/CPRE.2015.7102207.

[5] M. Hossain, M. I. Quinteros and H. Al Marhoon, "Testing Impedance Characteristics," 2019 72nd Conference for Protective Relay Engineers (CPRE), College Station, TX, USA, 2019, pp. 1-5, doi: 10.1109/CPRE.2019.8765887.

[6] M. Hossain, "Bus Protection in Time-Domain," 2022 75th Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, USA, 2022, pp. 1-4, doi: 10.1109/CPRE55809.2022.9776566.

[7] J. P. G. Ribeiro and F. V. Lopes, "Time-domain protection elements: Study and implementation," 2018 Simposio Brasileiro de Sistemas Eletricos (SBSE), Niteroi, Brazil, 2018, pp. 1-6, doi: 10.1109/SBSE.2018.8395541.