

Co-Design of Inverter-Based Resources and Protection Systems for Improved Compatibility

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Introduction

In grids increasingly dominated by inverter-based resources (IBRs), there is a need for some form of enhancement to the grid and/or some form of modification to inverters to provide system services.

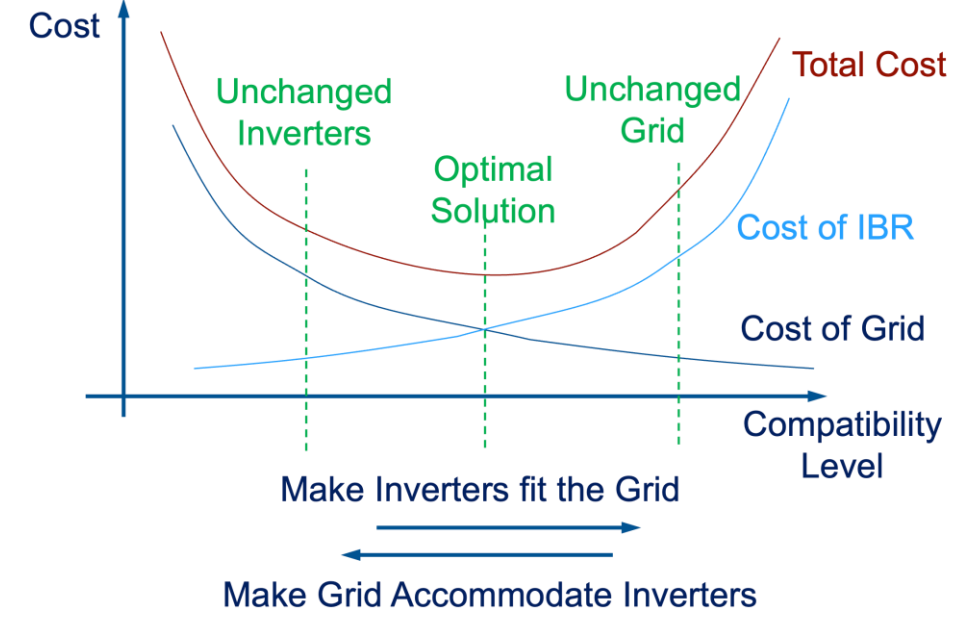
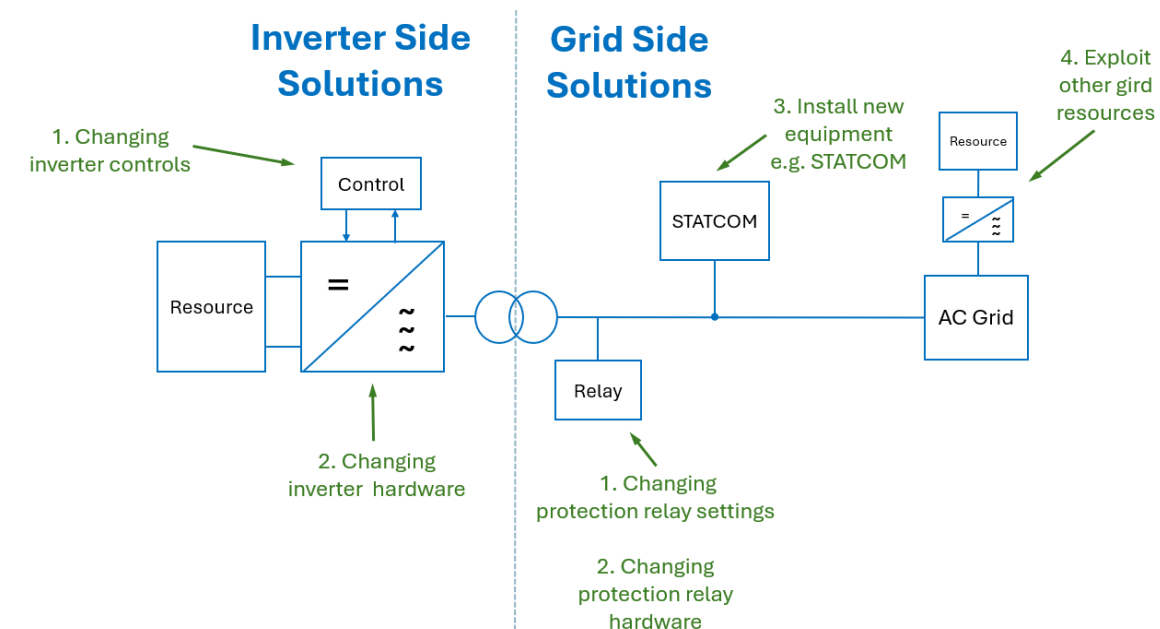


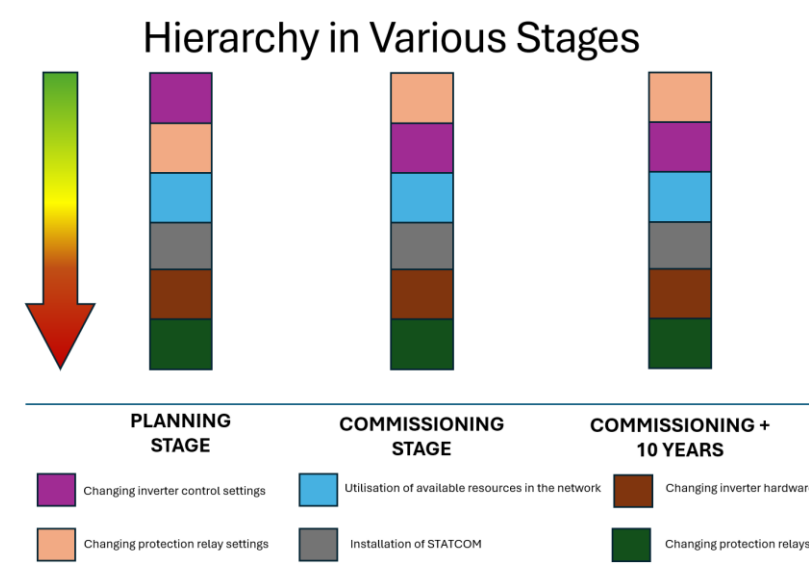
Figure 1: Total Cost of a Grid with IBRs [1]

This work presents a framework for evaluating the trade-off in grid and inverter co-design and proposes an enhanced fault current control method aimed at making distance protection more compatible with inverters.

Step 1: Outlining Possible Changes on the Grid and IBR sides to Meet Protection Needs



Step 2: Building a Hierarchy Based on Engineering Judgement



Step 3: Exploring Solutions Beginning with the Top (Simplest) in the Hierarchy

The planning stage is considered in this study and distance protection is explored because of its proliferation either as main or backup protection in various power systems.

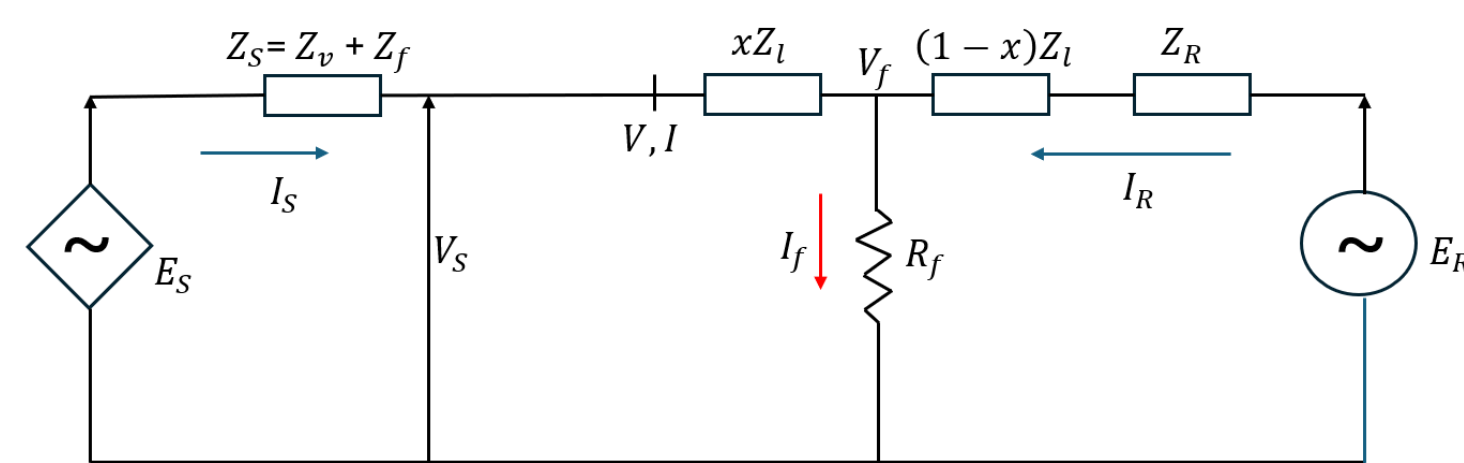


Figure 2: Three-Phase Fault Equivalent Sequence Circuit

$$\frac{V}{I} = xZ_l + R_f \frac{I + I_R}{I} \quad (1)$$

Step 3 (contd.)

- Figure 2 shows the equivalent sequence circuit diagram during a three-phase fault for an inverter connected to the electric grid through a transmission line (see model description).
- Distance protection works by calculating the apparent impedance of a line and selectively tripping the line if the calculated value differs from what is expected, which could signify the presence of a fault.
- Equation 1 represents the apparent impedance of the line as seen from the relay point (V, I) during a fault (at a point x along the line, Z_l). The apparent impedance includes an error term described by Equation 2. The Error term has to be allowed for in the settings of the protection relay. If I_R and I are in phase, the error will be resistive only, and this is relatively straightforward to reject in the relay settings. An angle difference between I_R and I will cause a reactive error, which is harder to distinguish from the genuine reactance of the line.

$$Error = R_f \frac{I + I_R}{I} \quad (2)$$

Method: Enhanced Fault Current Control

The fault current control algorithm used in this study is as described by Equations 3 - 4 for the GFL and Equation 5 for the GFM. The core idea is to, during a fault, emulate a synchronous generator's behaviour and keep I_R and I in phase based on the logic of the figure below:

IF $E_S \approx E_R \rightarrow E_S$ is held at pre-fault values since E_R remains at $1 \angle 0^\circ$ pu

AND $\angle Z_S \approx \angle Z_R \rightarrow \angle Z_S$ is set $\approx 90^\circ$ (since $\angle Z_R \approx 90^\circ$)

THEN $\angle I_S \approx \angle I_R$

The GFL inverter is modelled as a voltage source, E_S , behind a virtual impedance, Z_v , which, when added to the impedance of the LCL filter, Z_f , amounts to Z_S (See Step 3).

$$\angle I_S^{ref} = \angle (E_S - V_S) - \angle Z_S \quad (3)$$

$$\text{So } I_d^{ref} = |1.3| \cos \angle I_S^{ref}, I_q^{ref} = |1.3| \sin \angle I_S^{ref} \quad (4)$$

$$\omega = \omega^0, V_{dq}^{ref} = V_{dq}^{ref0} \quad (5)$$

Model Description

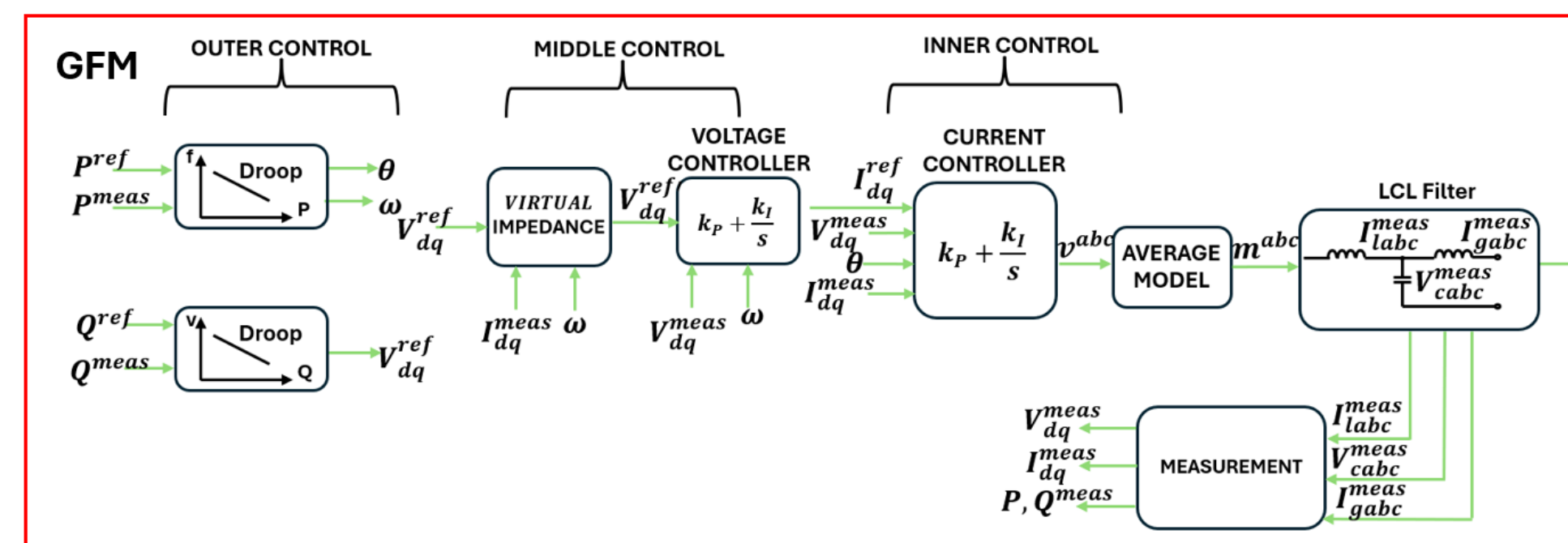
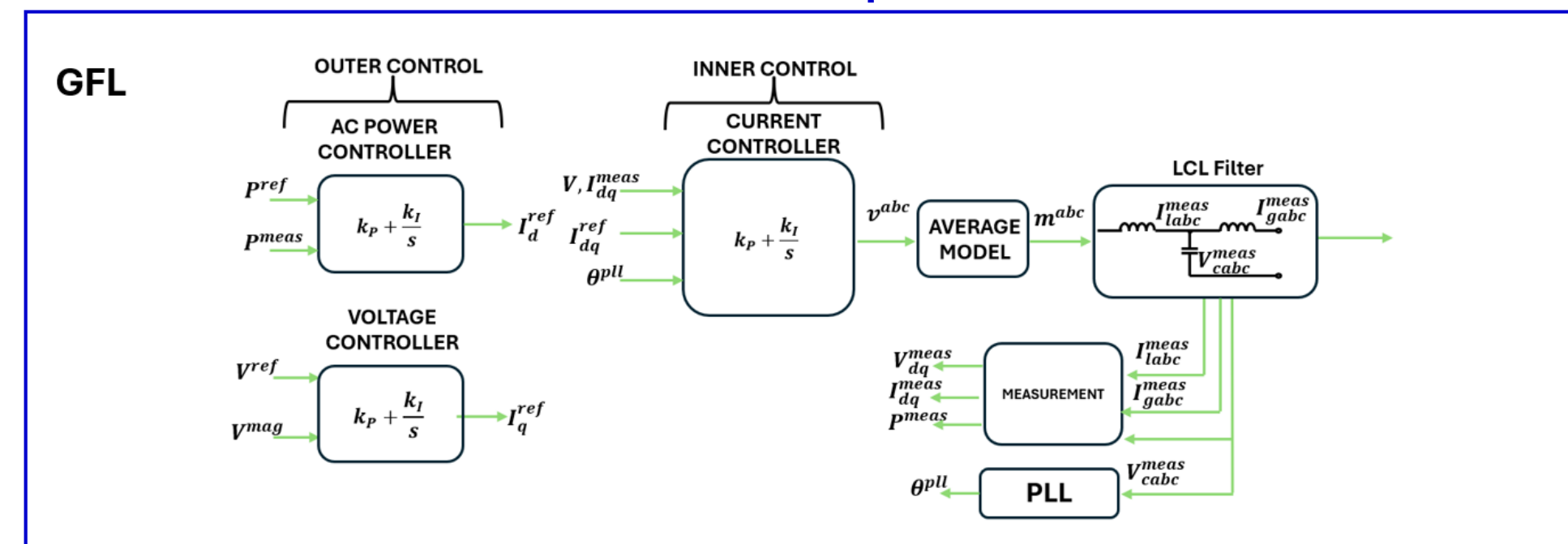


Figure 3: Model Description

Model Description (contd.)

The models used for this study are shown in Figures 3 and 4. Balanced faults of various resistance values ($0.01 \Omega - 15 \Omega$) are triggered in the middle of the transmission line.

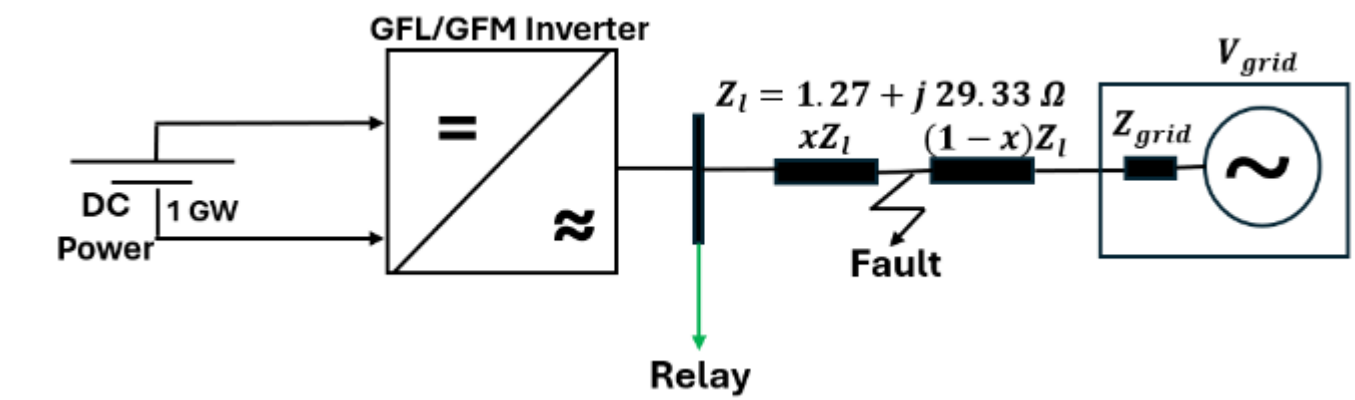


Figure 4: System Under Study

Results

Figure 5 shows the estimated apparent impedance on a complex plane. The blue line represents the impedance of the transmission line, and the red quadrilateral is the range within which the relay will operate to detect and clear faults. In this study, the top boundary is set to 0.85 pu of the transmission line's reactance, which is typical for zone 1 faults, while the right boundary (resistive reach) is set to 150 Ω . The resistive reach is an easily modifiable relay setting.

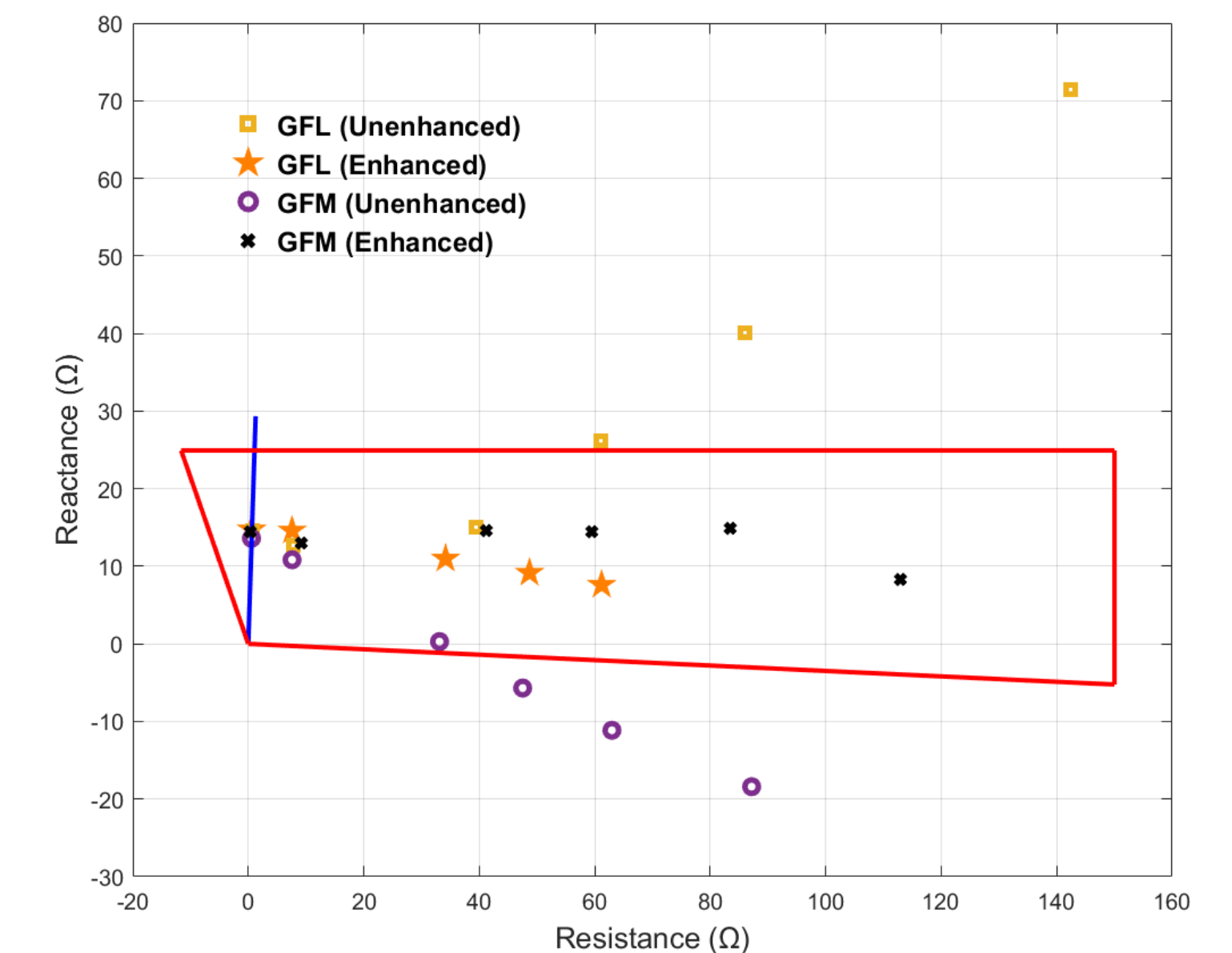


Figure 5: Impedance Estimations

Discussion and Conclusion

- The results indicate that GFL operation introduces a positive reactance bias relative to the true fault location, while GFM operation introduces a negative reactance bias.
- The enhanced control strategy improves relay performance by constraining all impedance estimates for both GFL and GFM within the quadrilateral protection characteristic, thereby ensuring reliable fault detection.
- The combination of modified resistive reach settings in the protection relay and modified inverter control settings illustrates a successful co-design approach for improved compatibility.
- Overall, the findings demonstrate that improved compatibility can be achieved through control-level modifications alone, without requiring additional hardware.

References

[1] Bialek, J., Bowen, T., Green, T., Lew, D., Li, Y., MacDowell, J., Matevosyan, J., Miller, N., O'Malley, M. and Ramasubramanian, D., 2021. System needs and services for systems with high IBR penetration. *Global PST Consortium*.