Fault Current Characteristics of IBR-Penetrated Grids

NERC IRPS Monthly Meeting, April 17, 2025

Presenter: Lingling Fan, Professor @ USF

Collaborators:

Zhixin Miao (USF), **Rahul H. Ramakrishna** (USF)

Jiyuan Fan (Southern States), **Normann Fischer** (SEL)

UNIVERSITY of SOUTH FLORIDA

DE-EE0011474
SPRING: Stability Prediction for IBR-Penetrated Grids Enabled by Digital Twins

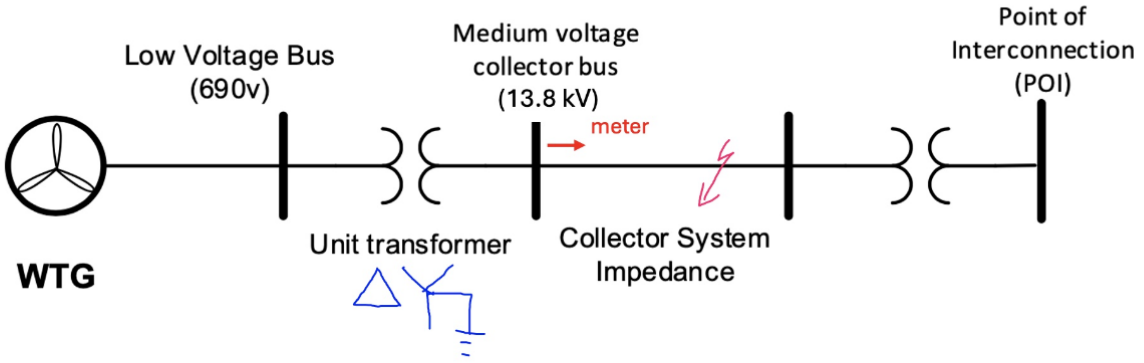
Acknowledgement

Outline

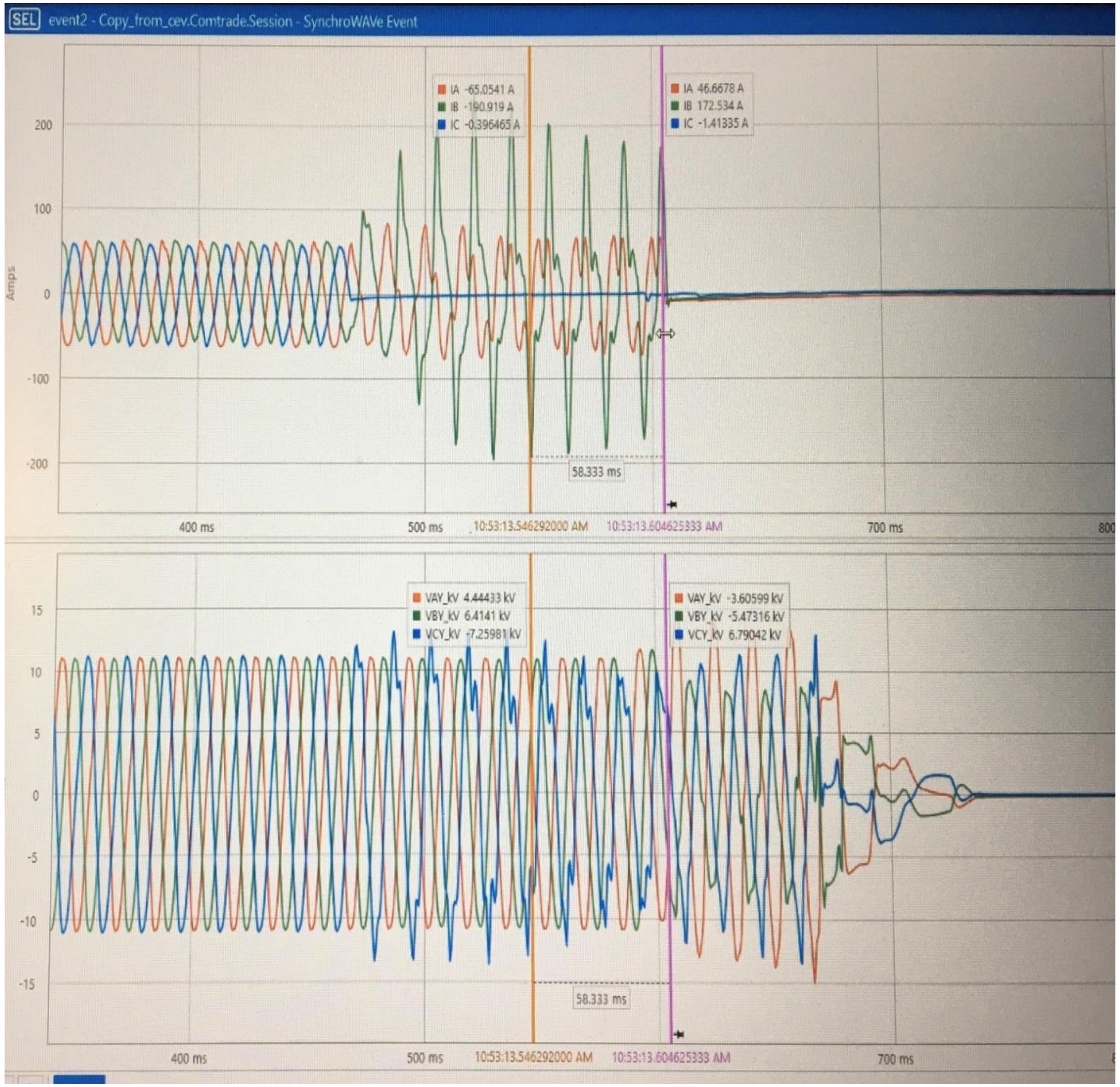
- **Two fault events** (single-phase open, single-line ground)
- **The difference** in fault characteristics (IBR-rich grids vs. grids)
- **IBR control** vs. **IBR representation** in fault analysis

Event 1: Singe-phase open-circuit

Single-phase open circuit

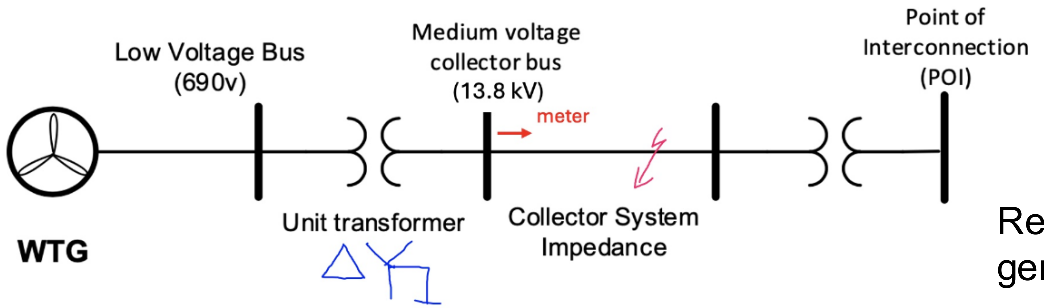


- Current (70 A) and voltage (11 kV) measurements of a type-4 wind farm
- Single-phase open. Phase C current goes to 0.
- Overcurrent in phase A and B;
- The wind farm tripped for this event.

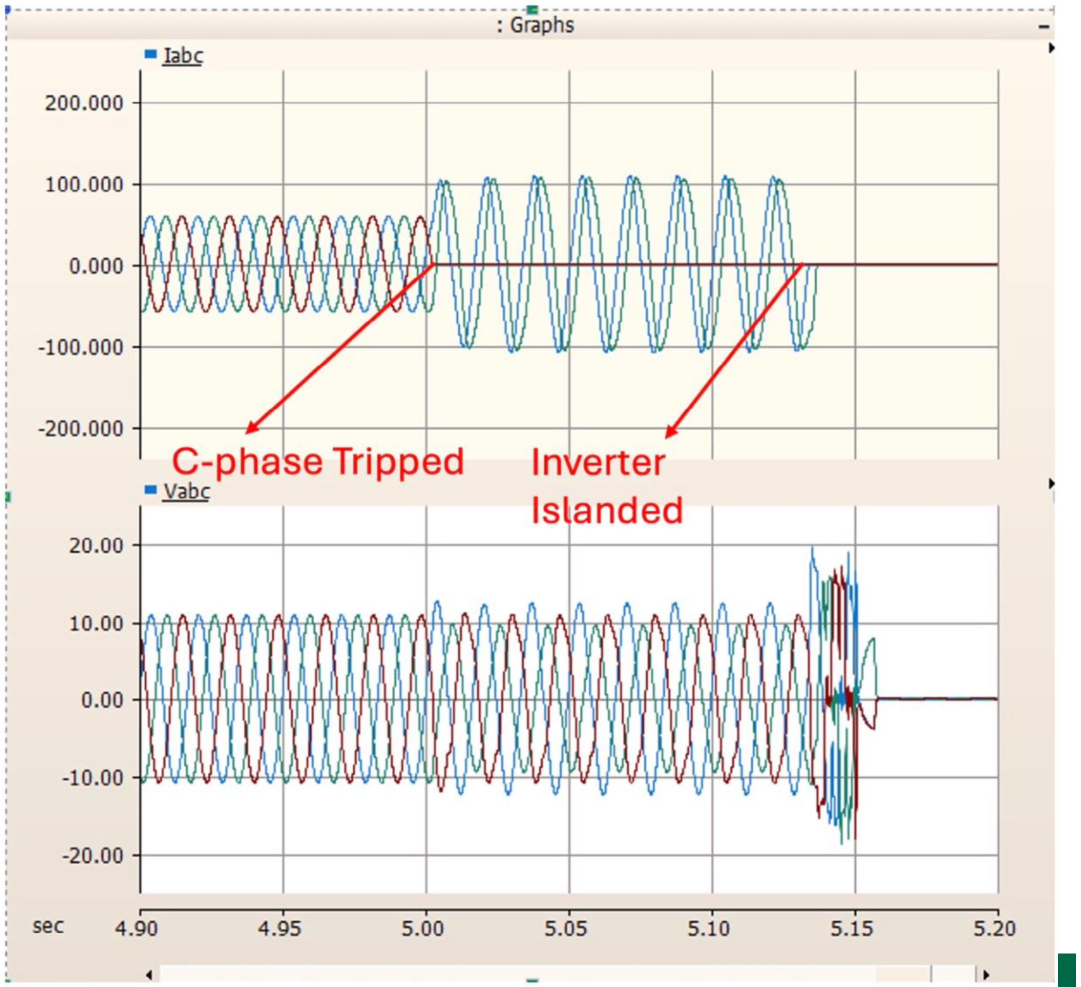


L. Fan, R.. Ramakrishna, Z. Miao, and J. Fan, "Challenges of Single-Phase Open Circuit Ride-Through in Wind Farms," IEEE PESGM 2025

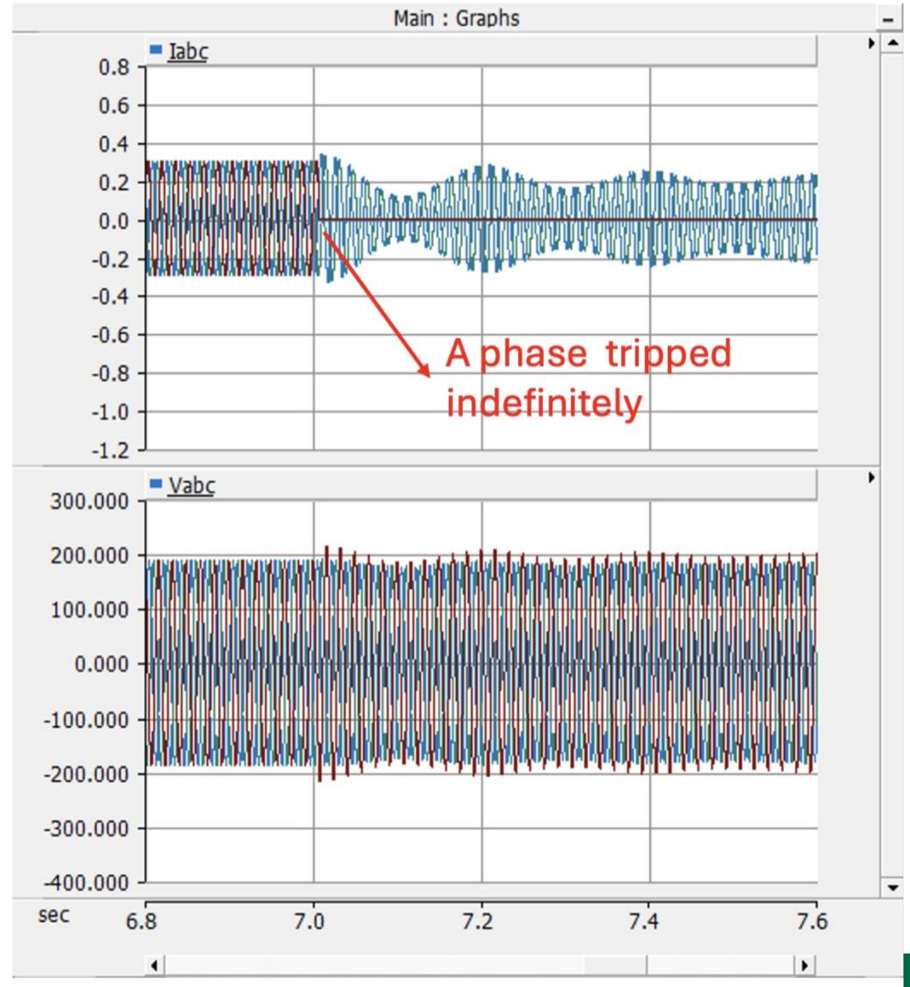
EMT studies



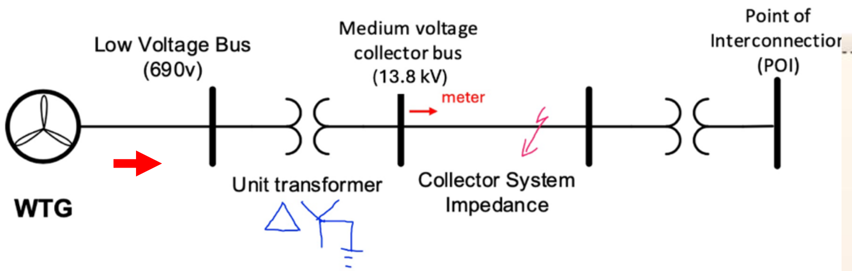
- Phase C open
- Overcurrent observed



Replace a wind farm by a synchronous generator:



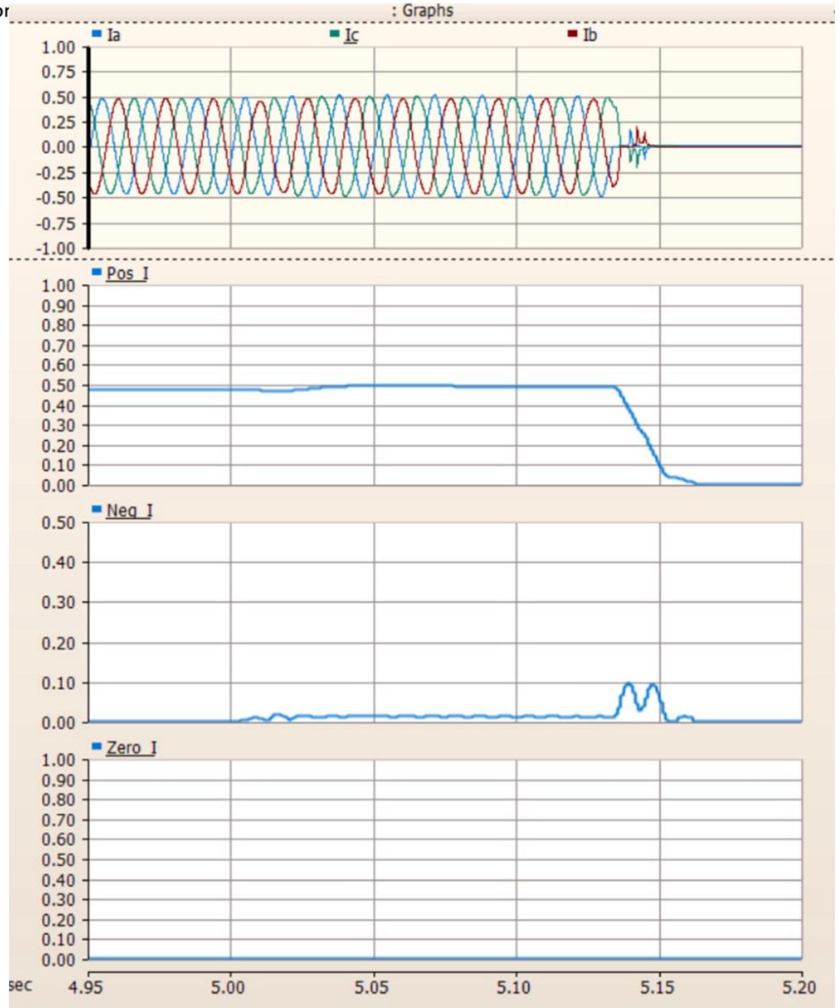
Why the difference between a wind farm & a sync gen?



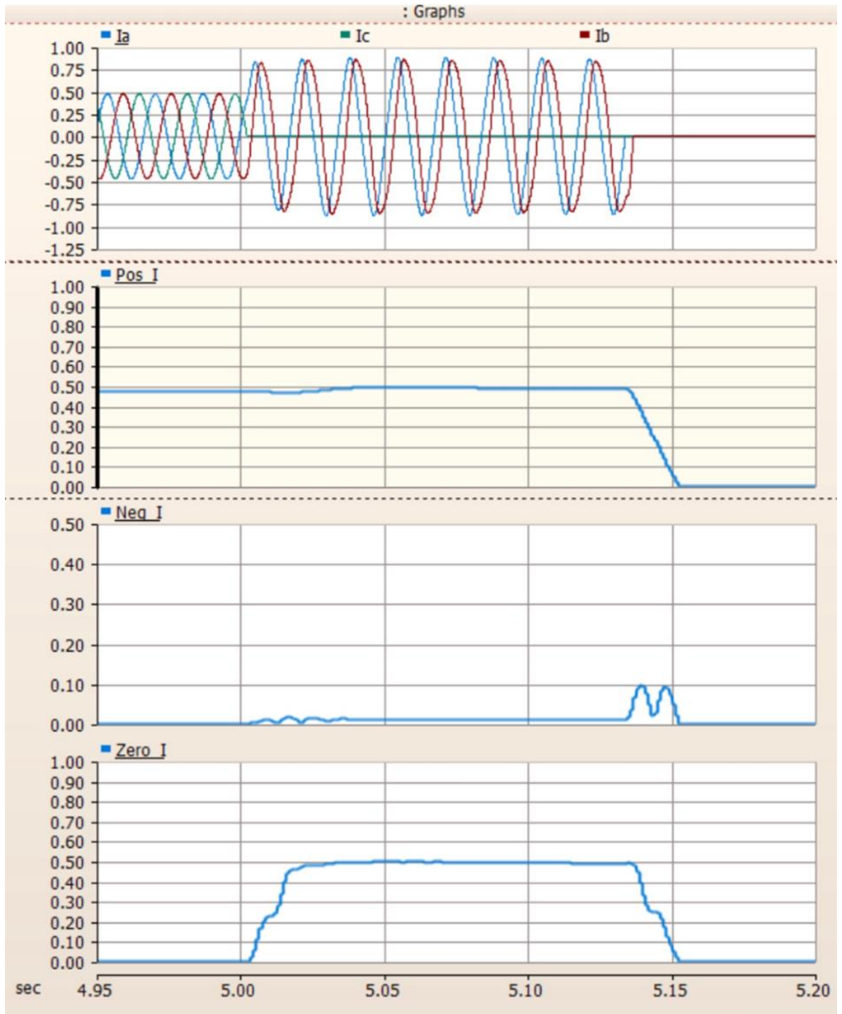
Δ side current
Y side current

- The inverter provides very small negative sequence current.
- At the grid side, $I_1 = I_0$

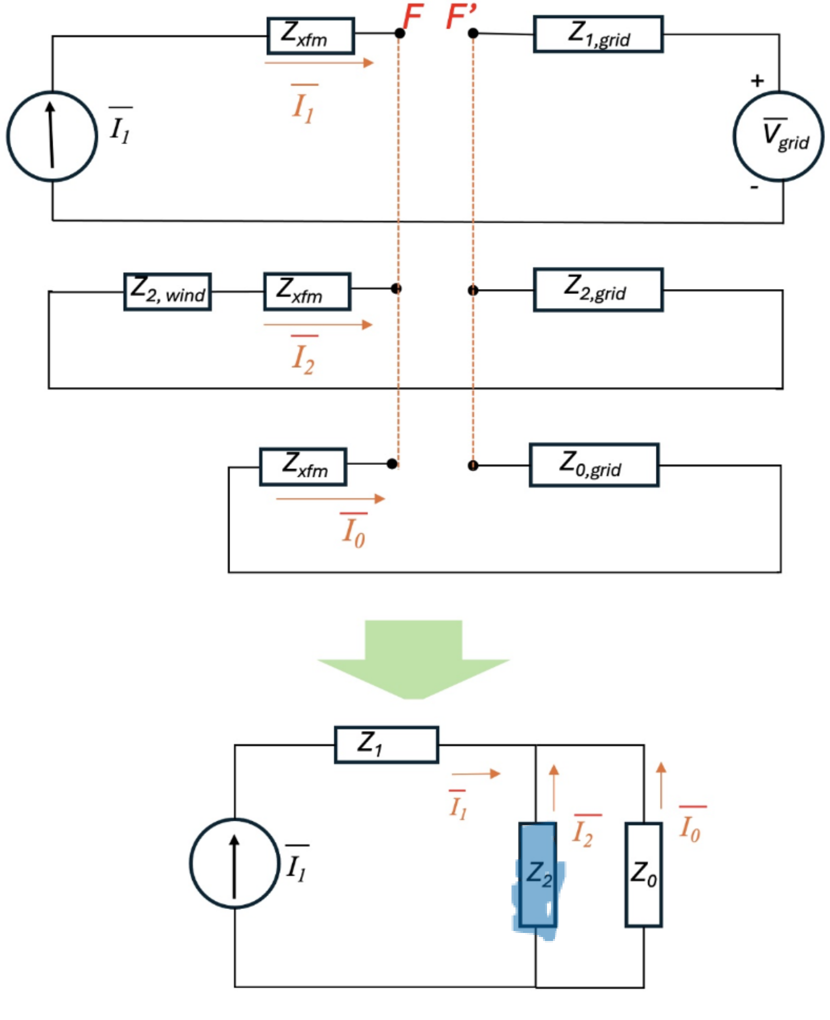
Δ side



Y side

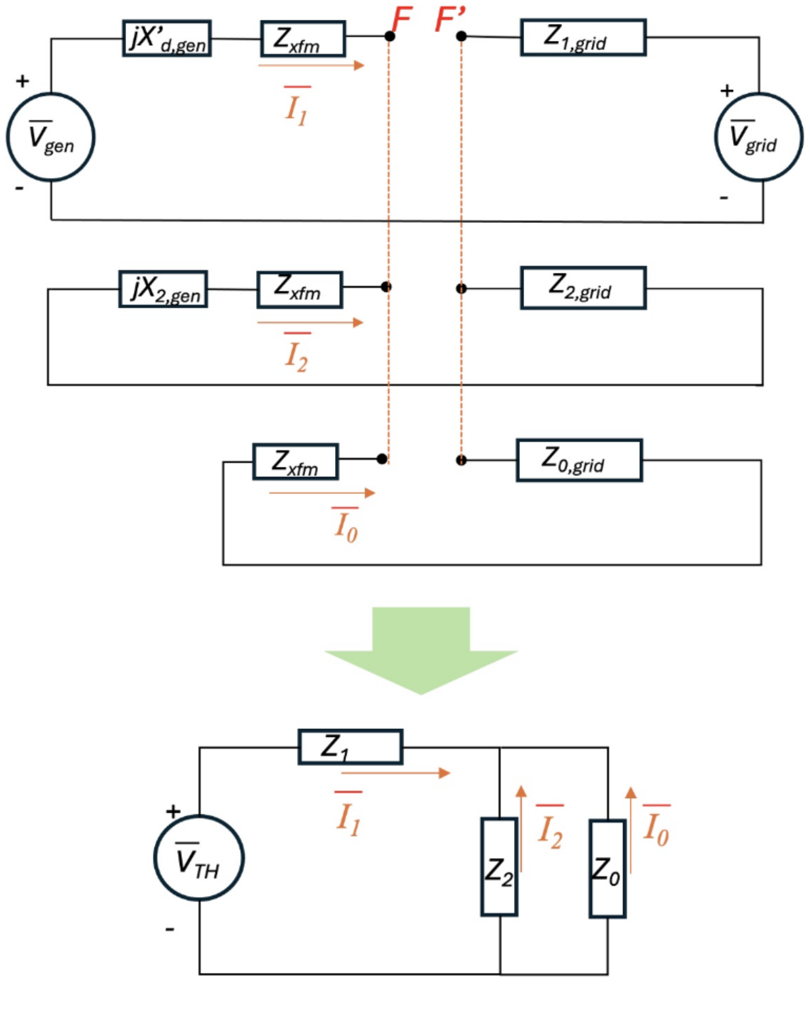


IBR



(a) Testbed 1

Sync Gen



(b) Testbed 2

IBR:

$$\overline{I}_1 = -\overline{I}_0$$

$$\overline{I}_b = \alpha^2\overline{I}_1 + \overline{I}_0 = (\alpha^2 - 1)\overline{I}_1 = 1.73\angle{-150^\circ}\,\overline{I}_{\text{pre}}$$

$$\overline{I}_c = \alpha\overline{I}_1 + \overline{I}_0 = (\alpha - 1)\overline{I}_1 = 1.73\angle{150^\circ}\,\overline{I}_{\text{pre}}$$

Overcurrent

Gen:

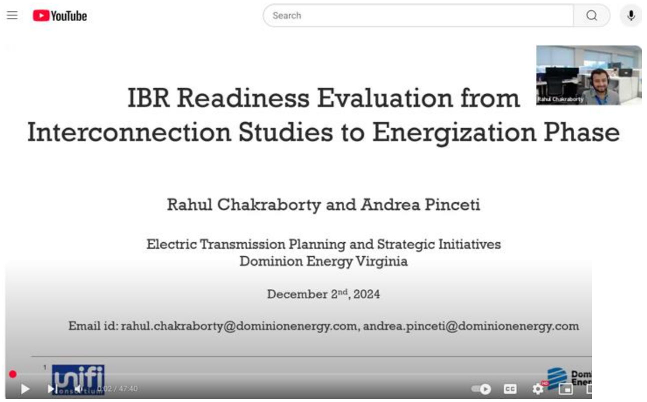
$$\overline{I}_1 = \frac{\overline{V}_{\text{TH}}}{Z_1 + 0.5Z_1} = \frac{2}{3}\frac{\overline{V}_{\text{TH}}}{Z_1} = \frac{2}{3}\overline{I}_{\text{pre}}$$

$$\overline{I}_b = \alpha^2\overline{I}_1 + \alpha\overline{I}_2 + \overline{I}_0 = 1.5\alpha^2\overline{I}_1 = \alpha^2\overline{I}_{\text{pre}}$$

$$\overline{I}_c = \alpha\overline{I}_1 + \alpha^2\overline{I}_2 + \overline{I}_0 = 1.5\alpha\overline{I}_1 = \alpha\overline{I}_{\text{pre}}$$

Current < pre-fault current

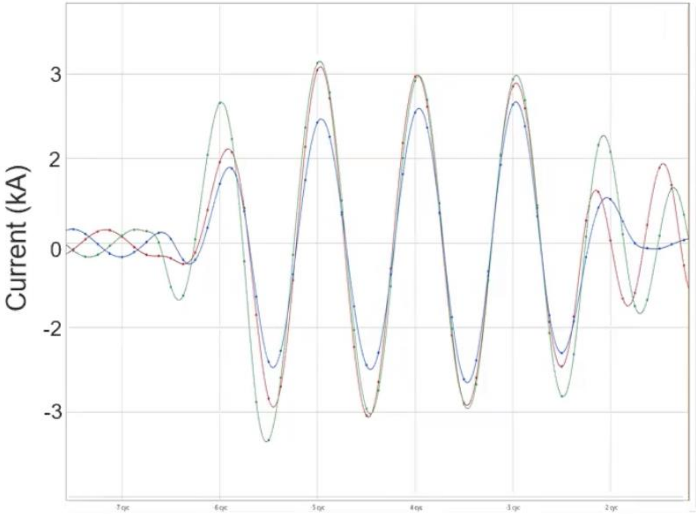
Event 2: Unbalanced line to ground faults



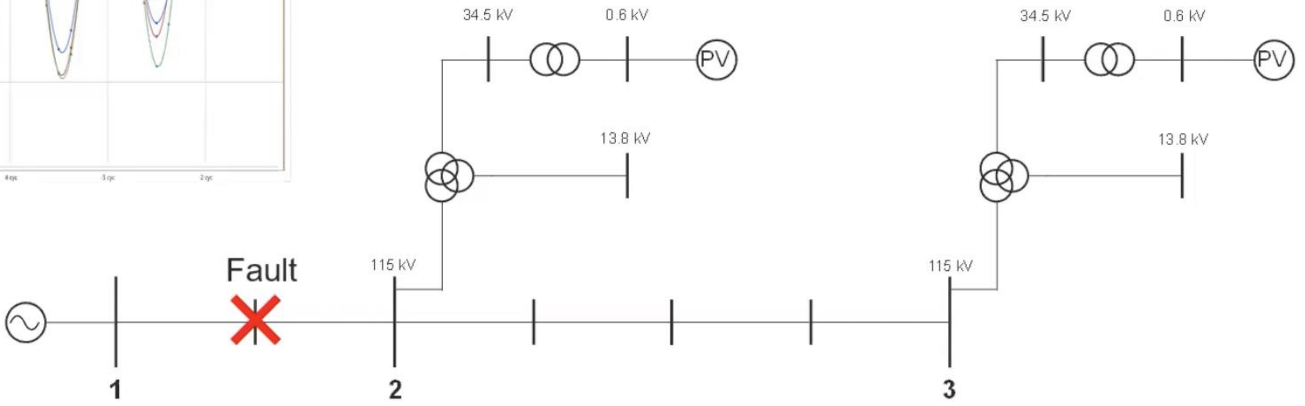
Emerging challenges: protection misoperations

IBR-side relays did not operate to clear the fault.

Directionality elements did not pick up the fault due to insignificant negative-sequence current.

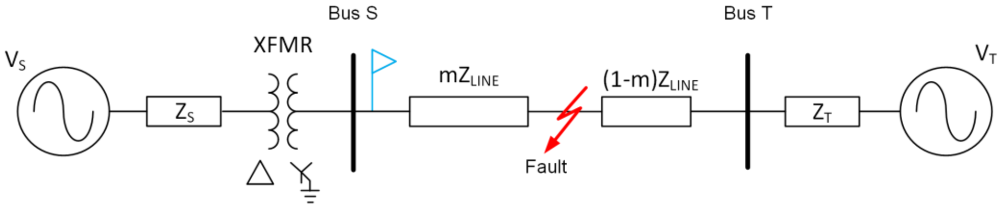


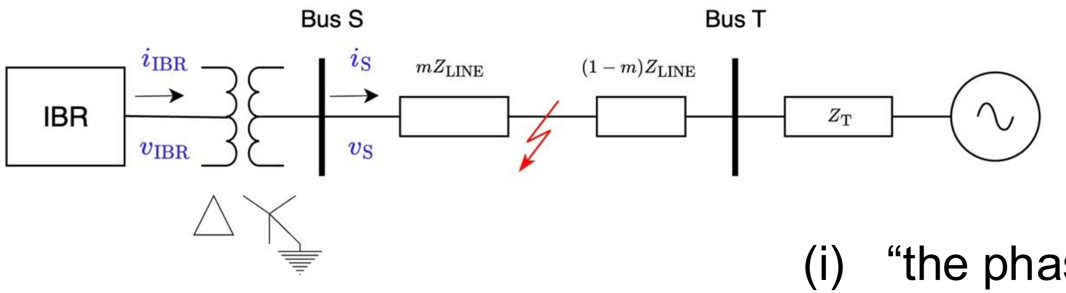
- Lower fault current
- No or limited negative sequence current
- Mis-operations have been observed

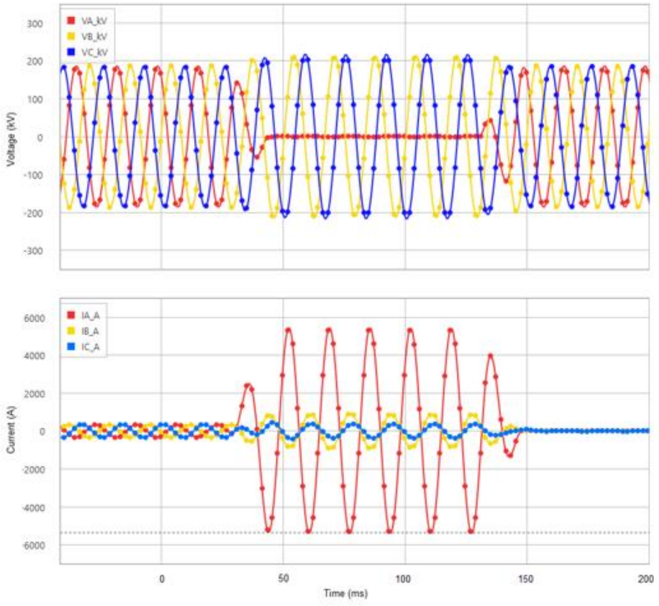


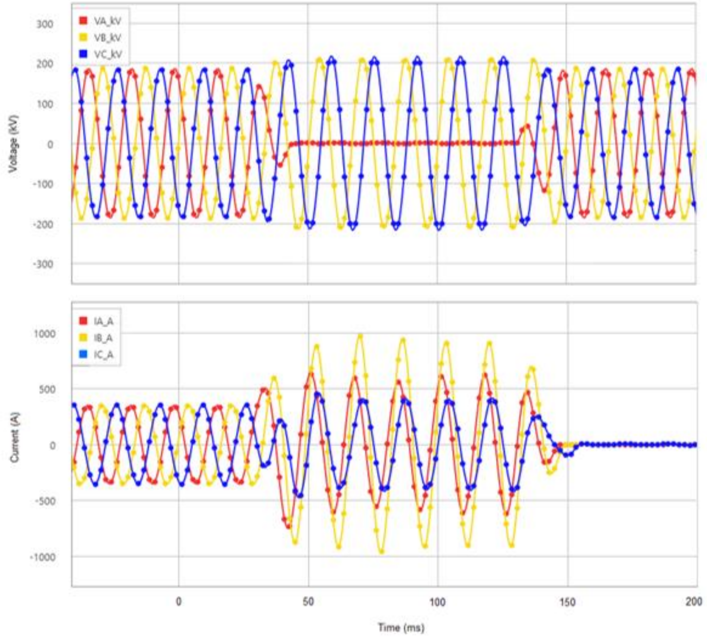
Normann Fischer's ESIG blog

https://www.esig.energy/protection-of-inverter-based-resources/ESIG blog





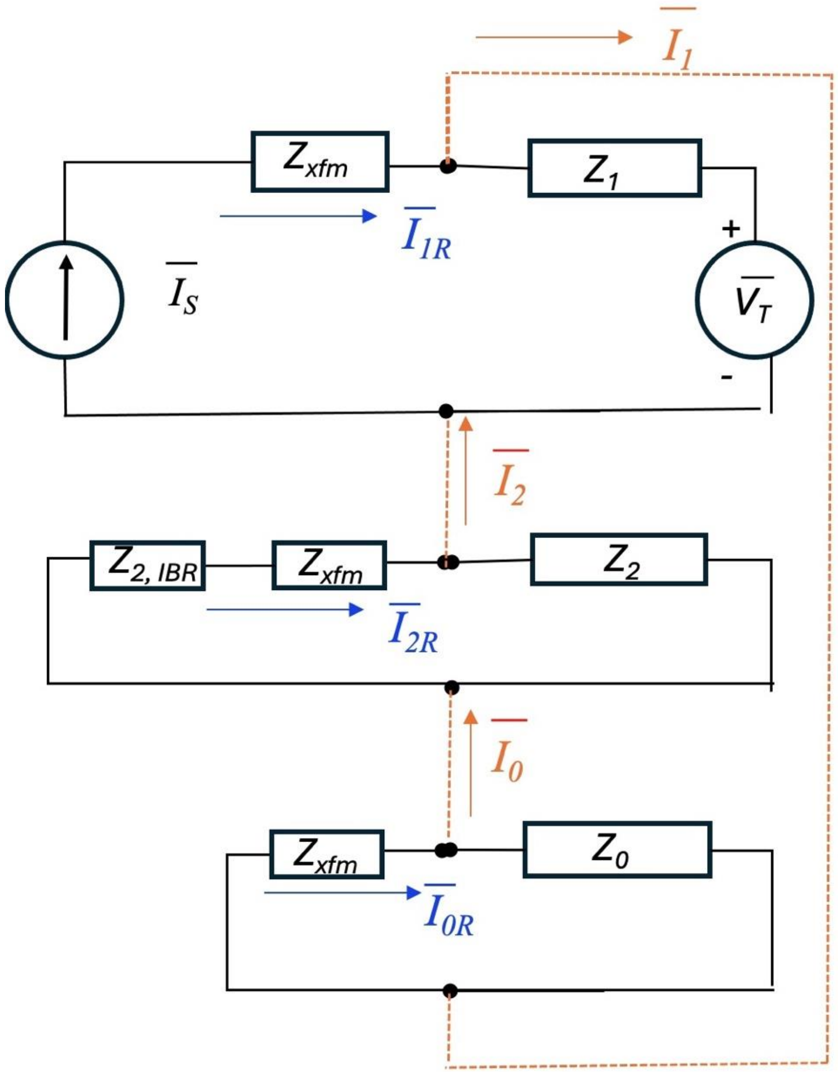


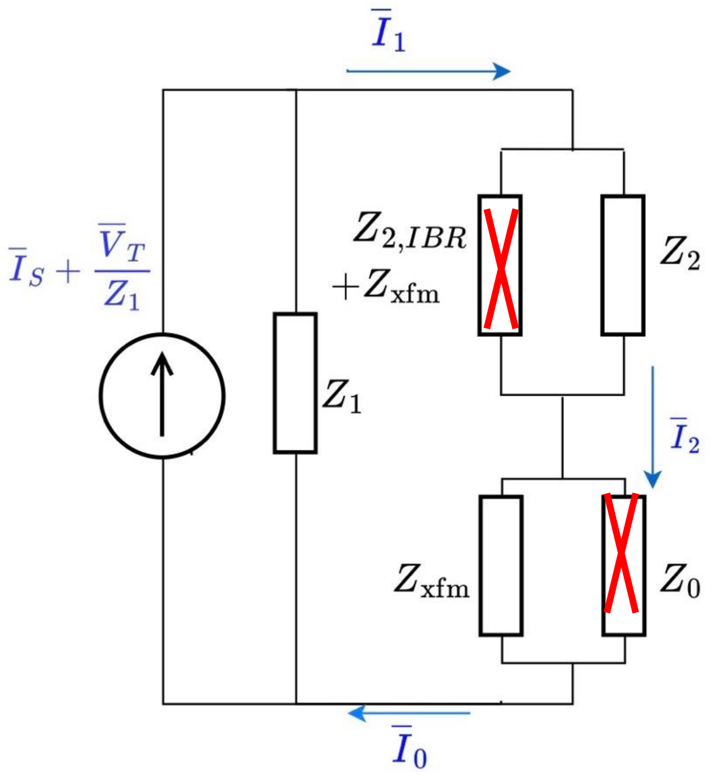


(i) "the phase currents are almost in phase with one another (this is due to the high zero-sequence current)"

(ii) " ... the phase currents are a composite of the inverter current (positive- and negative-sequence current) and the system current (zero-sequence current).

Analysis: assuming very large Z2 for IBR





Fault current:

$$\overline{I}_1 = \overline{I}_2 = \overline{I}_0 = \frac{1}{2}\left(\overline{I}_S + \frac{\overline{V}_T}{Z_1}\right)$$

Seen by the relay:

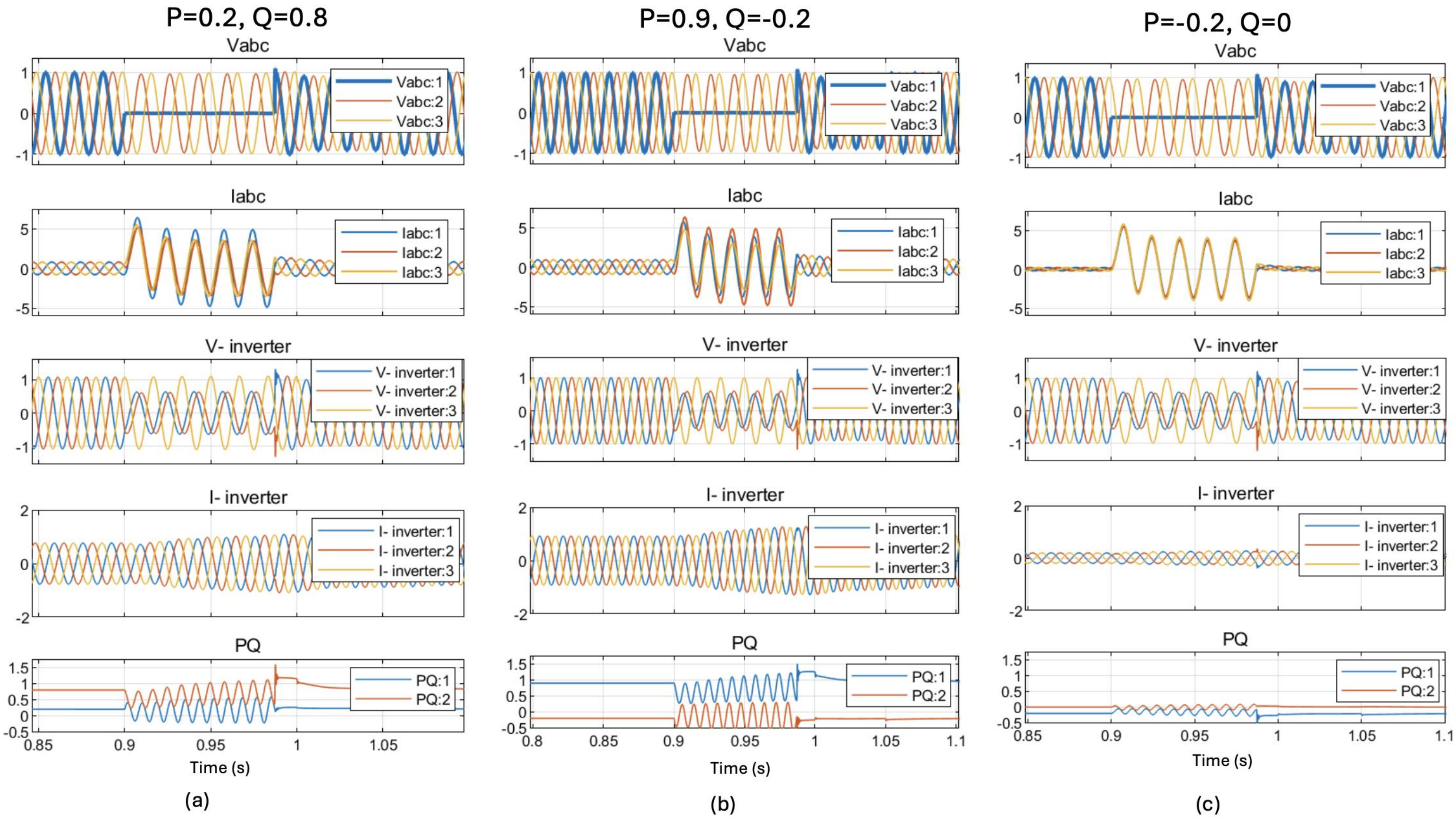
$$\overline{I}_{1R} = \overline{I}_S,\ \ \overline{I}_{2R} = 0,\ \ \overline{I}_{0R} = \frac{1}{2}\left(\overline{I}_S + \frac{\overline{V}_T}{Z_1}\right)$$

Remarks:

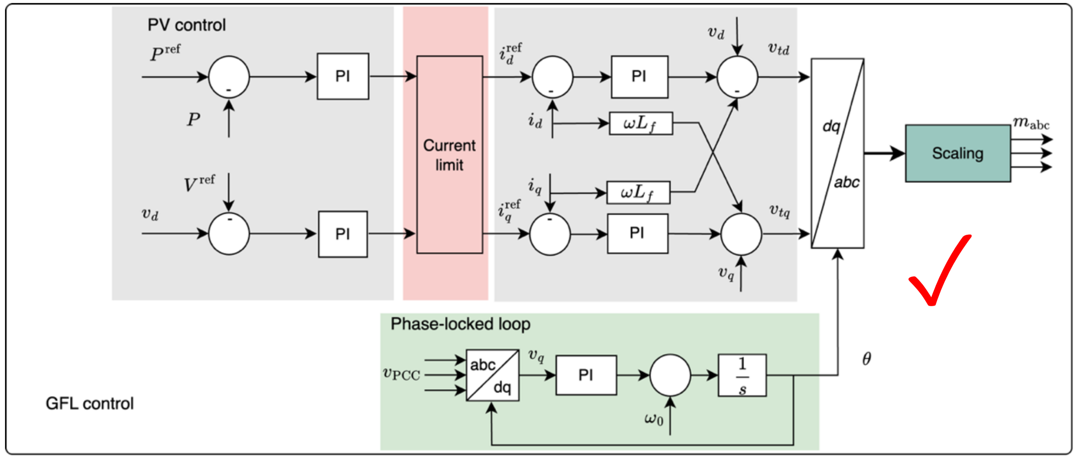
This analysis confirms that the **dominant fault current component is the zero-sequence component**.

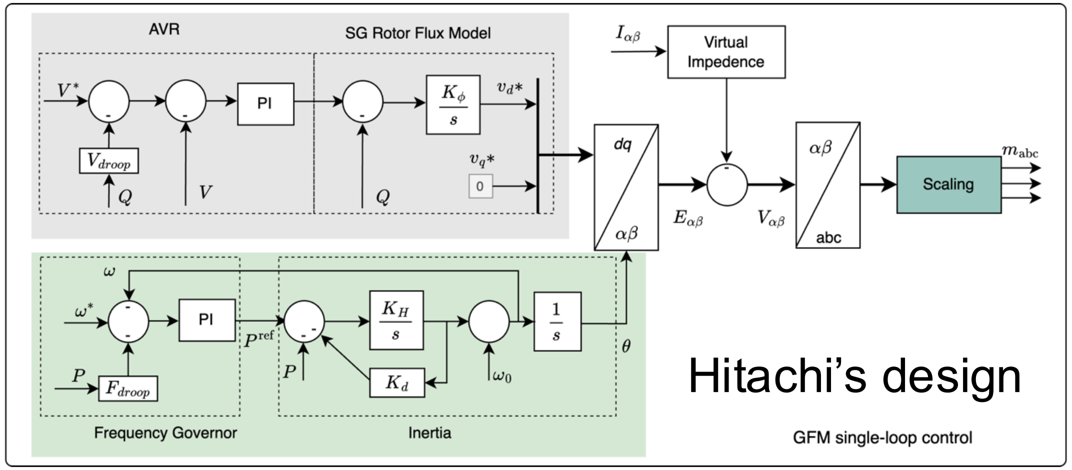
Z. Miao, L. Fan, N. Fischer, "Behavior of Single-Line-Ground Faults in Inverter-Based Resource Dominated Grids Explained', under 2nd review, IEEE Power Engineering Letters.

EMT simulation results: grid-following IBR, grid strength (SCR 5)



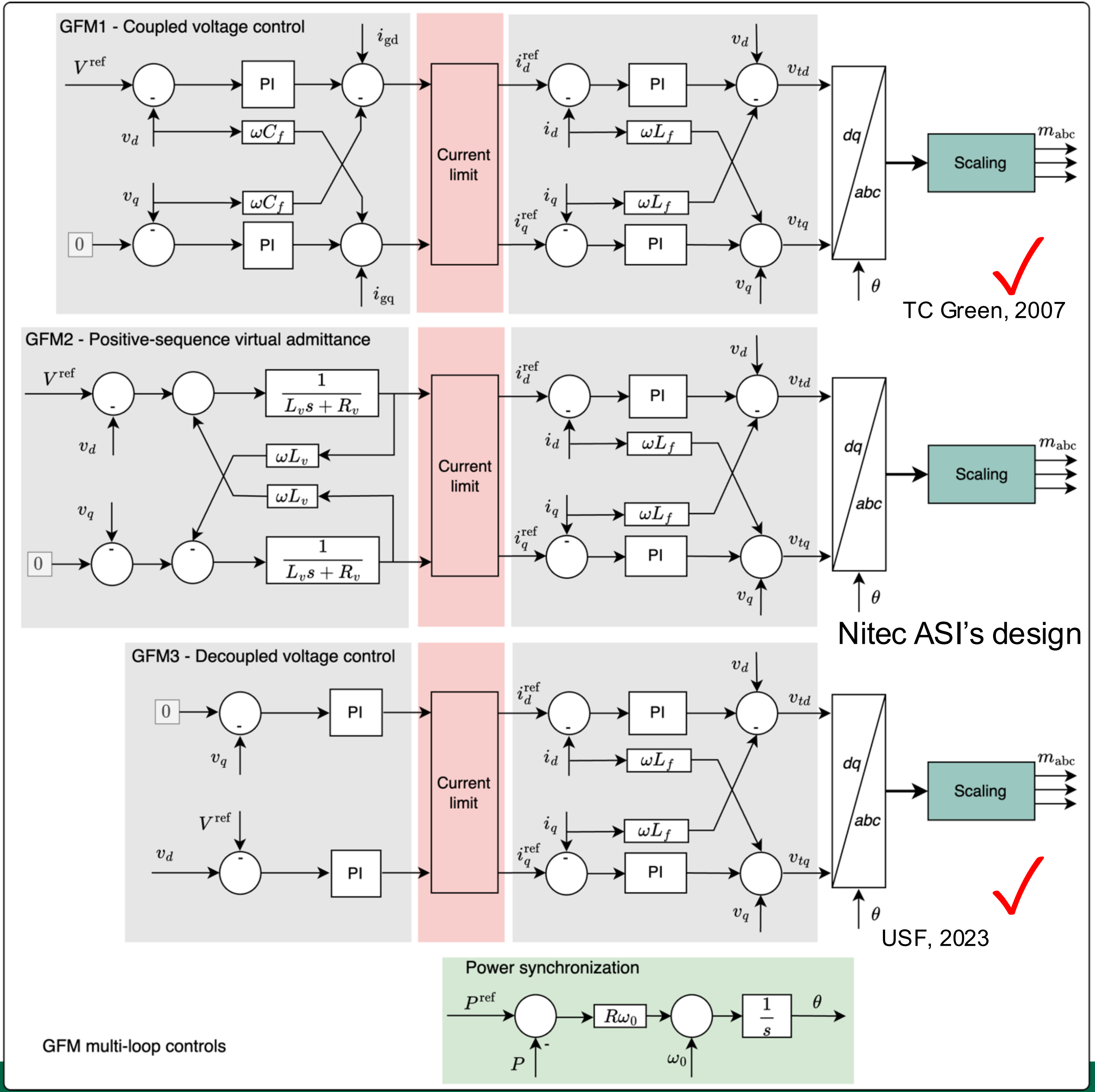
Why IBRs can be viewed as a current source?



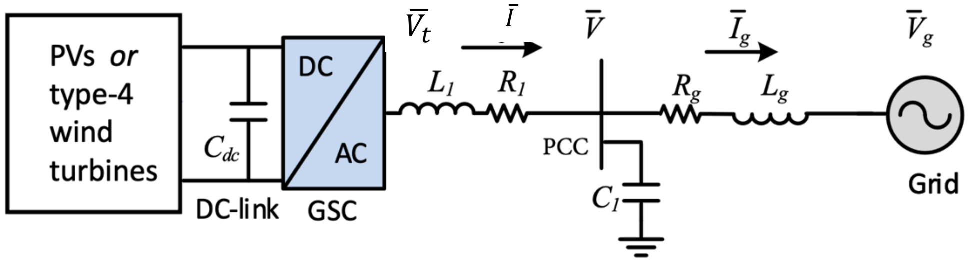


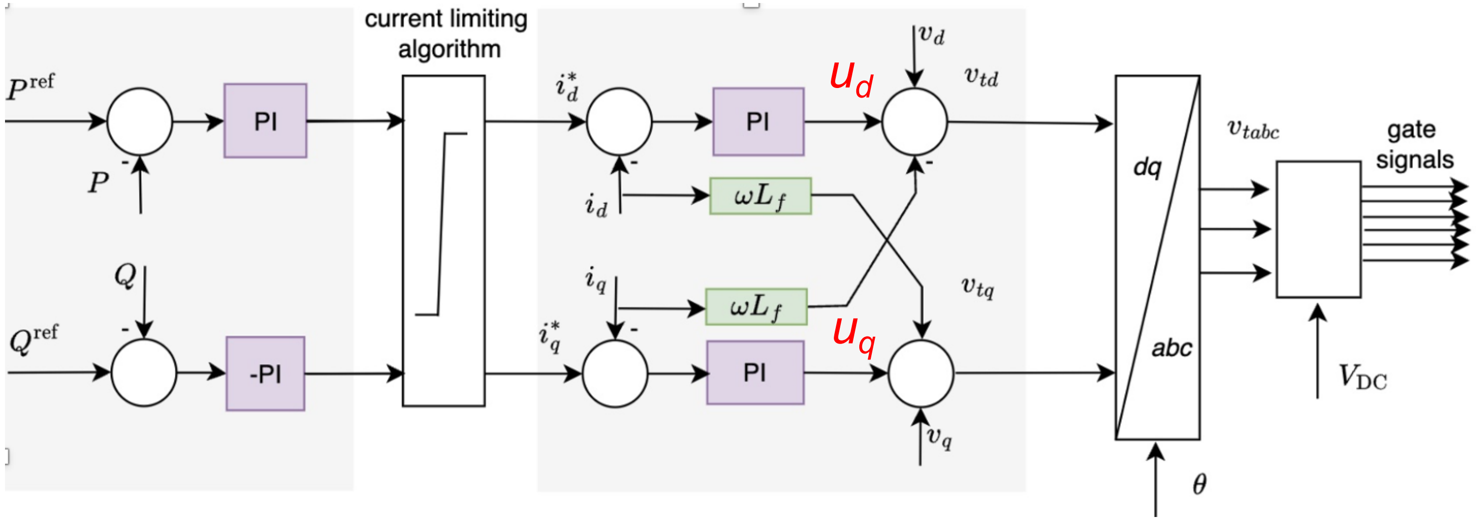
A. Tuckey and S. Round, "Grid-forming inverters for grid-connected microgrids: Developing "good citizens" to ensure the continued flow of stable, reliable power," IEEE Electrification Magazine, vol. 10, no. 1, pp. 39–51, 2022.

G.Postiglione, et al, "An improved modular statcom topology equipped with short- time energy storage and grid forming control for hv network voltage and frequency," CIGRE 2024 Paris Session, 2024.



L. Fan, Z. Miao, H. Ding, "Enabling Technology for Energy Sustainability: Power Electronic Control of IBRs."





$$\vec{v}_t - \vec{v} = (R+Ls)\,\vec{i}$$

$$(R+Ls)i_d = \underbrace{v_{td} - v_d + \omega L i_q}_{u_d}$$

$$(R+Ls)i_q = \underbrace{v_{tq} - v_q - \omega L i_d}_{u_q}$$

$$\underbrace{\left(K_p + \frac{K_i}{s}\right)}_{G_{\rm PI}}(\bar{I}^* - \bar{I}) = \bar{u} = (R+Ls)\bar{I}.$$

$$\frac{\Delta \bar{I}}{\Delta \bar{I}^*} = \frac{G_{\rm PI}}{G_{\rm PI} + R + Ls} = \frac{K_p s + K_i}{Ls^2 + K_p s + K_i}$$

This type of design **(ideally)** can make a current source: the converter current is only related to the current order.

Due to effect of the filters in the feedforward units, there are negative-sequence currents generated.

In converter control design, the inner current control has **the PCC bus voltage feedforward unit**, ensuring that the converter is transformed into **a current source (bandwidth > 150 Hz, sub-cycle time scale).**

Concluding Remarks

- Accurate fault analysis relies on translating IBR's control characteristics into proper circuit representations.

- The sequence network interconnection technique works great for fault analysis.
  - Edith Clarke pioneered the technique of putting PNZ circuits together for fault analysis around 1931, after Fortescue developed the symmetrical component theory in 1918.

Simultaneous Faults on Three-Phase Systems

BY EDITH CLARKE*

Associate, A. I. E. E.

Synopsis.—The method of symmetrical components now so extensively used to determine short-circuit currents and stability limits during transient conditions for three-phase transmission systems when a fault involving one or more of the three conductors occurs at any one point of the system, has been extended to apply to three-phase systems during simultaneous faults at two or more points of the system.

A general equivalent circuit is developed to replace, in the positive phase diagram, two simultaneous faults involving any combination of the six conductors. An approximate equivalent circuit to be used with the d-c. calculating table when resistance is neglected is also given.

Special equivalent circuits are employed to replace two simultaneous faults and the lines upon which they occur, when the lines are unloaded feeders radiating from a common point or lines of equal impedances bussed at both ends.

The methods and formulas given in this paper were developed in answer to such questions as the following:

1. Which is a more severe shock to a system, a double line-to-ground fault on one circuit or two single line-to-ground faults occurring simultaneously on two separate circuits?

2. Do simultaneous double line-to-ground faults which involve the same pha…
ground curren…
cuit and phase…

WHEN double circuit towers carry two three-phase circuits, disturbances may involve one or more conductors of each circuit. From published records[1] of the number of flashovers on double circuit towers which have tripped out both circuits, and from opinions expressed by operating engineers of various power companies who have been consulted, it seems reasonable to conclude that in the neighborhood of 20 per cent of the faults on double circuit towers involve conductors of both circuits. In addition there are instances where faults in substations have involved conductors of circuits not on the same towers.

It seems worth while therefore, to have in convenient form, methods for calculating short-circuit currents, and of determining the stability limit of a system when faults occur simultaneously at two separate and distinct points of the system. The general case will cover simultaneous faults at any two points of the system, involving one, two or three conductors at each point, while short circuits on parallel circuits on the same tower will be a special case in which the two points of fault are symmetrical with respect to the system, although they will not be symmetrical with respect to ground unless the faults are on the same phase or phases in both circuits.

Mr. C. L. Fortescue has shown[2] that any system of three vectors may be replaced by three sets of balanced components. The fundamental equations expressing actual currents and voltages in terms of their symmetrical components, and expressing the symmetrical components of current and voltage in terms of the actual currents and voltages respectively are given in Appendix A.

SINGLE FAULT

When one or more of the conductors of a three-phase

circuit bec…
the three c…
are no long…
ages to gro…
and three li…
I_c, are res…
it will be fo…
between th…
component…
in terms of…
fault, I_{a1}, a…
Z_0 and Z_2 …
this require…
Since the…
sequence v…
component curre…

At a point of fault there are certain relations between the positive, negative, and zero components of current which flow into the fault, and also between the positive, negative, and zero components of voltage at the fault. These relations between the components of current and voltage, depending upon the type of fault, provide additional equations connecting the unknowns. For all types of fault there will be three independent equations connecting the components of current and voltage at the point of fault. These equations are tabulated in Table I, and the manner of their derivation shown in Appendix B.

From five equations with six unknowns, the four unknowns V_{a0}, V_{a2}, I_{a0} and I_{a2} may be eliminated, and V_{a1} expressed in terms of I_{a1} thus:

$$V_{a1} = K\, I_{a1} \tag{3}$$

where K is a function of Z_0 and Z_2 depending upon the type of fault. For line-to-ground faults $K = Z_0 + Z_2$, for line-to-line faults $K = Z_2$, and for double- line-to-

*Central Station Engg. Dept. General Electric Company, Schenectady, N. Y.

Edith Clarke