Development and Implementation of Short Circuit Models for Wind Turbine Generators

Summary paper prepared from the report published by IEEE PES PSRC working group C24

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Scope of Working Group C24

1. To survey WTG manufacturers to determine what parameters they could provide that could be used by steady state short circuit program developers in various time frames.
2. Use the result of this survey to prepare a report that can be used by steady state program developers to refine their models.

Representation

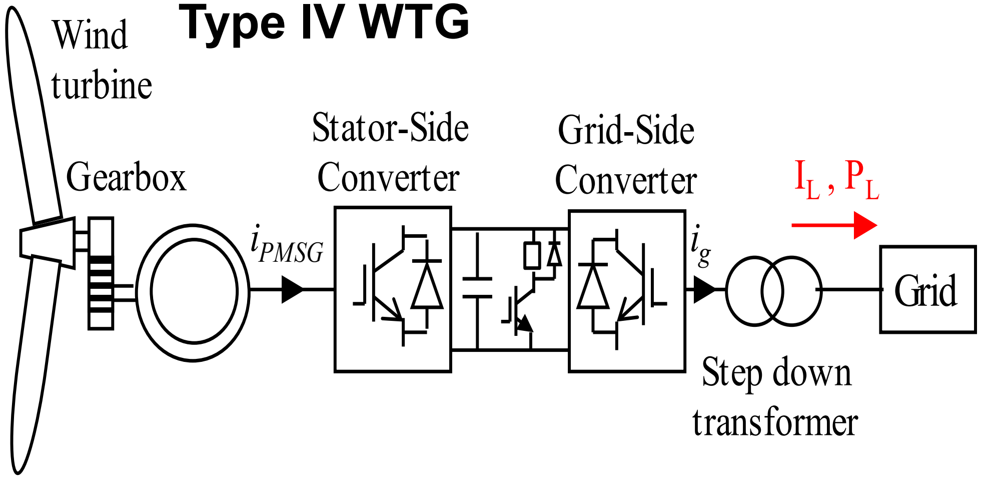
1. WTG manufacturers: GE, Siemens Gamesa, Vestas
2. Software Vendor: Siemens (PSS®CAPE), ASPEN, ETAP
3. Utilities
4. Consultants
5. Relay Manufacturers
6. Research Enterprises and Universities

Motivation

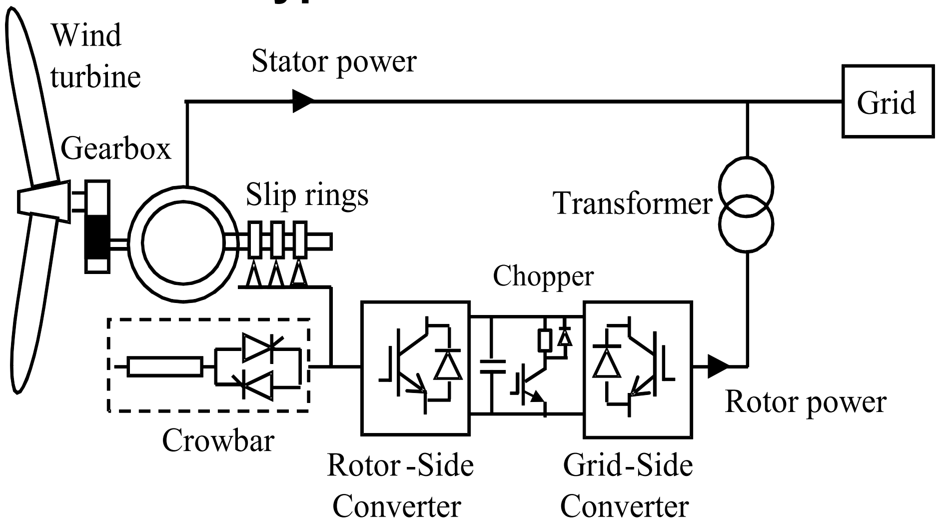
- Type III and Type IV wind turbine generators (WTGs) connect through inverters. So do solar PV.
- Highly nonlinear response of inverters to faults.
- Conventional phasor domain short circuit analysis assumes
  – Linear response of sources (Thevenin Equivalent)
  – Load currents negligible compared to fault currents.
- These assumptions are no longer valid.
- Inverter controls are proprietary – hampers EMT modeling as well.

Inverter Based Resources

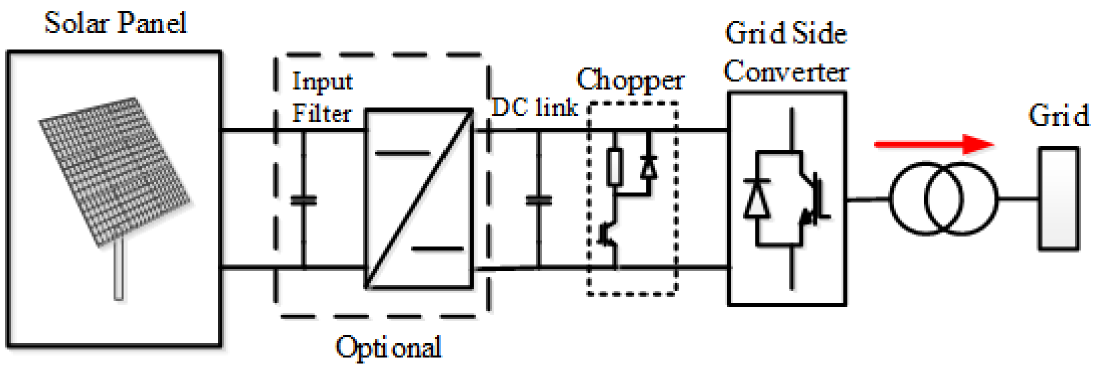
Type IV WTG



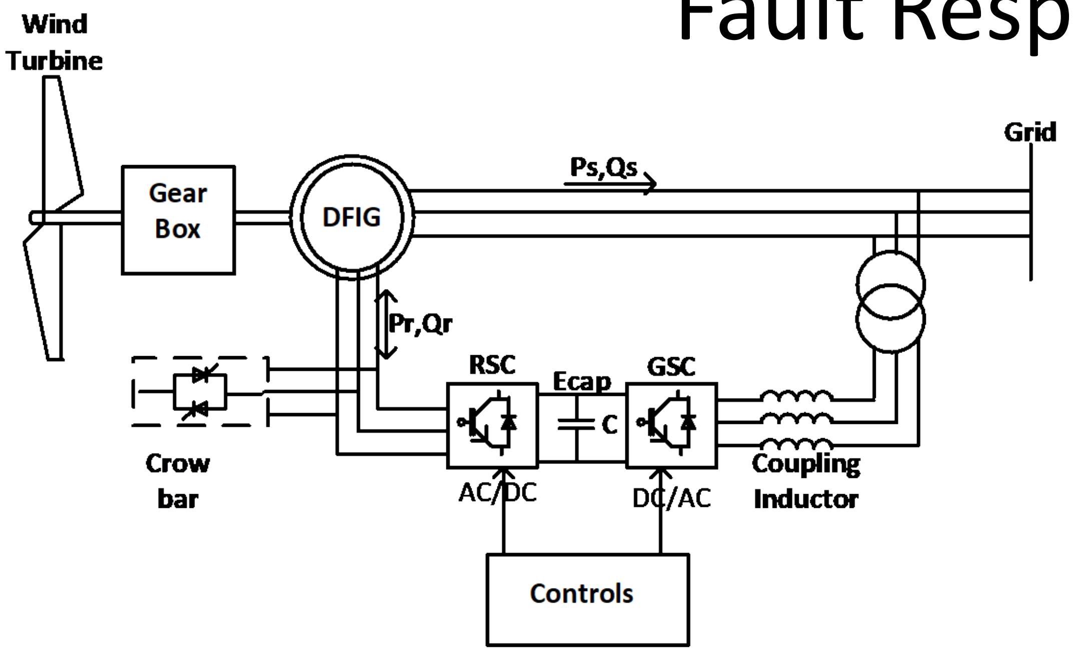
Type III WTG

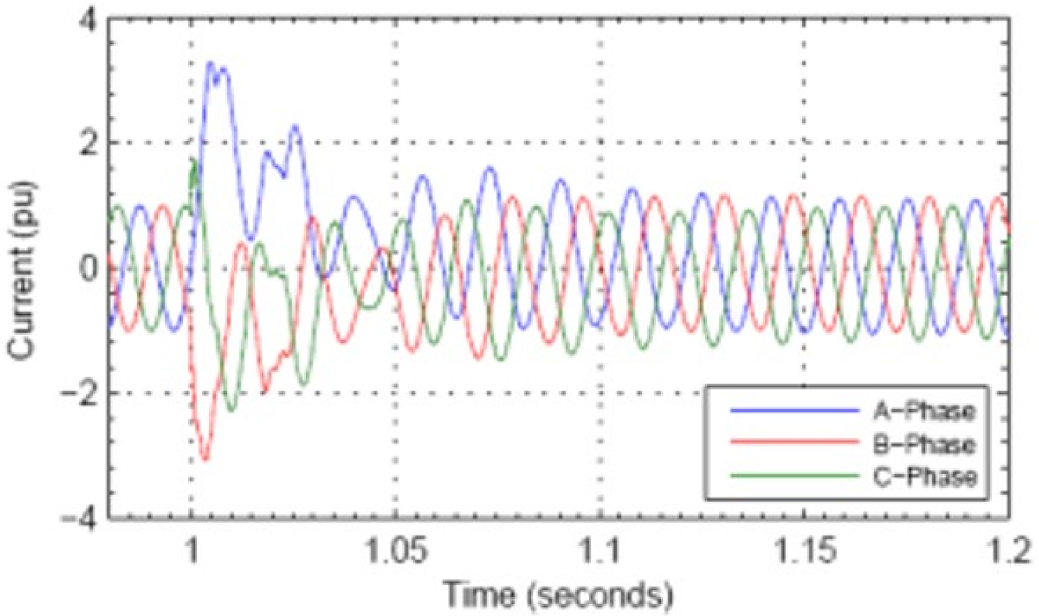


Solar PV



Fault Response – Type III

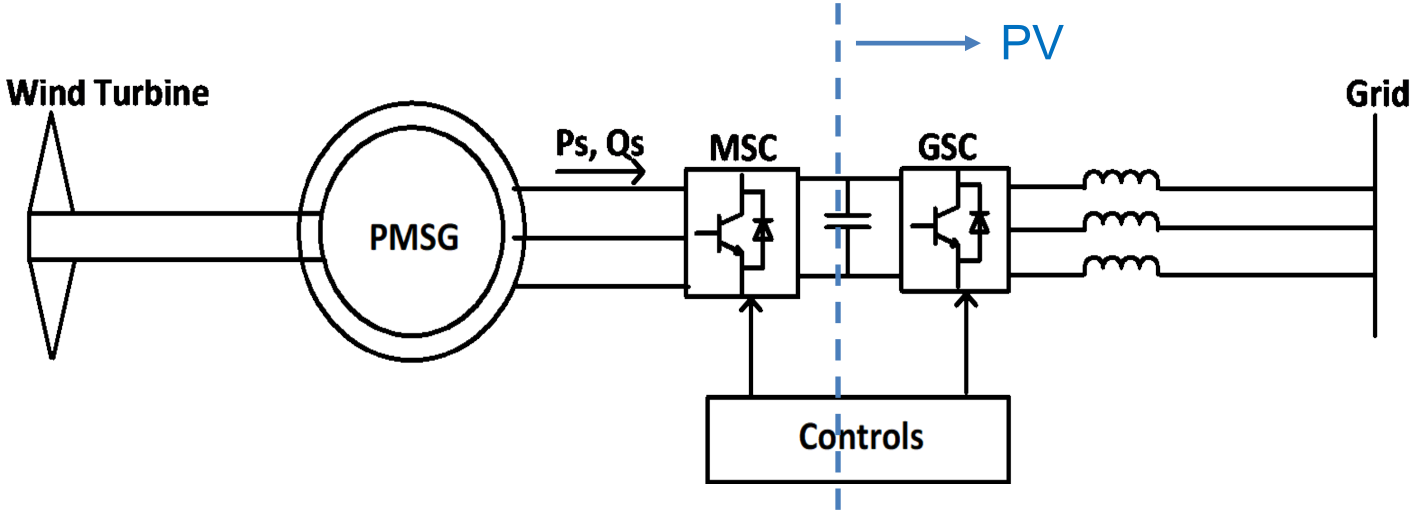




From PSRCC C17 WG report "Fault Current Contributions from Wind Plants" - IEEE PES Technical Report TR-26

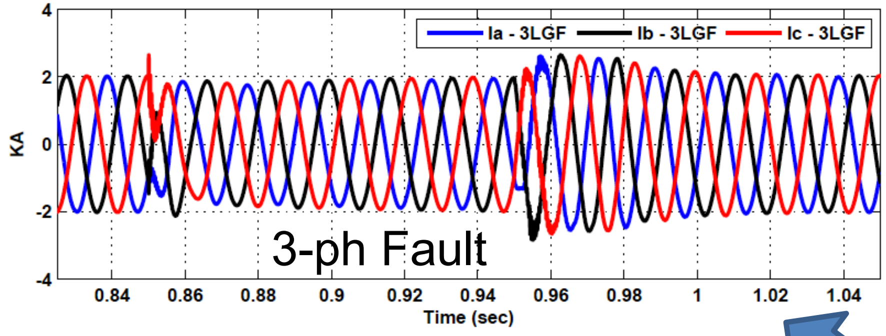
- **Type III Wind Turbine Generators (WTGs) can have the most complex behavior –**
  - **older models crowbar for close-in faults to protect the converter circuit – behavior similar to induction generators.**
  - **current-controlled mode for remote faults.**
  - **can switch from one mode to another during fault.**
  - **newer models can remain in control in all conditions.**

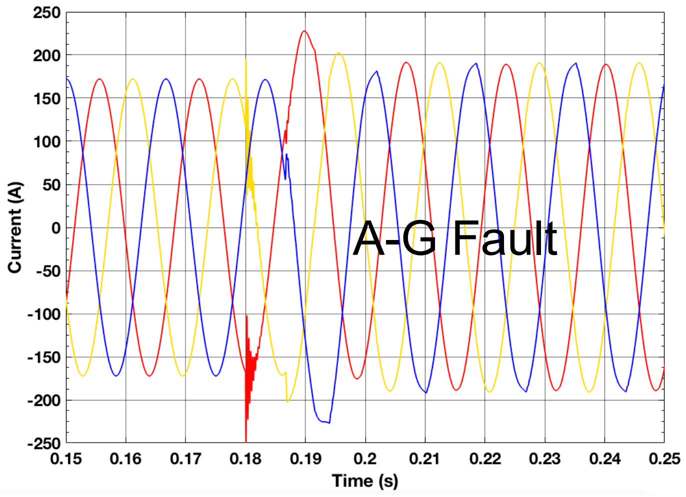
Type IV-Full Converter



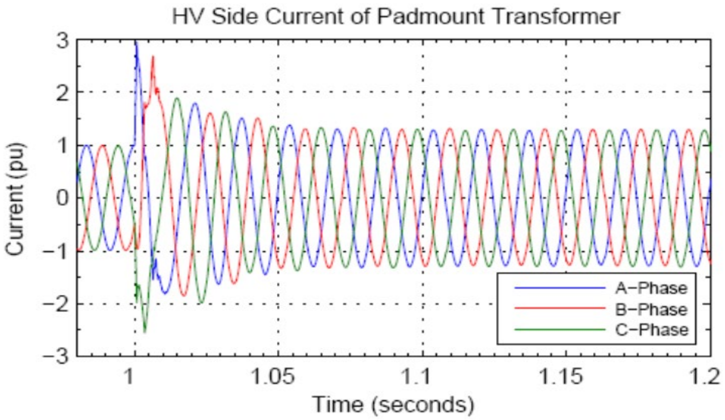
- **Type IV WTGs and PV connect to the system through inverters**
  - **response determined solely by inverter.**
  - **typical features – current controlled, purely positive sequence current.**
  - **low voltage ride through can be implemented – change in power factor during fault.**
  - **completely nonlinear response - voltage controlled current source.**

Fault Response – Type IV-Full Converter





Model – 1 (Clemson)

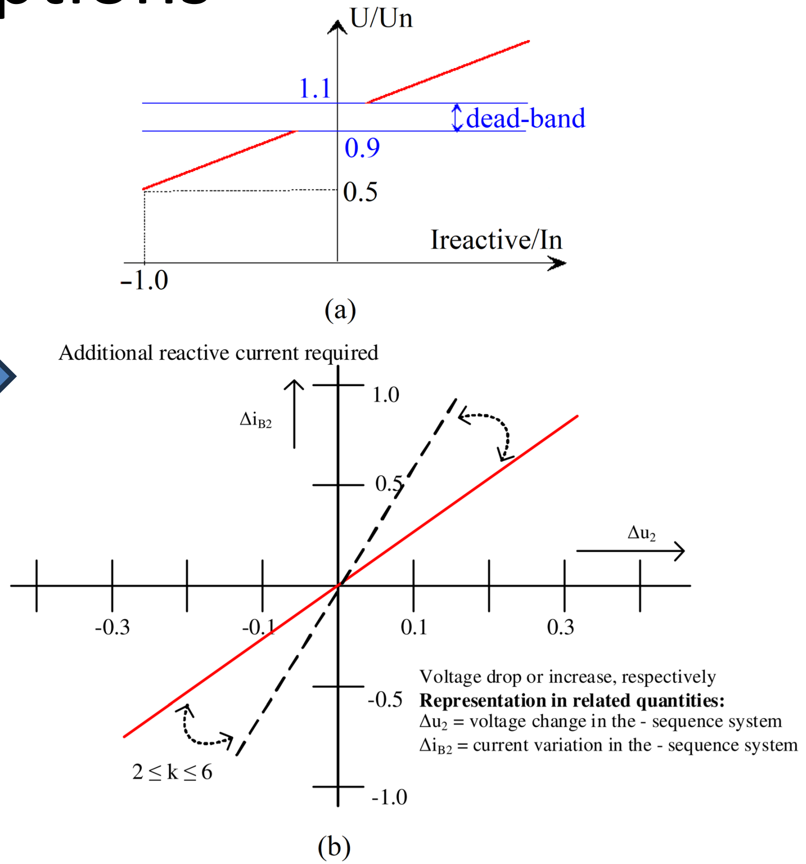


Model - 2 (PSRCC C17 WG report)

- **Time for control to take over is different for different models.**
- **Notice purely (or mostly) positive sequence current with magnitude comparable to load current – 1.1 to 1.5 pu typical.**

Inverter Generic Control Mode Options

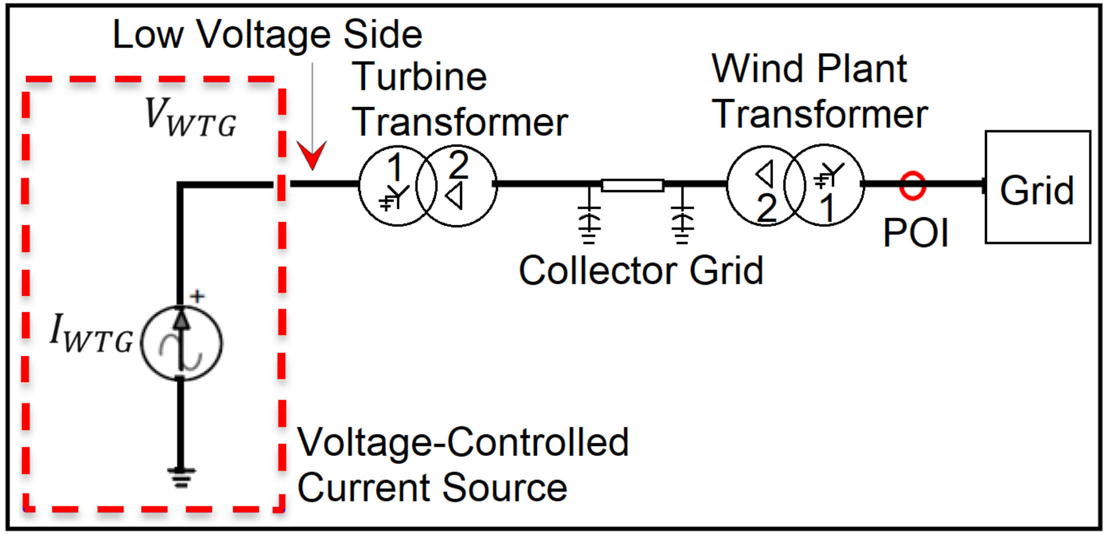
Function	Control Mode	Performance Description
Reactive power/voltage control during ride-through	Reactive power control	Enables fixed desired injection/absorption of reactive power
	Power factor control	Enables injection/absorption of reactive power based on a desired power factor
	Voltage control	Enables control of voltage at desired setpoint
	Dynamic reactive current control (also known as Fault Ride-Through (FRT))	Enables positive and negative sequence reactive current injection based on a reference curve (e.g., grid code)
	Control Priority	**Performance Description**
	Active current priority (P-priority)	The active current output is given priority and the reactive current output is constrained to the remaining current capacity.
	Reactive current priority (Q-priority)	The reactive current output is given priority and the active current output is constrained to the remaining current capacity.



Dynamic reactive current control curve for (a) positive sequence reactive current and (b) negative sequence reactive current based on VDE-AR-N 4120 Technical Connection Rules

- Underscores how different the fault response could be.
- Note: Source power factor during fault is NOT determined by line impedance angle(s) for remote faults.
- Markedly nonlinear behavior – how to incorporate in fault analysis?

Phasor Domain Model to Capture IBR-Behavior



- Voltage controlled current source
- Iterative solution (nonlinear behavior)
  - Considers the impact of controls on the short circuit response.
  - Respects inverter current limits.
  - Filter Capacitor has uncontrolled response right after fault, but no fundamental current.

WG Recommendation

1. **PSRCC WG C24 has consulted with all stake-holders (utilities, software developers, WTG Manufacturers, EPRI, consultants) and come up with the following data requirements from manufacturers for different time-frames:**

Time frame 1,2,3 (unit-seconds or cycles)		Fault Type:
Positive sequence voltage (as specified in item 3) (pu)	Positive sequence current (pu)	Positive sequence current angle with respect to positive sequence voltage (deg)
1.0		
0.9		
0.8		
0.7		
0.6		
0.5		
0.4		
0.3		
0.2		
0.1		

Time frame 1,2,3 (unit-seconds or cycles)		Fault Type:
Negative sequence voltage (as specified in item 3) (pu)	Negative sequence current (pu)	Negative sequence current angle with respect to negative sequence voltage (deg)
1.0		
0.9		
0.8		
0.7		
0.6		
0.5		
0.4		
0.3		
0.2		
0.1		

2. **EPRI has also contributed field tested generic models that can be used instead of tables – caution – these do not mimic all designs.**

- **Inverters are ungrounded – do not contribute zero-sequence currents.**

Traditional Fault Analysis

In general, in a n-bus system, for a fault at bus "k" with fault impedance Z_F,

$$I_F = \frac{V_{PFk}}{Z_{kk} + Z_F}, and\ \Delta V_i = -Z_{ik} I_F, i = 1....n.$$

- To find the final bus-voltages, we must add the pre-fault and fault voltages at all buses:

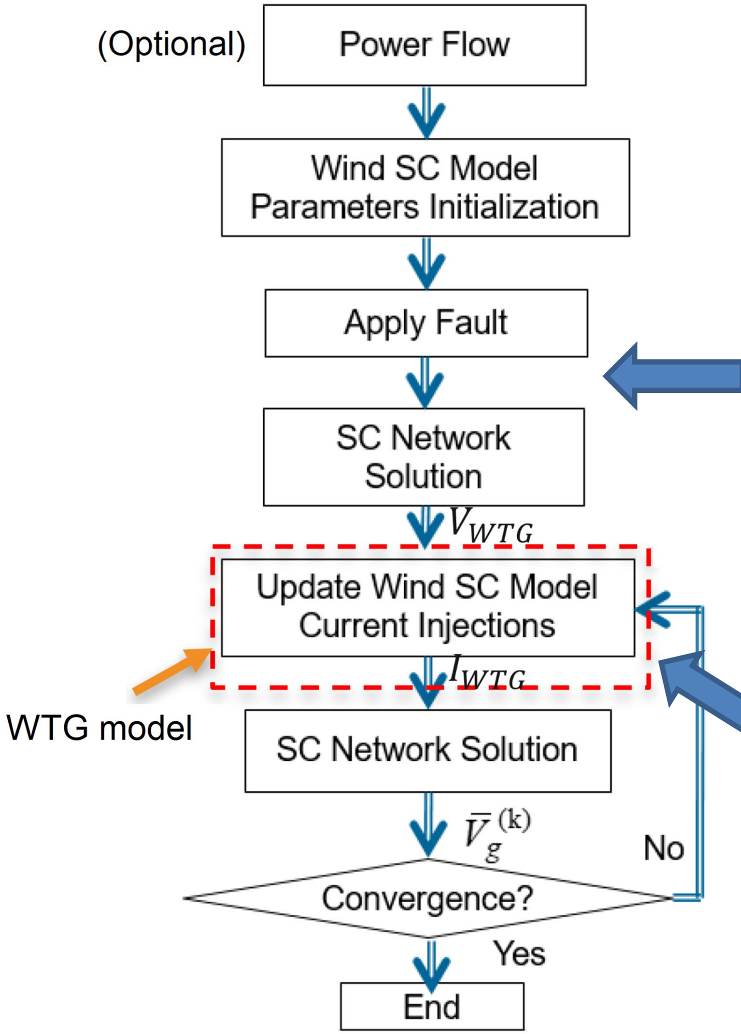
$$\begin{bmatrix} V_1 \\ V_2 \\ \cdots\cdots \\ V_k \\ \cdots\cdots \\ V_n \end{bmatrix} = \begin{bmatrix} -I_F Z_{1k} \\ -I_F Z_{2k} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ -I_F Z_{kk} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ -I_F Z_{nk} \end{bmatrix} + \begin{bmatrix} V_{PF1} \\ V_{PF2} \\ \cdots\cdots \\ V_{PFk} \\ \cdots\cdots \\ \Delta V_{PFn} \end{bmatrix}, or, V_i = -I_F Z_{ik} + V_{PFi}, i = 1.....n \quad (4)$$

- To find the currents between buses "i" and "j" after fault, we use:

$$I_{i-j} = \frac{V_i - V_j}{z_{ij}} \quad (5)$$

Note that z_{ij} is the *actual* impedance of line i-j.

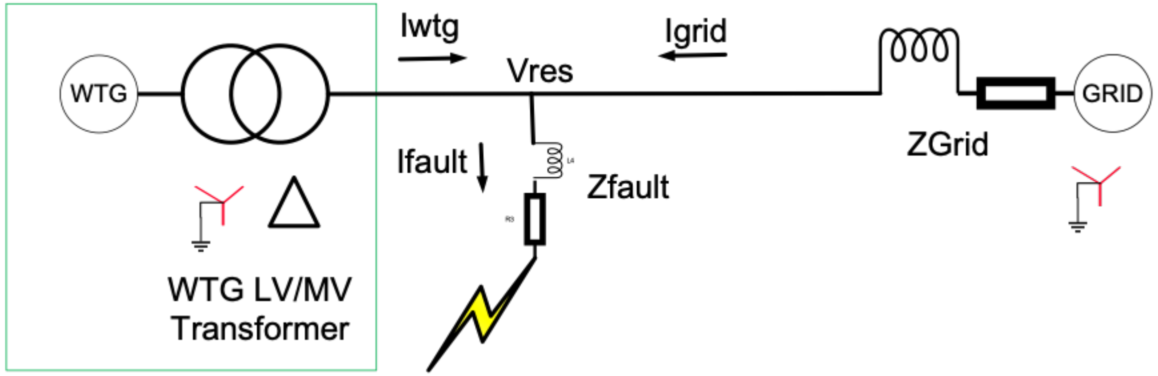
Implementation of Tables



$$\begin{bmatrix} V_1 \\ V_2 \\ \cdots\cdots \\ V_k \\ \cdots\cdots \\ V_n \end{bmatrix} = \begin{bmatrix} -I_F Z_{1k} \\ -I_F Z_{2k} \\ \cdots\cdots\cdots\cdots \\ -I_F Z_{kk} \\ \cdots\cdots\cdots\cdots \\ -I_F Z_{nk} \end{bmatrix} + \begin{bmatrix} V_{PF1} \\ V_{PF2} \\ \cdots\cdots \\ V_{PFk} \\ \cdots\cdots \\ \Delta V_{PFn} \end{bmatrix},$$

Time frame 1,2,3 (unit-seconds or cycles)		Fault Type:	Time frame 1,2,3 (unit-seconds or cycles)		Fault Type:
Positive sequence voltage (as specified in item 3) (pu)	Positive sequence current (pu)	Positive sequence current angle with respect to positive sequence voltage (deg)	Negative sequence voltage (as specified in item 3) (pu)	Negative sequence current (pu)	Negative sequence current angle with respect to negative sequence voltage (deg)
1.0			1.0		
0.9			0.9		
0.8			0.8		
0.7			0.7		
0.6			0.6		
0.5			0.5		
0.4			0.4		
0.3			0.3		
0.2			0.2		
0.1			0.1		

Sample Tables from GE



System Chosen to Create Tables

3-phase-G Fault – Positive Sequence

Time (Cycle)	Parameter	Residual Voltage Scenario 1	2	3	4	5	6	7	8	9	10
-1	Voltage (pu)	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
	Current (pu)	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
	Angle (Deg)	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70
0	Voltage (pu)	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
	Current (pu)	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
	Angle (Deg)	7.69	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70
1	Voltage (pu)	0.00	0.13	0.25	0.39	0.53	0.65	0.75	0.84	0.93	1.02
	Current (pu)	1.59	1.33	1.17	1.16	1.14	1.03	0.93	0.91	0.94	0.92
	Angle (Deg)	_	-62.31	-56.01	-51.54	-49.88	-48.04	-33.92	-18.58	-7.52	-0.26
2	Voltage (pu)	0.00	0.09	0.20	0.31	0.43	0.62	0.75	0.87	0.96	1.04
	Current (pu)	0.41	0.45	0.78	0.82	0.75	1.30	1.31	1.22	1.06	0.98
	Angle (Deg)	_	-71.11	-46.88	-42.43	-41.67	-34.18	-29.15	-25.77	-17.67	-4.73
3	Voltage (pu)	0.00	0.13	0.26	0.39	0.53	0.68	0.81	0.92	0.99	1.05
	Current (pu)	1.22	1.20	1.38	1.42	1.31	1.44	1.41	1.20	1.00	0.97
	Angle (Deg)	_	-84.84	-59.09	-54.13	-52.58	-47.69	-41.53	-34.40	-21.67	-5.77
4	Voltage (pu)	0.00	0.13	0.25	0.38	0.53	0.68	0.82	0.95	1.02	1.05
	Current (pu)	1.33	1.29	1.41	1.33	1.33	1.35	1.25	1.22	1.06	0.97
	Angle (Deg)	_	-81.14	-52.05	-54.92	-52.89	-46.75	-44.52	-38.51	-24.99	-6.67
5	Voltage (pu)	0.00	0.12	0.23	0.38	0.52	0.66	0.81	0.95	1.02	1.06
	Current (pu)	1.21	1.24	1.28	1.20	1.22	1.36	1.29	1.23	1.09	0.97
	Angle (Deg)	_	-78.92	-51.20	-65.27	-59.05	-42.08	-40.84	-37.08	-25.29	-7.43
6	Voltage (pu)	0.00	0.12	0.24	0.38	0.53	0.65	0.80	0.95	1.03	1.06
	Current (pu)	1.20	1.15	1.21	1.15	1.18	1.37	1.33	1.26	1.10	0.97
	Angle (Deg)	_	-83.61	-58.28	-76.48	-63.98	-40.17	-37.79	-35.04	-24.68	-8.12

SLG Fault – Positive Sequence

Time (Cycle)	Parameter	Residual Voltage Scenario 1	2	3	4	5	6	7	8	9	10
-1	Voltage (pu)	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
	Current (pu)	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
	Angle (Deg)	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70	7.70
0	Voltage (pu)	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
	Current (pu)	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
	Angle (Deg)	7.76	7.72	7.71	7.71	7.71	7.70	7.70	7.70	7.70	7.70
1	Voltage (pu)	0.75	0.79	0.88	0.91	0.94	0.96	0.99	1.01	1.04	1.07
	Current (pu)	1.19	1.12	1.06	0.99	0.94	0.90	0.89	0.90	0.92	0.92
	Angle (Deg)	-13.00	-15.29	-22.70	-20.45	-16.76	-12.08	-6.95	-1.68	2.29	4.87
2	Voltage (pu)	0.76	0.77	0.81	0.87	0.92	0.97	1.00	1.03	1.06	1.08
	Current (pu)	0.82	0.68	1.31	1.33	1.27	1.16	1.08	1.02	0.97	0.94
	Angle (Deg)	-34.86	-35.27	-4.74	-5.99	-8.07	-9.69	-7.74	-4.92	-1.02	3.37
3	Voltage (pu)	0.81	0.84	0.82	0.86	0.92	0.96	1.02	1.04	1.06	1.08
	Current (pu)	1.23	1.18	1.41	1.40	1.26	1.15	1.08	1.01	0.96	0.93
	Angle (Deg)	-18.31	-17.63	-9.01	-8.03	-8.66	-7.61	-9.82	-6.09	-1.55	3.14
4	Voltage (pu)	0.78	0.81	0.86	0.91	0.95	0.98	1.02	1.06	1.07	1.09
	Current (pu)	1.36	1.36	1.34	1.37	1.23	1.15	1.01	1.00	0.96	0.93
	Angle (Deg)	-13.58	-12.67	-12.71	-13.29	-12.52	-11.16	-10.35	-8.22	-2.14	2.80
5	Voltage (pu)	0.79	0.83	0.87	0.92	0.97	1.01	1.04	1.06	1.07	1.09
	Current (pu)	1.29	1.31	1.33	1.36	1.24	1.15	1.06	1.00	0.96	0.93
	Angle (Deg)	-17.60	-16.42	-15.96	-15.13	-16.01	-15.73	-12.65	-7.69	-2.59	2.54
6	Voltage (pu)	0.80	0.84	0.88	0.92	0.97	1.02	1.05	1.06	1.08	1.09
	Current (pu)	1.16	1.19	1.26	1.30	1.20	1.10	1.04	0.99	0.95	0.92
	Angle (Deg)	-20.86	-19.45	-16.80	-14.79	-15.89	-17.76	-15.48	-8.30	-3.08	2.28

SLG Fault – Negative Sequence

Time (Cycle)	Parameter	Residual Voltage Scenario 1	2	3	4	5	6	7	8	9	10
-1	Voltage (pu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Current (pu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Angle (Deg.)	_	_	_	_	_	_	_	_	_	_
	Resistance (pu)										
	Reactance (pu)	_	_	_	_	_	_	_	_	_	_
0	Voltage (pu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Current (pu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Angle (Deg.)	_	_	_	_	_	_	_	_	_	_
	Resistance (pu)										
	Reactance (pu)	_	_	_	_	_	_	_	_	_	_
1	Voltage (pu)	0.21	0.19	0.19	0.17	0.14	0.12	0.09	0.07	0.06	0.03
	Current (pu)	0.77	0.69	0.62	0.54	0.45	0.37	0.28	0.20	0.12	0.05
	Angle (Deg.)	141.78	143.88	121.34	120.76	122.64	125.15	129.04	136.46	148.53	153.25
	Resistance (pu)	0.22	0.22	0.16	0.16	0.17	0.18	0.21	0.27	0.39	0.48
	Reactance (pu)	0.17	0.16	0.26	0.26	0.26	0.26	0.26	0.25	0.24	0.24
2	Voltage (pu)	0.23	0.20	0.19	0.17	0.14	0.12	0.10	0.08	0.05	0.03
	Current (pu)	0.78	0.67	0.56	0.49	0.43	0.36	0.28	0.19	0.11	0.05
	Angle (Deg.)	111.76	110.79	130.40	132.51	140.10	148.14	149.94	155.06	157.13	152.49
	Resistance (pu)	0.11	0.11	0.22	0.23	0.25	0.29	0.30	0.36	0.47	0.42
	Reactance (pu)	0.27	0.28	0.25	0.25	0.21	0.18	0.18	0.17	0.20	0.22
3	Voltage (pu)	0.25	0.23	0.18	0.17	0.15	0.13	0.10	0.08	0.06	0.03
	Current (pu)	0.77	0.68	0.61	0.50	0.40	0.32	0.26	0.17	0.10	0.05
	Angle (Deg.)	122.96	123.41	133.47	134.37	133.92	139.42	149.67	149.69	147.05	144.57
	Resistance (pu)	0.18	0.19	0.20	0.23	0.26	0.32	0.34	0.42	0.51	0.46
	Reactance (pu)	0.27	0.29	0.21	0.24	0.27	0.27	0.20	0.24	0.33	0.33
4	Voltage (pu)	0.24	0.21	0.20	0.18	0.16	0.14	0.12	0.09	0.06	0.03
	Current (pu)	0.75	0.66	0.58	0.50	0.39	0.31	0.22	0.16	0.09	0.04
	Angle (Deg.)	123.95	126.19	128.39	130.42	132.29	132.62	140.39	147.06	140.52	136.93
	Resistance (pu)	0.18	0.19	0.21	0.23	0.27	0.30	0.41	0.48	0.53	0.48
	Reactance (pu)	0.26	0.26	0.27	0.28	0.30	0.33	0.34	0.31	0.43	0.44
5	Voltage (pu)	0.24	0.22	0.20	0.18	0.17	0.14	0.12	0.09	0.06	0.03
	Current (pu)	0.75	0.66	0.58	0.50	0.39	0.31	0.22	0.15	0.08	0.04
	Angle (Deg.)	121.89	122.96	126.93	129.48	128.06	124.25	131.51	143.94	132.96	130.96
	Resistance (pu)	0.17	0.18	0.21	0.23	0.26	0.26	0.36	0.49	0.54	0.48
	Reactance (pu)	0.27	0.28	0.28	0.28	0.33	0.39	0.41	0.36	0.58	0.56
6	Voltage (pu)	0.25	0.22	0.20	0.18	0.16	0.14	0.12	0.10	0.06	0.03
	Current (pu)	0.72	0.65	0.57	0.49	0.40	0.30	0.21	0.14	0.08	0.04
	Angle (Deg.)	121.89	123.52	129.82	133.92	133.90	127.45	127.10	143.88	129.58	126.77
	Resistance (pu)	0.18	0.19	0.23	0.26	0.28	0.29	0.35	0.55	0.53	0.49
	Reactance (pu)	0.29	0.29	0.28	0.27	0.29	0.38	0.46	0.40	0.64	0.65

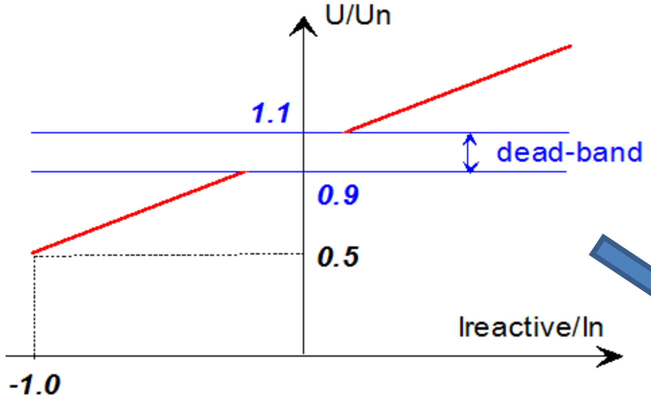
Current Limiter - Q Priority – Implemented by EPRI for Type-IV

This Logic is Provided by Siemens

$I_{active\text{-}pu} = P_{pre\text{-}Fault\text{-}pu}/Vt^{(1)}$ ⇒ post-fault pu voltage

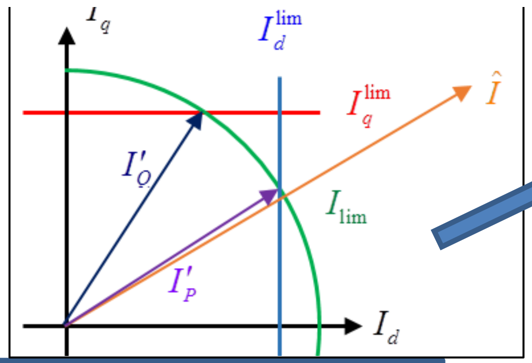
$I_{reactive\text{-}pu} = I_{reactive,PreFlt\text{-}pu} + K(1 - Vt^{(1)})$ pu for $Vt^{(1)} < 0.9$

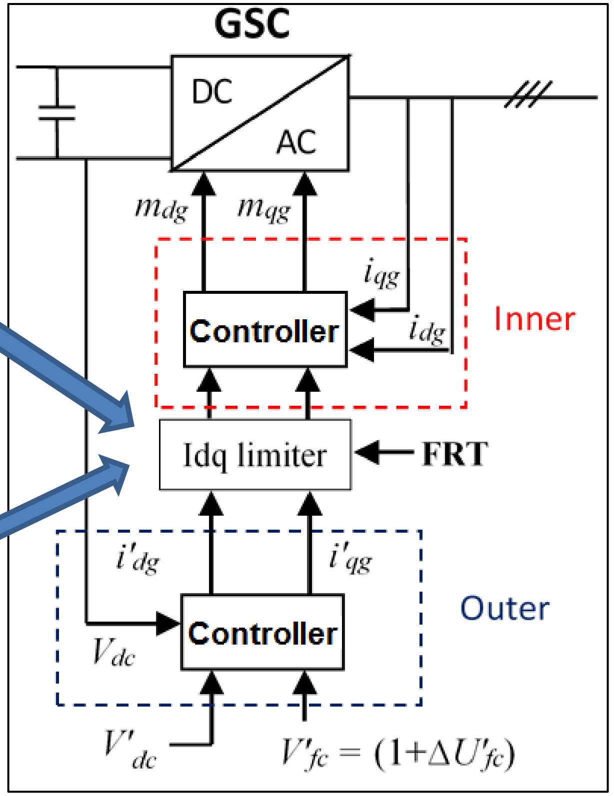
↑ Typically, 0 ↑ Typically, 2



$I_{post\text{-}fault\text{-}pu} = I_{active\text{-}pu} + jI_{reactive\text{-}pu}$

↑ Limit magnitude to 1-1.5 pu, typically





Example:
Assume:

Active Power: 1 p.u.

Post fault voltage: 0.7 pu

Control mode: FRT with slope 2

Q priority I_{limit}=1.1 pu

Desired Currents:

Iactive= 1/0.7=1.43 p.u

Ireactive=2(1-0.7) = 0.6 p.u

Itotal=1.55 pu (exceeds limit)

Upon current limiter:

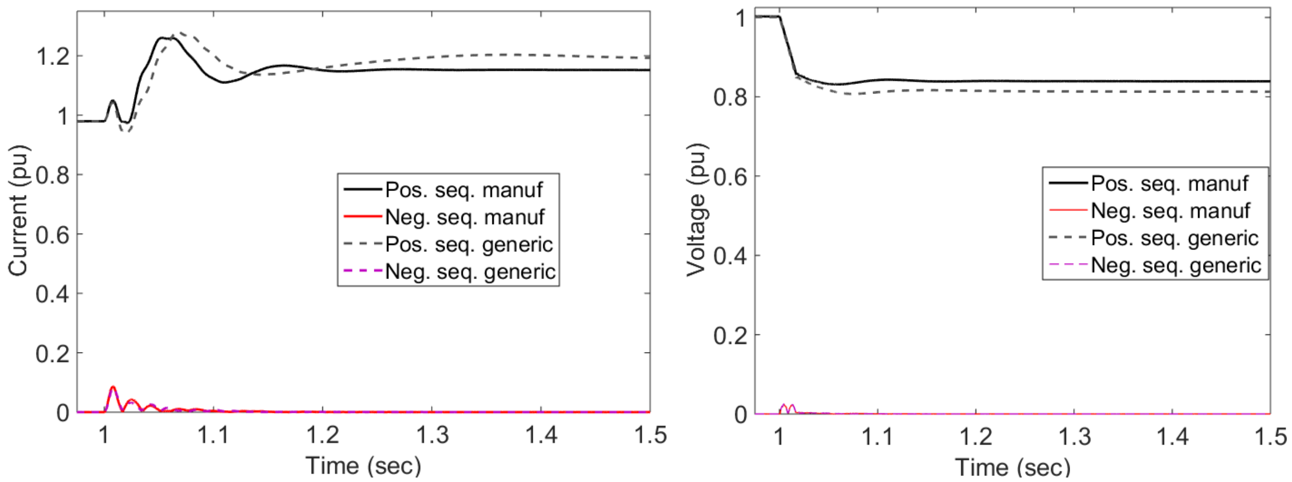
Iactive= 0.92 (reduced to satisfy limit)

Ireactive= 0.6 p.u

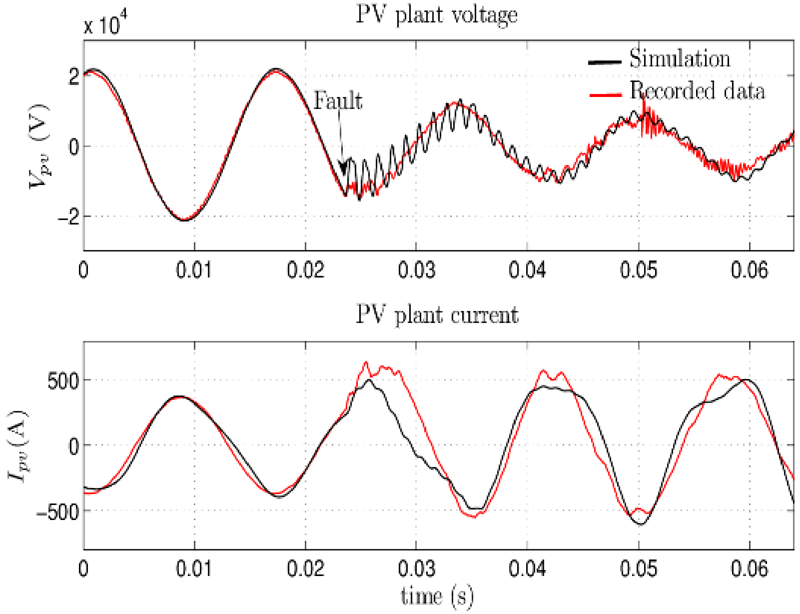
Itotal= 1.1 pu

- If you have this information about the controller, this can replace the tables.
- If not, this is a generic model, in absence of any other information.

Generic Models: EPRI Model Validation – Type IV

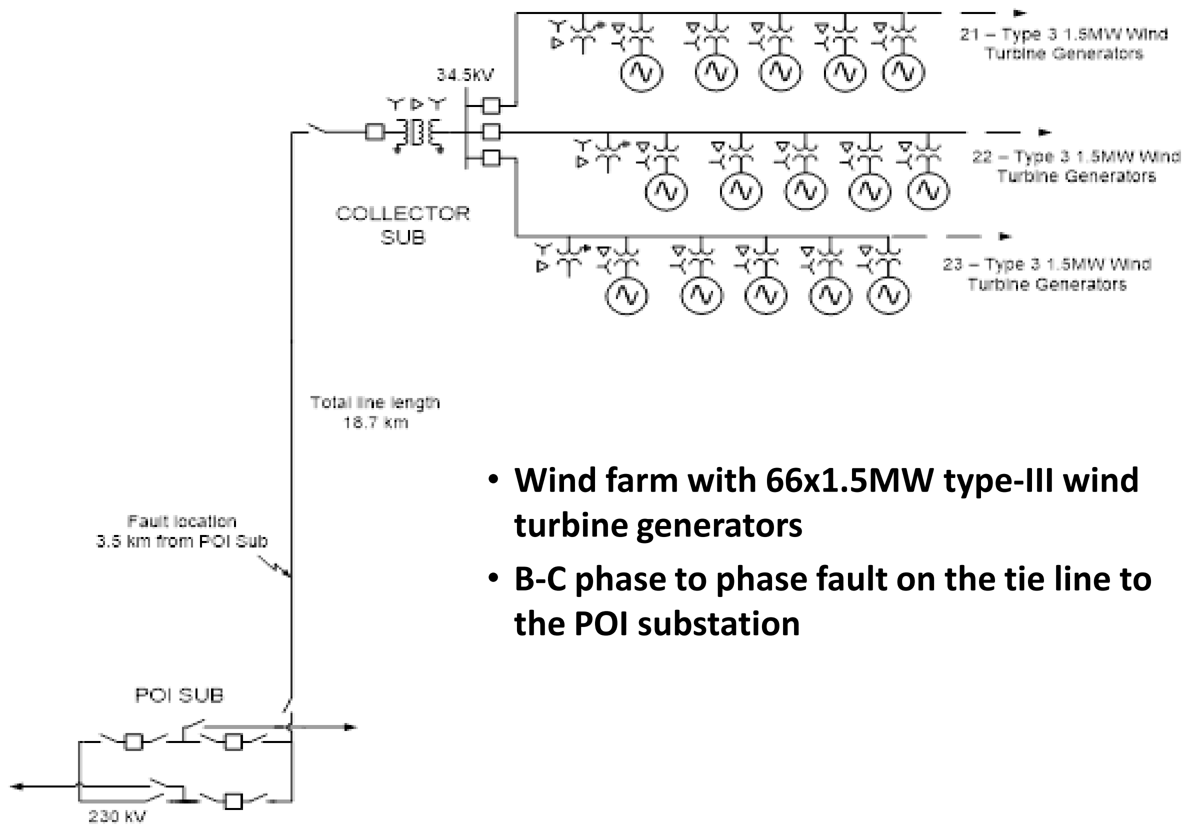


Manufacturer EMT Models



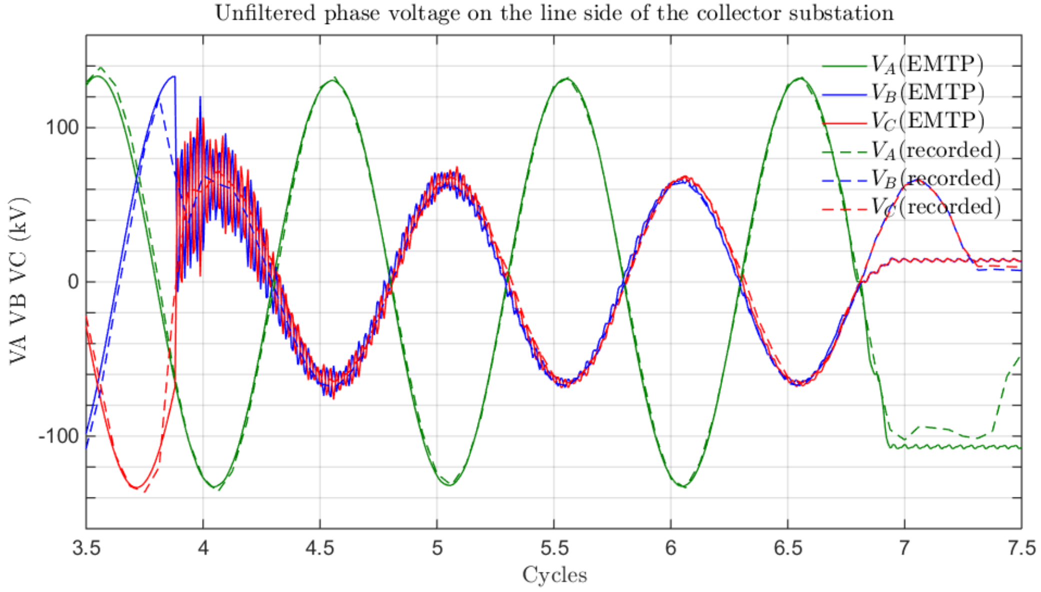
Fault Records – Full Converter

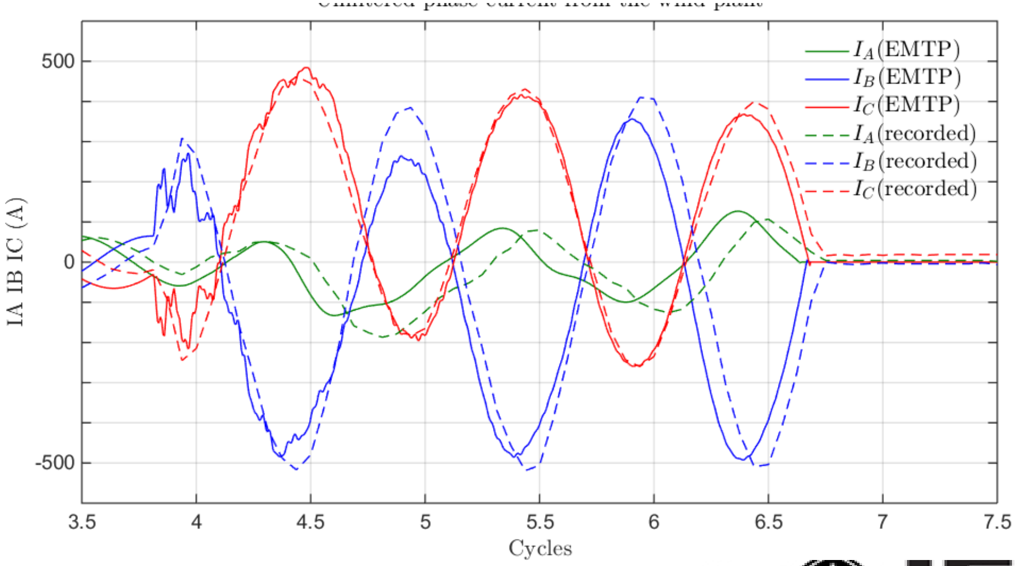
Generic Models: EPRI Model Validation – Type III



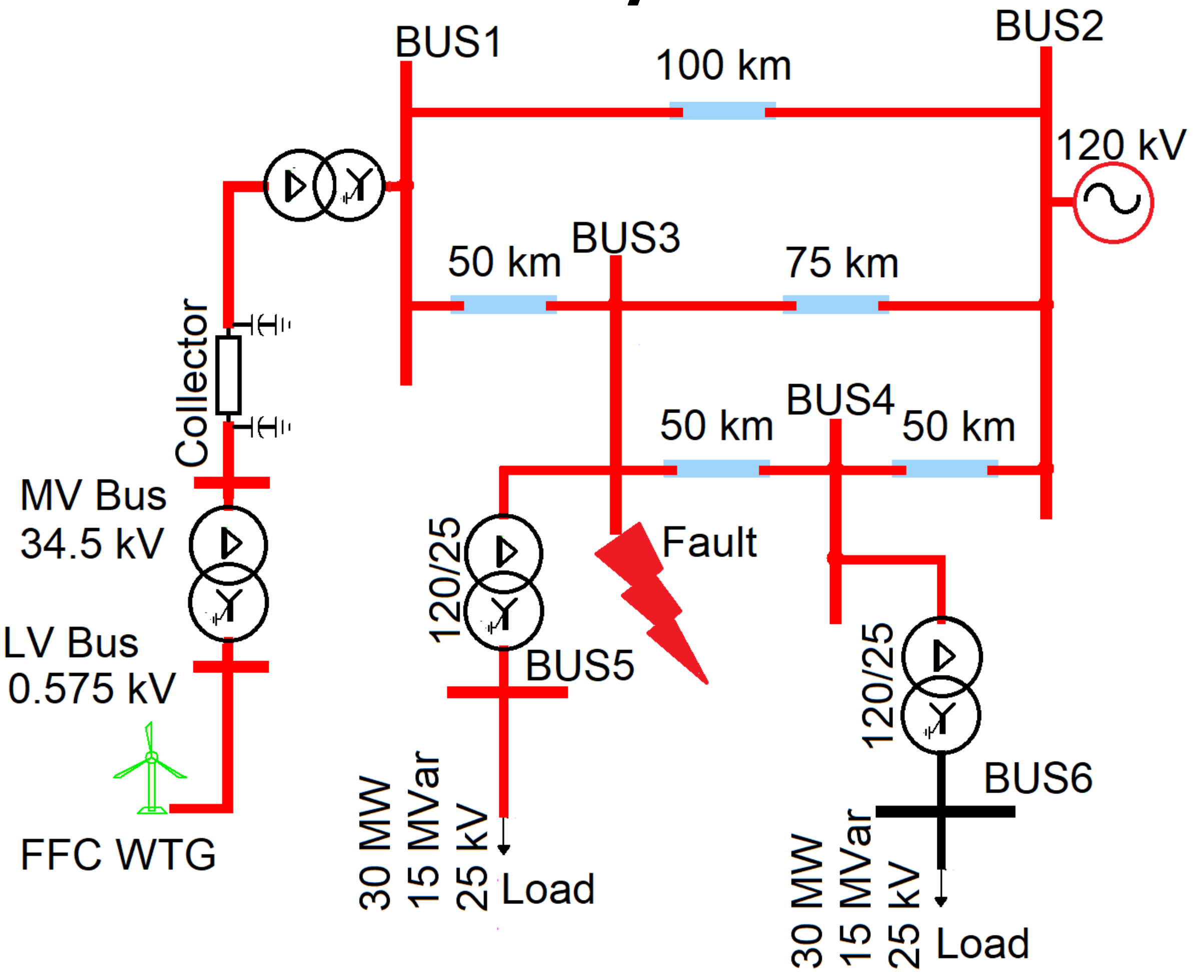
- **Wind farm with 66x1.5MW type-III wind turbine generators**
- **B-C phase to phase fault on the tie line to the POI substation**

Fault Records – Type III





Test System



45×1.5 MW Type IV WTGs operated under FRT control with Q-priority

Solution Platforms

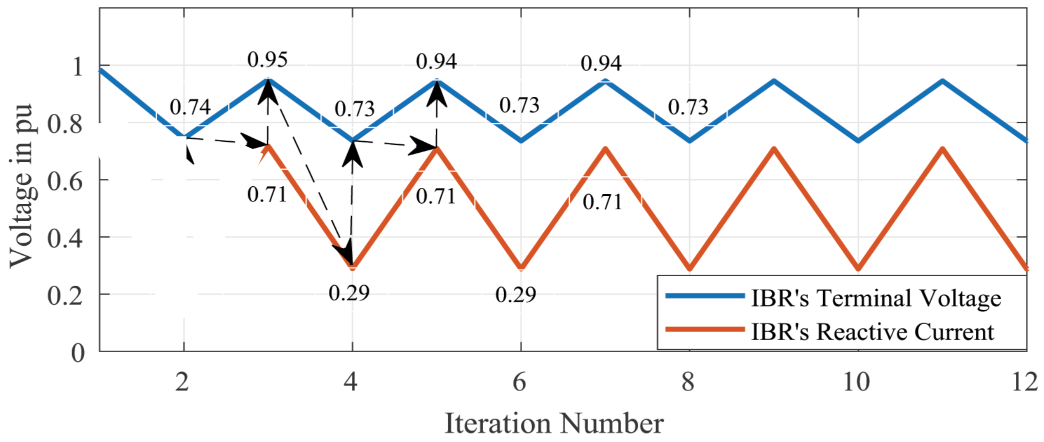
1. An ASPEN OneLiner implementation representing the WTGs by a VCCS table placed at the LV Bus;
2. A PSS®CAPE implementation representing the wind plant by a VCCS table placed at the LV Bus;
3. A PSS®CAPE implementation representing the wind plant by the "EPRI TYPE-IV WTG" generic model at the LV Bus;
4. An ETAP implementation at the LV Bus;
5. An algorithm code developed by EPRI with iterative solution;
6. An EMTP implementation with detailed generic EMT model of the wind plant including control schemes, power electronics and hardware - potentially provide the highest accuracy.

Results

Quantity	Implementation	3Ph-G Fault on BUS 3		ABG Fault on BUS 3	
		Mag	Ang (deg)	Mag	Ang (deg)
V1_LV (pu)	ASPEN VCCS LV	0.50	0.00	0.70	0.00
	CAPE VCCS LV	0.49	0.00	0.70	0.00
	CAPE (EPRI TYPE-IV WTG)	0.50	0.00	0.73	0.00
	ETAP	0.50	0.00	0.71	0.00
	EPRI Code	0.50	0.00	0.71	0.00
	EMTP	0.50	0.00	0.71	0.00
I1_LV (A)	ASPEN VCCS LV	85940	-66.80	85484	-35.70
	CAPE VCCS LV	85864	-66.80	85444	-35.30
	CAPE (EPRI TYPE-IV WTG)	85950	-64.85	85448	-32.64
	ETAP	85948	-66.24	85487	-34.53
	EPRI Code	85948	-65.67	85492	-34.60
	EMTP	85906	-66.03	85491	-33.95
V1_MV (pu)	ASPEN VCCS LV	0.45	-32.40	0.67	-33.70
	CAPE VCCS LV	0.43	-32.70	0.67	-33.80
	CAPE (EPRI TYPE-IV WTG)	0.45	-32.41	0.70	-33.66
	ETAP	0.45	-32.68	0.68	-33.85
	EPRI Code	0.45	-32.71	0.68	-33.80
	EMTP	0.45	-32.54	0.68	-32.91
I1_MV (A)	ASPEN VCCS LV	1432	-96.80	1425	-65.70
	CAPE VCCS LV	1431	-96.80	1424	-65.30
	CAPE (EPRI TYPE-IV WTG)	1432	-94.81	1423	-62.66
	ETAP	1432	-96.24	1425	-64.53
	EPRI Code	1432	-95.96	1425	-64.60
	EMTP	1414	-96.03	1425	-63.95

Some Issues with the Approach

- Loads are ignored. No longer a valid assumption with high penetration of IBRs [1].
  - How loads should be modeled at low voltages?
- Even for moderate penetration of IBRs the solution “hunts around”, especially for remote faults [2]



$V_{IBR} = 0.74\ pu$	$I_{qIBR} = 0.71\ pu$
$V_{IBR} = 0.95\ pu$	$I_{qIBR} = 0.29\ pu$
$V_{IBR} = 0.73\ pu$	$I_{qIBR} = 0.71\ pu$
⋮	⋮

- Not tested with high IBR penetration.

WG C45 is formed to gather industry experience with the proposed models.

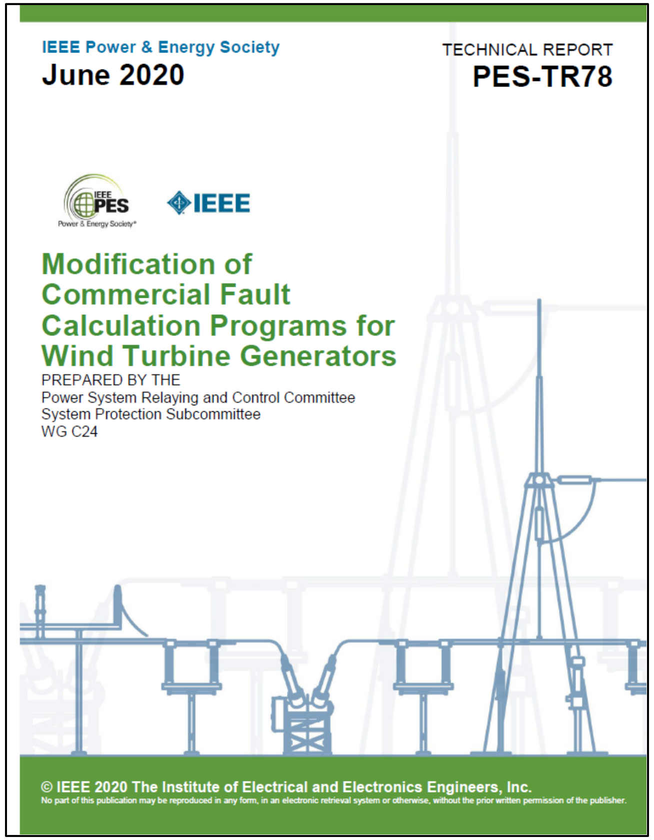
- One bright spot: DLL files can replace the tables. This may help model Grid Forming Inverters as well.

[1]. A. Haddadi, E. Farantatos, M. Patel and I. Kocar, “Need for Load Modeling in Short Circuit Analysis of an Inverter-Based Resource-Dominated Power System,” *in IEEE Transactions on Power Delivery*, vol. 38, no. 3, pp. 1882-1890, June 2023.
[2]. M. Patel, A. Haddadi, E. Farantatos, “Challenges with Integrating Short-Circuit Model of Inverter-Based Resources into Phasor-Domain Short-Circuit Programs”, *IEEE PES General Meeting*, 2023.

Dissemination

- Models adopted by Siemens (PSS®CAPE), ASPEN, ETAP.

Full Report



https://resourcecenter.ieee-pes.org/technical-publications/technical-reports/PES_TP_TR78_PSRC_FAULT_062320.html

Authors' copy: https://www.pes-psrc.org/kb/report/093.pdf