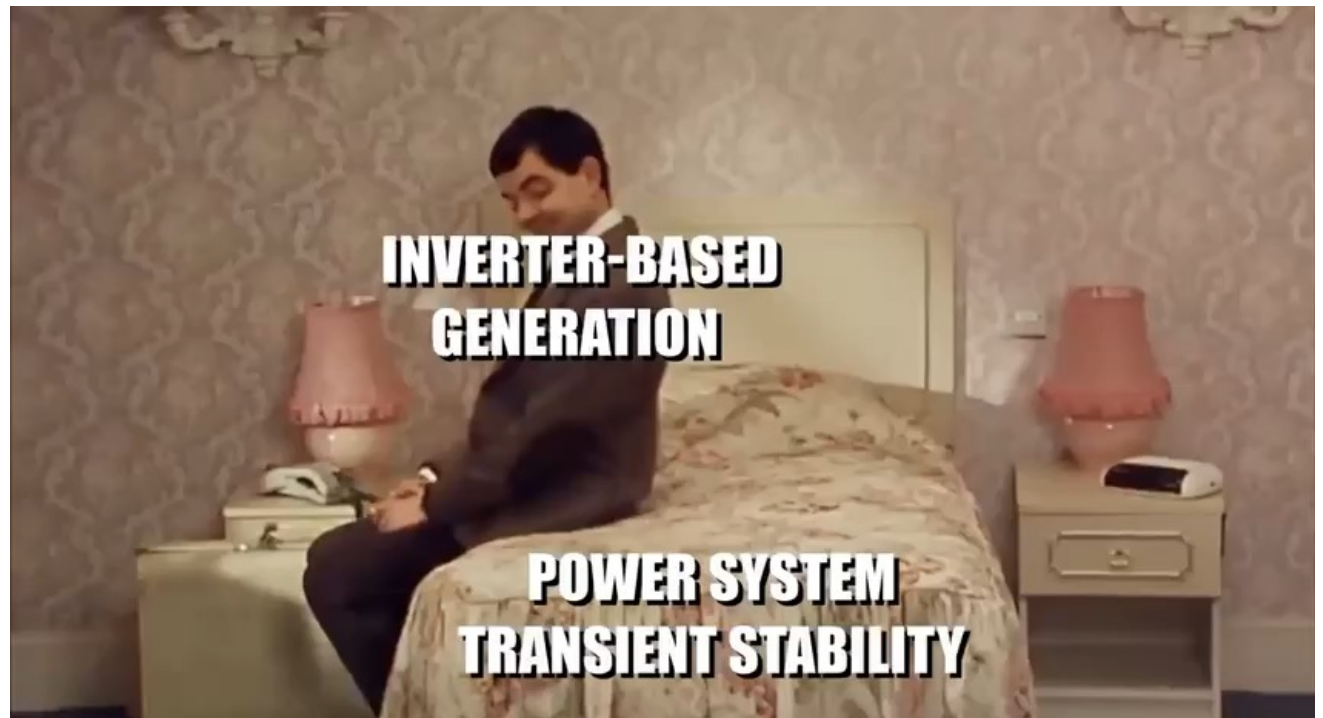


Co-Design of Inverters and Protection Systems for Improved Compatibility in Modern Power Systems

Agenda

- Introduction and Problem Statement
- Protection Types
- Distance Protection
- Test System
- Results and Discussion
- Summary of Results
- Concluding Remarks

Challenges of Inverter-Based Generation

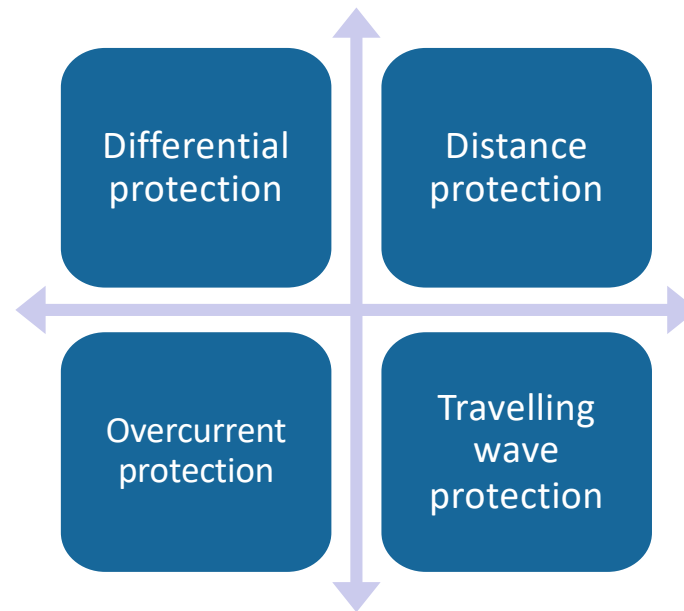


Introduction and Problem Statement

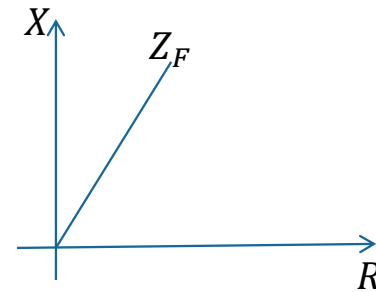
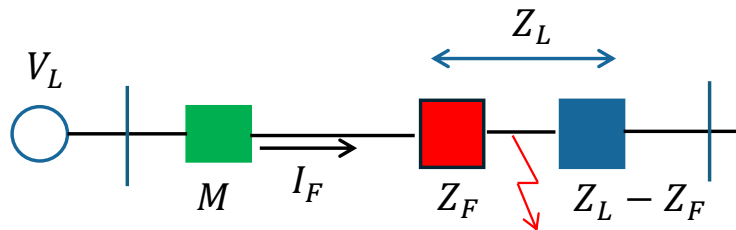
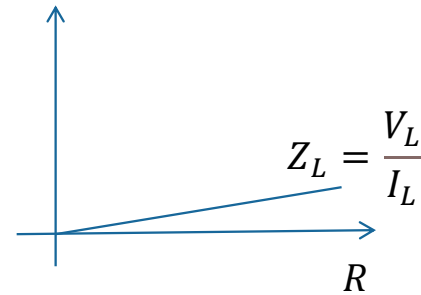
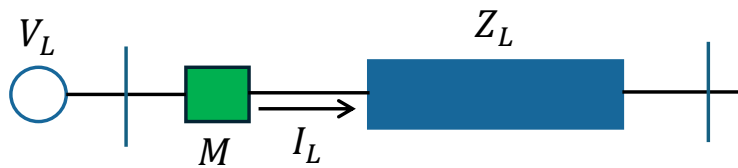
- Challenges with increasing penetration of inverter-based resources
- Assumption that GFM is the solution to almost everything
- Outstanding questions about how much GFM is needed in a system and what is the best part of the grid to connect a GFM
- Sparse comparison based on “external factors” (fault resistance, fault distance, grid short-circuit level)

Preliminary results are presented

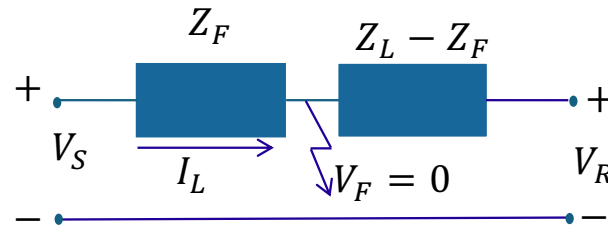
Protection Types



Distance Protection Fundamentals



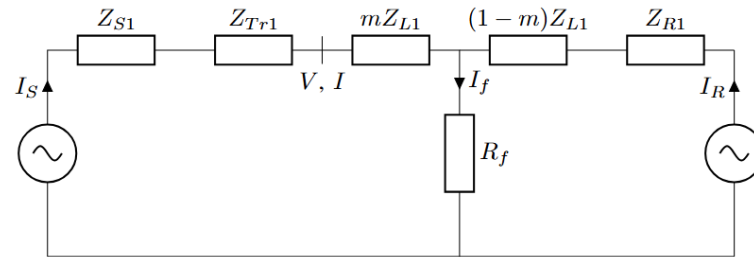
Distance Protection Fundamentals



$$Z_F = \frac{V_S}{I_L}$$

$$Z_F = R_F + jX_F = r * d_f + jx * d_f = d_f(r + jx) = d_f * z$$

$$d_f = \frac{V_S}{z * I_L}$$



Three Phase Fault Circuit Diagram Distance Element

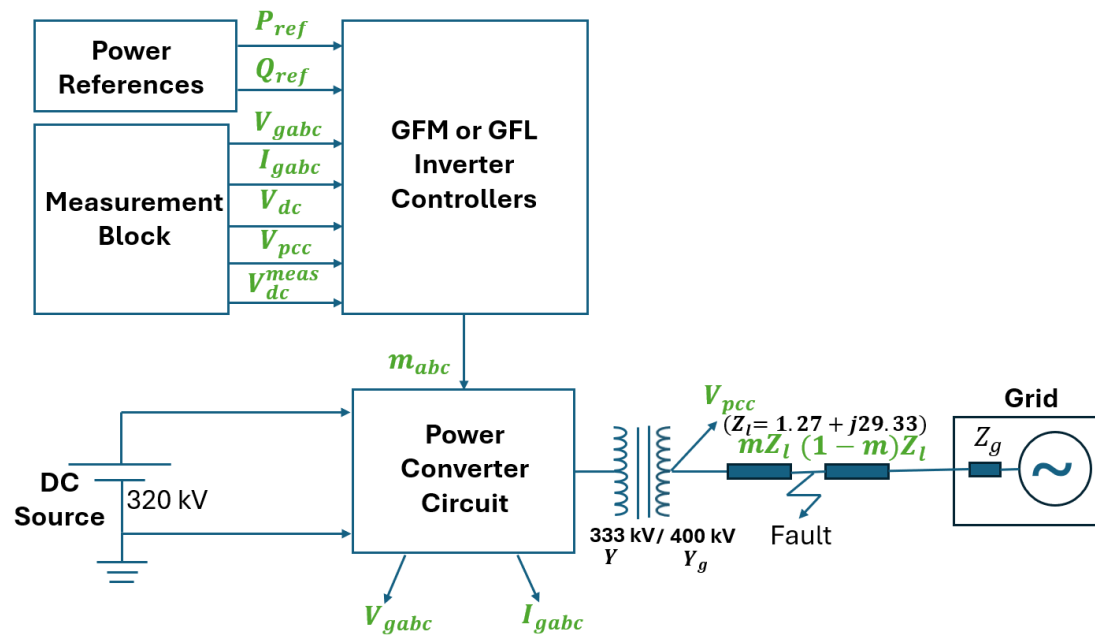
The apparent impedance seen by the relay:

$$\frac{V}{I} = mZ_{L1} + R_f \frac{I + I_R}{I}$$

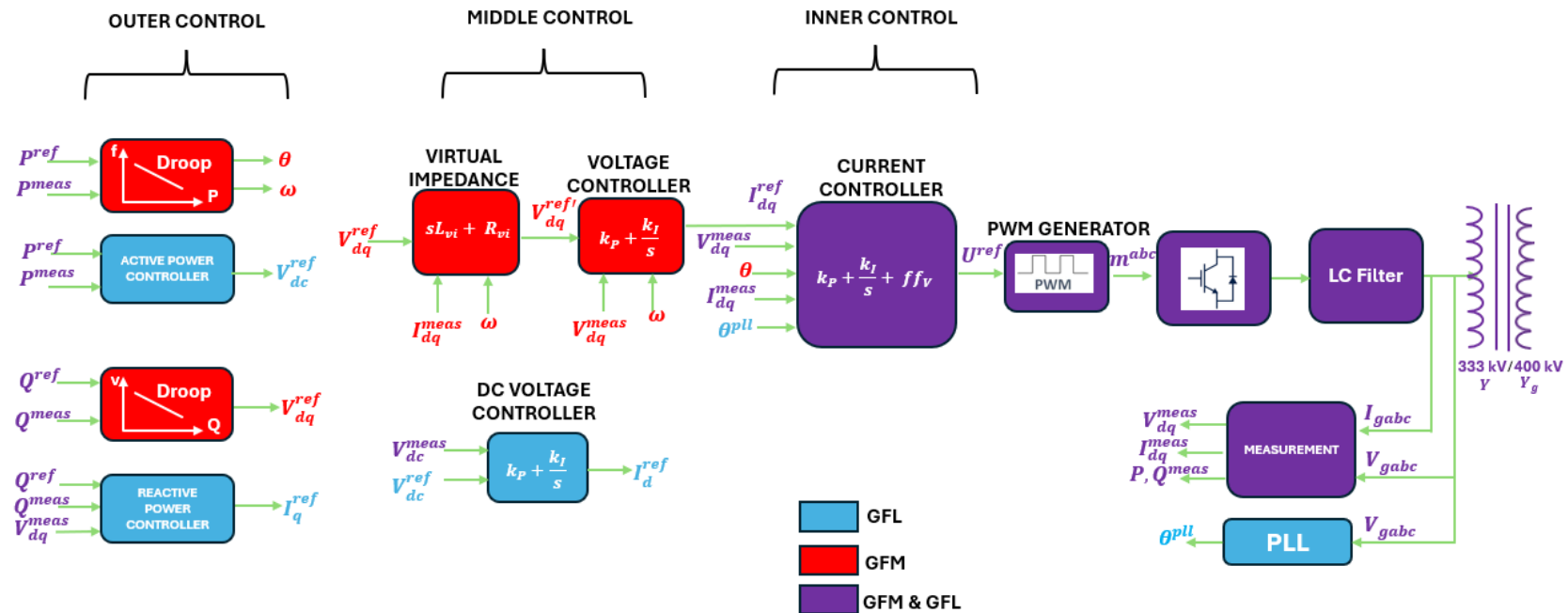
And so only represents the true distance to the fault if $R_f = 0$, otherwise, there appears an error term of (ϵ_{ABCG}) defined as:

$$\epsilon_{ABCG} = R_f \left(1 + \frac{I_R}{I} \right)$$

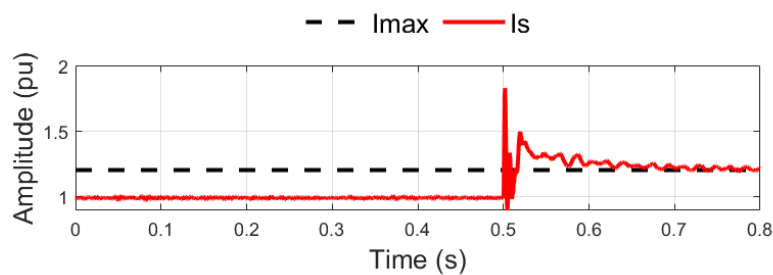
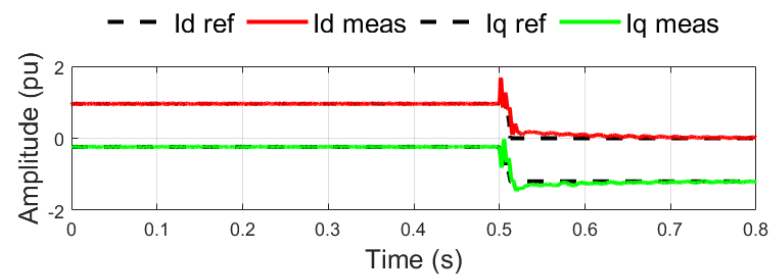
Test System



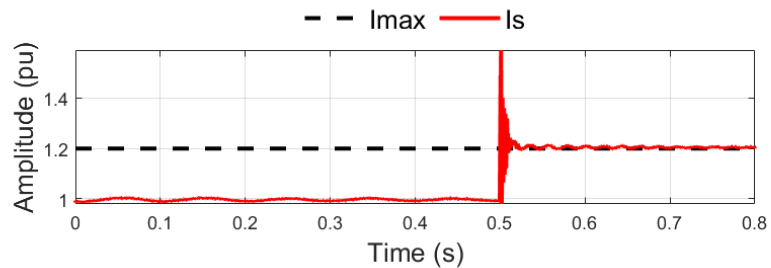
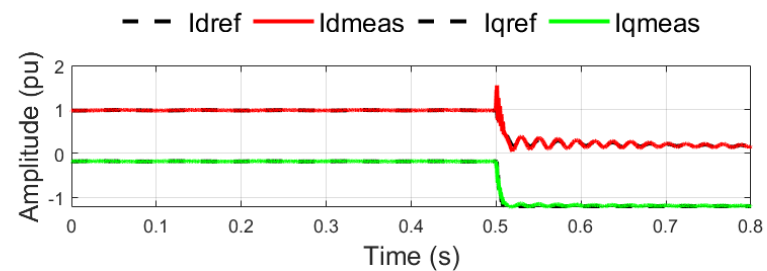
Test System



GFL and GFM Fault Response



GFL Fault Response



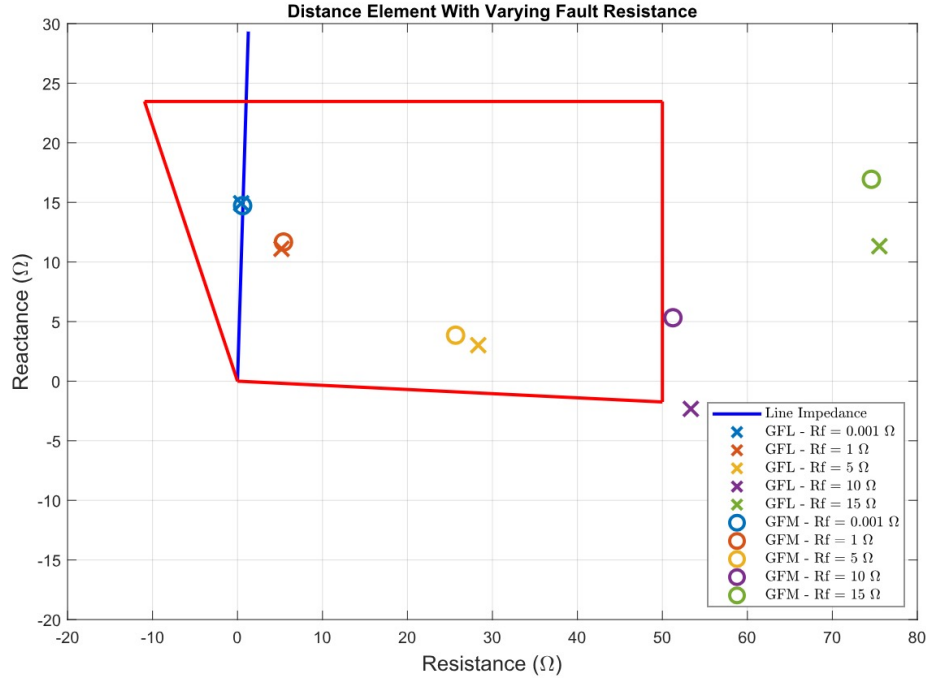
GFM Fault Response

Table of Test Parameters (a-b-c-g fault)

TABLE I
TABLE OF TEST PARAMETERS

Test	R_f (Ω)	m (pu)	SCL (GVA)
Test A1	0.001	0.5	20
Test A2	1	0.5	20
Test A3	5	0.5	20
Test A4	10	0.5	20
Test A5	15	0.5	20
Test B1	5	0.2	20
Test B2	5	0.5	20
Test B3	5	0.7	20
Test C1	5	0.5	5
Test C2	5	0.5	20
Test C3	5	0.5	40

Results and Discussion for Variation of Resistance



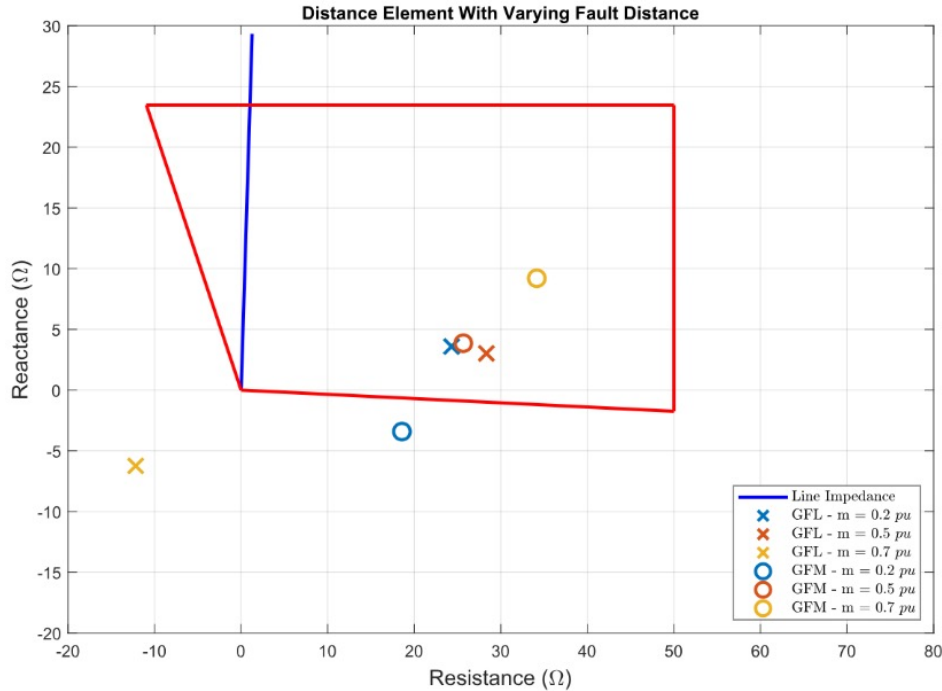
RESULTS WITH VARIED FAULT RESISTANCE

Results with varying fault resistance				
Distance = 0.5 pu — SCL = 20 GVA				
$R_f (\Omega)$	IBR Type	$\frac{I_R}{I}$	$\angle \frac{I_R}{I}$	Error (Ω)
0.001	GFL $\times$	5.46	-45.52°	$0.0048 - j0.0039$
	GFM $\circ$	5.79	-18.67°	$0.0065 - j0.0019$
1	GFL $\times$	5.41	-46.48°	$4.7277 - j3.9252$
	GFM $\circ$	5.74	-18.54°	$6.4429 - j1.8255$
5	GFL $\times$	5.12	-27.40°	$27.7305 - j11.7800$
	GFM $\circ$	5.45	-28.12°	$31.5345 - j6.1965$
10	GFL $\times$	4.61	-21.78°	$52.7940 - j17.0990$
	GFM $\circ$	4.94	-4.65°	$59.2780 - j4.0090$
15	GFL $\times$	4.04	-3.34°	$75.4410 - j3.5280$
	GFM $\circ$	4.38	-0.46°	$80.6925 - j0.5310$

$$\epsilon_{ABCG} = R_f \left(1 + \frac{I_R}{I} \right)$$

- The estimated impedance moves in the resistive direction (rightward), also initially becoming less reactive and subsequently more reactive.
- As fault resistance increases, the direct change of the resistance value increases the error, but the other two factors (magnitude and angle of the ratio) tend to reduce the error.

Results and Discussion for Variation of Distance



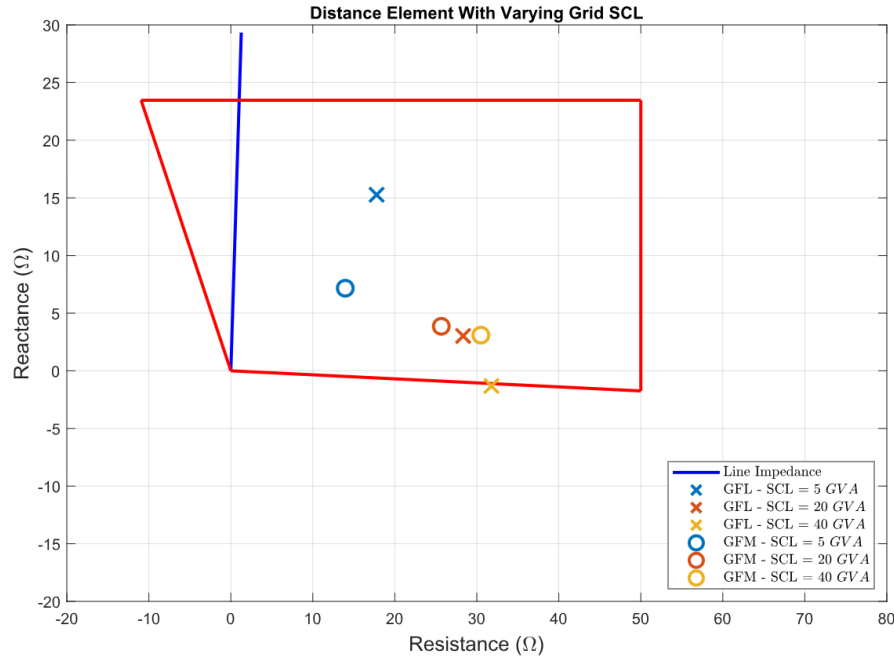
RESULTS WITH VARIED FAULT DISTANCE

Results with varying fault distance				
Resistance = 5 Ω — SCL = 20 GVA				
Dist (pu)	IBR Type	$\frac{I_R}{I}$	$\angle \frac{I_R}{I}$	Error (Ω)
0.2	GFL ×	3.80	-6.60°	23.8930 - j2.1865
	GFM ○	3.97	-17.24°	23.9645 - j5.8860
0.5	GFL ×	5.12	-27.40°	27.7305 - j11.7800
	GFM ○	5.45	-13.14°	31.5345 - j6.1965
0.7	GFL ×	6.85	-123.05°	-13.6755 - j28.7040
	GFM ○	7.17	-9.26°	40.4055 - j5.7730

$$\epsilon_{ABCG} = R_f \left(1 + \frac{I_R}{I} \right)$$

- For a fault close to the IBR (0.2pu), the errors in distance estimation are almost equal for both GFM and GFL. More disparity is seen in estimations for faults closer to the grid source and the disparity seems more influenced by the angle of the current ratio than its magnitude.
- The GFM also has more consistent behaviour, with all three points forming a positive slope almost equidistantly as the fault distance increases.

Results and Discussion for Variation of SCL



RESULTS WITH VARIED SCL

Results with varying SCL				
Resistance = 5 Ω — Distance = 0.5 pu				
SCL (GVA)	IBR Type	$\frac{I_R}{I}$	$\angle \frac{I_R}{I}$	Error (Ω)
5	GFL ×	2.83	-1.65°	19.1615 - j0.4070
	GFM ○	2.71	-23.44°	17.4220 - j5.3850
20	GFL ×	5.12	-27.40°	27.7305 - j11.7800
	GFM ○	5.45	-13.14°	31.5345 - j6.1965
40	GFL ×	6.15	-31.93°	31.1020 - j16.2630
	GFM ○	6.55	-10.73°	37.1870 - j6.0995

$$\epsilon_{ABCG} = R_f \left(1 + \frac{I_R}{I} \right)$$

- Errors in distance estimation increase with increasing SCL of the grid source.
- For the GFM, the angle of the current ratio reduces as the SCL of the grid source increases, but increases for the GFL
- At higher SCL levels, however, the error in impedance estimation is higher with the GFM than with the GFL, suggesting that the GFL may only outperform the GFM in accurately estimating fault location for very high values of grid SCL.

Summary of Results

Test	$R_f \ \Omega$	m (pu)	SCL (GVA)	Higher error	Higher $\angle \frac{I_R}{I}$	Higher $\frac{I_R}{I}$
Test A1	0.001	0.5	20	GFM	GFL	GFM
Test A2	1	0.5	20	GFM	GFL	GFM
Test A3	5	0.5	20	GFM	GFM	GFM
Test A4	10	0.5	20	GFM	GFL	GFM
Test A5	15	0.5	20	GFM	GFL	GFM
Test B1	5	0.2	20	GFM	GFM	GFM
Test B2	5	0.5	20	GFM	GFL	GFM
Test B3	5	0.7	20	GFM	GFL	GFM
Test C1	5	0.5	5	GFL	GFM	GFL
Test C2	5	0.5	20	GFM	GFL	GFM
Test C3	5	0.5	40	GFM	GFL	GFM

- The magnitude of the error correlates positively with the magnitude of the current ratio for most test cases
- The only case where a higher error is observed with the GFL is when the GFL has a higher magnitude of the current ratio. The higher error is observed despite the lower angle deviation.
- The magnitude of the current ratio appears to have more impact on the value of the error than the angle of the current ratio because in 8 cases the GFM had a lower angle deviation and higher magnitude of the current ratio, and this resulted in higher error

Concluding Remarks

- In most of the scenarios considered, the error seen in the presence of the GFL is less than that seen for the GFM, proving that, **within the scope of the considerations in this work, the GFL has a higher accuracy** in the impedance estimation of distance protection
- It can also be noted that **for high values of fault resistance, the horizontal expansion of the quadrilateral will improve the performance of distance protection**
- **For varied fault distances, the GFM has more consistent behaviour**, but minor extensions of the boundaries of the quadrilateral might still be needed to improve the performance of fault impedance estimation.
- Variation in SCL of grid source appears to not be an issue of serious concern since most of the estimated results fall within the boundaries of the quadrilateral. Only minor modifications (if any at all) of the quadrilateral are needed to improve the performance of distance protection. **The GFM inverter may only outperform the GFL in cases with low SCL values.**

Thank you!

