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IMPACT OF THE PENETRATION OF INVERTER-BASED SYSTEMS ON GRID PROTECTION

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OUTLINE

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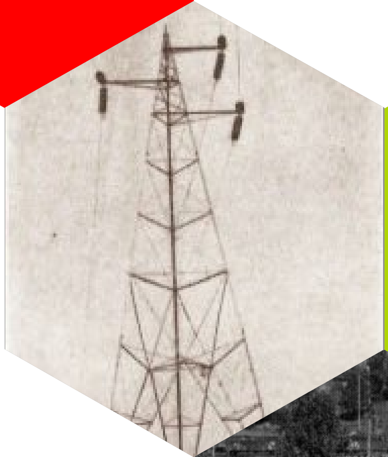
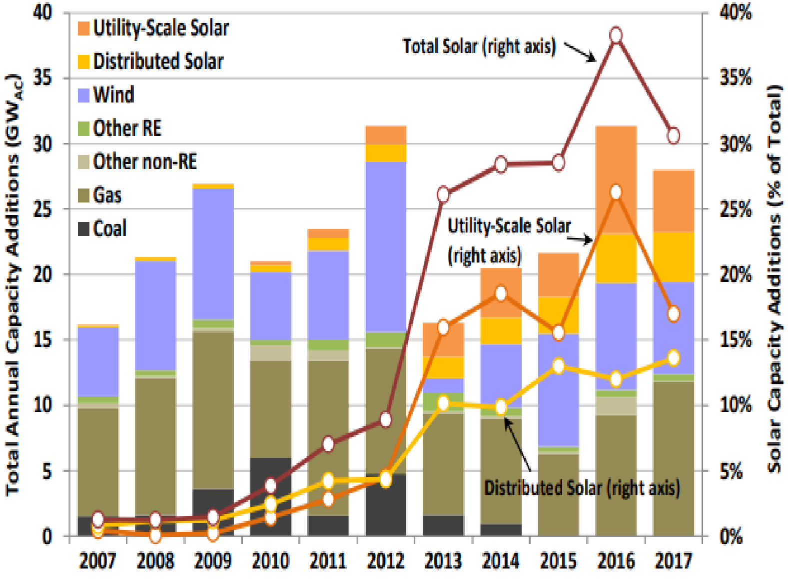


INTRODUCTION

INTRODUCTION

Utility Scale Renewable Generation

- In recent years a large number of utility scale inverter based renewable generation are coming online
- These inverter based generations are large on shore and off shore wind farms, solar PV and battery storage
- In 2017 6.2 GW of new utility scale solar PV of size 5 MW or more came online in the United States
- In 2018 7.6 GW of new utility scale wind capacity added in the United States

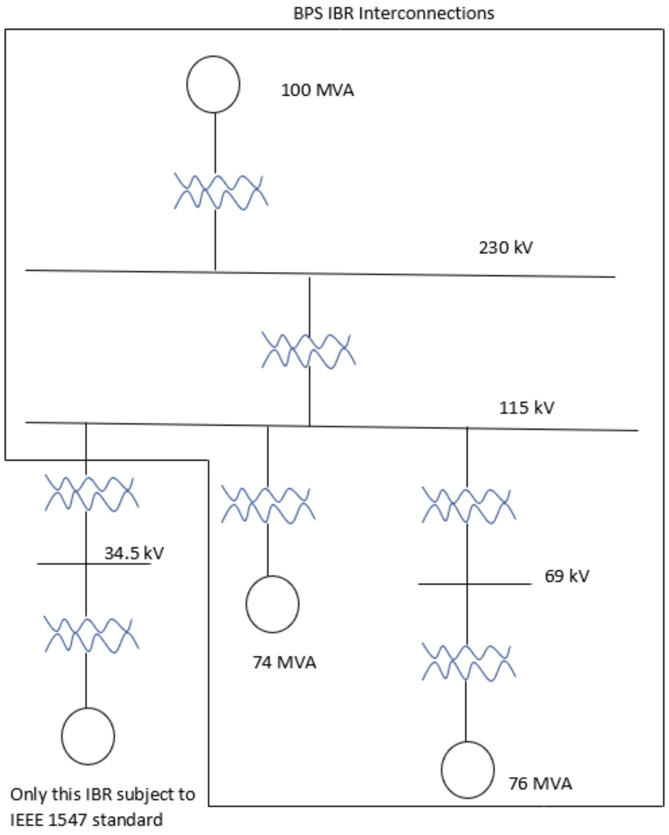


Source: ABB, AWEA, GTM/SEIA, Berkeley Lab

INTRODUCTION

BPS Interconnections

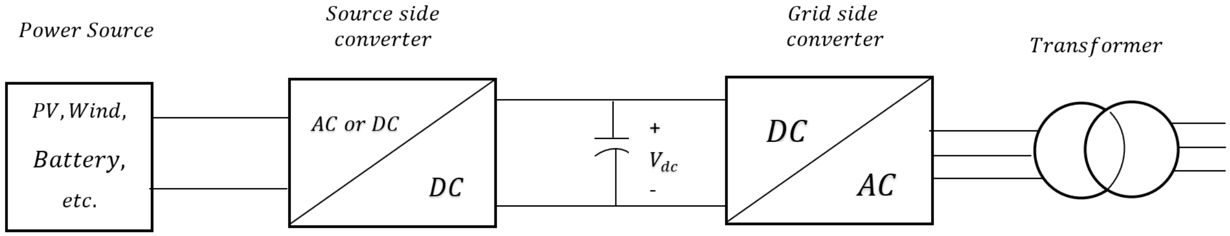
- The focus of our paper is the impact on protection systems from Bulk Power System (BPS) level connected IBRs of utility scale
- These IBRs are outside the domain of IEEE 1547-2018 standard
- Generator types used is synchronous generators, induction machines or solar arrays
- 100% renewable generation in some jurisdictions in 20 years time
- Upcoming IEEE P2800 standard will address EPS connected IBRs



WHAT ARE INVERTER BASED RESOURCES?

Inverter Based Resources

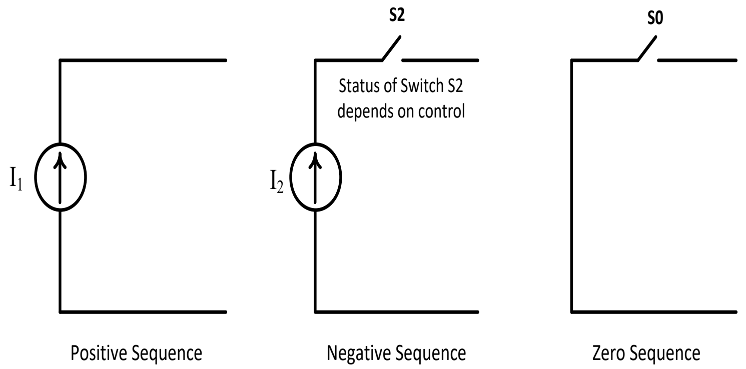
- IBR insert a power electronics between energy source and utility grid
- Type 3, type 4 wind turbine generators, solar PV generation and battery storage are common types
- Designed to limit current flow due to power electronics rating concerns
- Fault currents limited to 1.1-1.5 times the rated output current

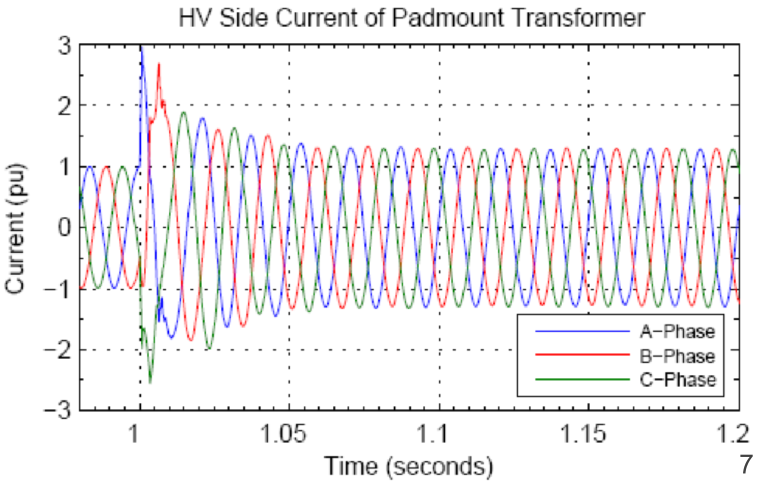


FAULT CHARACTERISTICS OF IBR

IBR Behavior During Faults

- Solid state devices limit fault current magnitudes
- Bridge structure does not provide a path for negative sequence currents
- Typical IBR configuration does not provide path for zero sequence currents
- Other elements of the fault current response is dictated by controls and not by the physics of the generating source or connected network
- Most IBR controls suppresses negative sequence currents
- Wide range of control philosophy from manufacturers





INVERTER POWER ELECTRONICS AND CONTROL SYSTEM

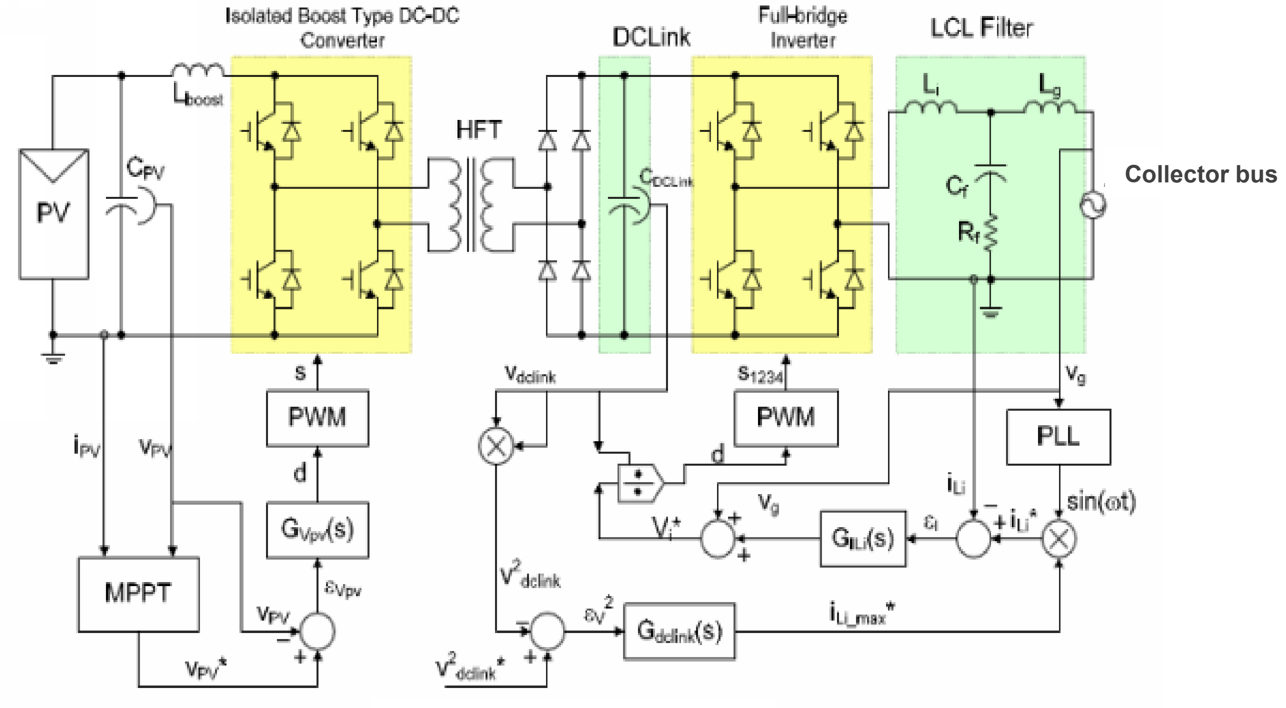


Fig.1 Grid integrated PV system

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Key Points

- Basic assumption is prefault current can be ignored in classical short circuit
- Modeling of generator assumes voltage source (EMF) behind an impedance
- Inverters cannot be represented that way
- Most models are simplistic user defined current limited models
- At least one short circuit calculation program in widespread use employs iterative loop solutions to determine the fault current contribution based on the chosen control strategy and current limits
- These programs do not work if all the generators in the system are IBRs
- At least one program assumes a particular structure for the low voltage to medium voltage transformers that may not be universally used

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Type 3 (Doubly Fed Induction Generator) Modeling and Issues

- Type 3 IBR exhibits three different fault behavior depending on the severity
- Crowbar action can modify fault characteristics
- In short, type 3 WTG can't be represented by a voltage source behind an impedance or with a single current control action
- Models assumes control action suppresses negative sequence currents giving rise to no response for unbalanced faults

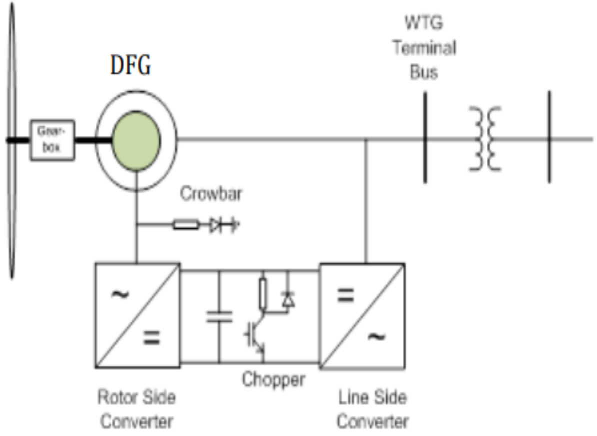


Figure 3-23: Topology of a typical double-fed (Type III) wind generator.

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Type 4 (Full Inverter) Modeling and Issues

- Modeling based on iterative loop solutions depending on voltage and selected control mode
- Without infeed between the IBR generator and the fault, the iterative solution may not converge
- Generators that do not converge are "disconnected"
- Algorithm uses wide variety of heuristics – no guarantee iterations will converge reliably

Low voltage to medium voltage Xfmr

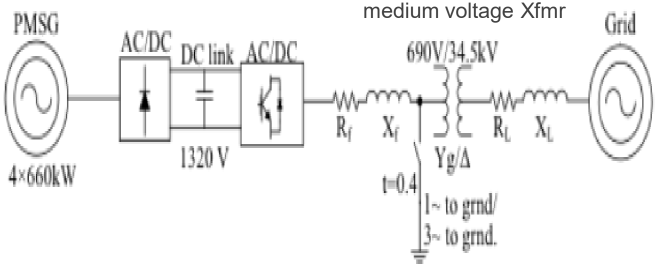


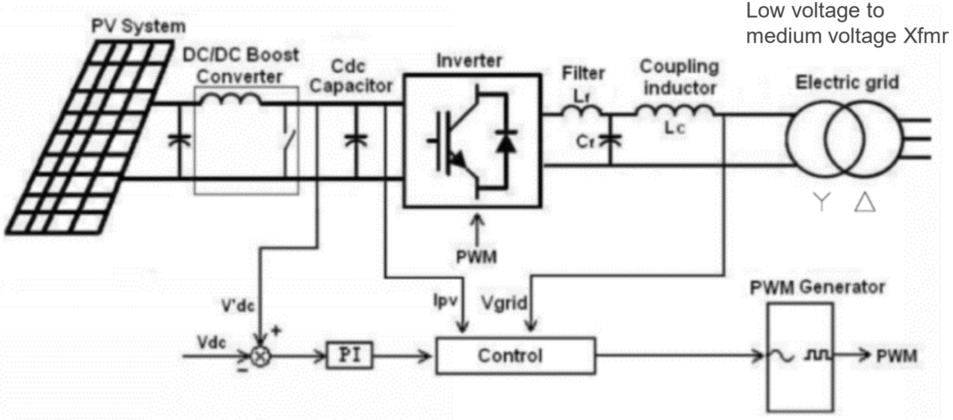
Figure 3-27: Single-line to ground/Three phase fault at WTG teminal.

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Photovoltaic Solar

- Modeling of photovoltaic solar is similar to Type 4 modeling
- The string inverters are connected to the medium voltage by ungrounded wye – delta transformer
- The solar PV system is coupled to the electric grid normally with a wye grounded – wye grounded – delta tertiary transformer
- Fault currents limited by control action

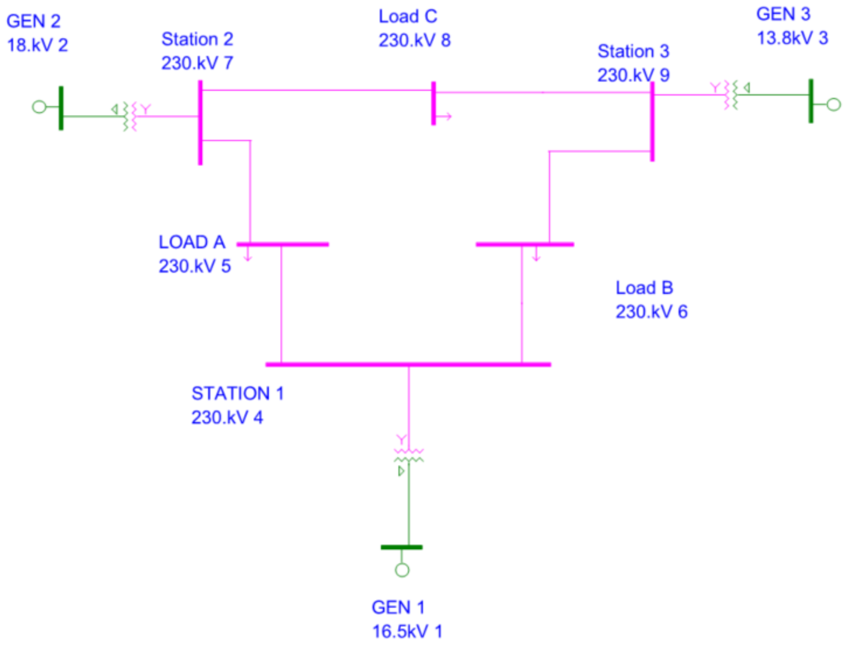
Low voltage to medium voltage Xfmr



MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Short Circuit Programs

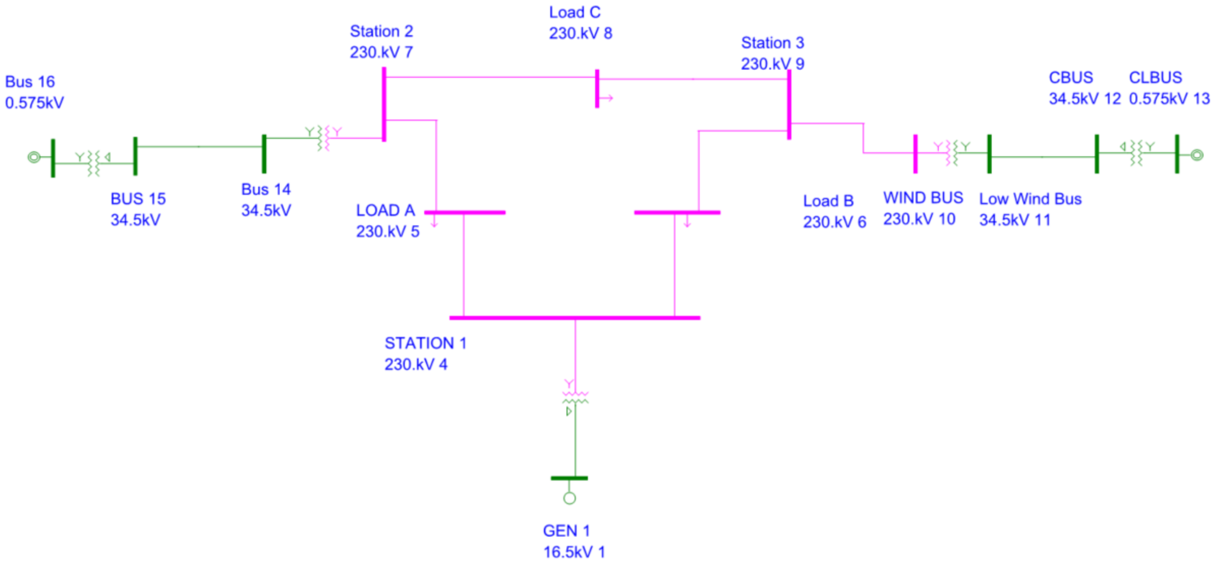
Anderson & Fouad 9 bus test system



MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Short Circuit Programs

Modified 9 bus test system



MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Fault Currents

- Modified Anderson and Fouad (WSCC) nine bus test case
- IBRs connected to Station 2 and 3
- The two IBRs have different voltage-current characteristics
- Low voltage to medium voltage transformer connected as wye grounded – delta
- Main transformer connected as wye grounded – wye grounded
- Synchronous generator GSU transformer connected as delta – wye grounded
- At high penetration precipitous drop in sequence quantities across the system
- Phase angle relationship is also unconventional

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Single Line To Ground Faults

Fault	SLG	All Synchronous Generator		Two IBR case		
Bus No	Bus	3I0 A	Phase angle	3I0 A	Phase Angle	Percent Change
5	Load A	2183	-85	968	-73	-55.66
6	Load B	2071	-83	926	-71	-55.29
8	Load C	2341	-86	549	-56	-76.55
4	Station 1	3711	-88	1909	-83	-48.56
7	Station 2	3240	-88	580	-57	-82.10
9	Station 3	2991	-87	559	-53	-81.31

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Line To Line Faults

Fault	**L-L**	All Synchronous Generator		Two IBR case		
Bus No	Bus	I2 A	Phase angle	I2 A	Phase Angle	Percent Change
5	Load A	1080	94	441	105	-59.17
6	Load B	1024	96	424	108	-58.59
8	Load C	1088	94	267	126	-75.46
4	Station 1	1599	92	769	95	-51.91
7	Station 2	1351	92	278	125	-79.42
9	Station 3	1213	93	272	129	-77.58

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Three Phase To Ground Faults

Fault	**3LG**	All Synchronous Generator		Two IBR case		
Bus No	Bus	I1 A	Phase angle	I1 A	Phase Angle	Percent Change
5	Load A	2160	-86	772	-88	-64.26
6	Load B	2048	-84	729	-86	-64.40
8	Load C	2177	-86	422	-51	-80.62
4	Station 1	3197	-88	1580	-100	-50.58
7	Station 2	2703	-88	417	-54	-84.57
9	Station 3	2426	-87	436	-50	-82.03

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Comparison of All Synchronous Generator Test Case

- Models were run on short circuit program A and B
- Sanity check
- Gives identical results

Fault	SLG	All Synchronous Generator - SC Program A		All Synchronous Generator - SC Program B		
Bus No	Bus	3I0 A	Phase angle	3I0 A	Phase Angle	Percent Change
5	Load A	2183	-85	2183	-85	0.00
6	Load B	2071	-83	2071	-83	0.00
8	Load C	2341	-86	2341	-86	0.00
4	Station 1	3711	-88	3711	-88	0.00
7	Station 2	3240	-88	3240	-88	0.00
9	Station 3	2991	-87	2991	-87	0.00

Fault	L-L	All Synchronous Generator - SC Program A		All Synchronous Generator - SC Program B		
Bus No	Bus	I2 A	Phase angle	I2 A	Phase Angle	Percent Change
5	Load A	1080	94	1080	94	0.00
6	Load B	1024	96	1024	96	0.00
8	Load C	1088	94	1088	94	0.00
4	Station 1	1599	92	1599	92	0.00
7	Station 2	1351	92	1351	92	0.00
9	Station 3	1213	93	1213	93	0.00

Fault	3LG	All Synchronous Generator - SC Program A		All Synchronous Generator - SC Program B		
Bus No	Bus	I1 A	Phase angle	I1 A	Phase Angle	Percent Change
5	Load A	2160	-86	2160	-86	0.00
6	Load B	2048	-84	2048	-84	0.00
8	Load C	2177	-86	2177	-86	0.00
4	Station 1	3197	-88	3197	-88	0.00
7	Station 2	2703	-88	2703	-88	0.00
9	Station 3	2425	-87	2426	-87	0.04

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

Comparison of One IBR Test Case

- Generator 3 replaced by similar rating IBR
- Models were run on short circuit program A and B
- Difference in fault current magnitudes and phase angles
- Largest deviations at bus nearest to the inverter based generation
- Conclusion: can't trust results from either of the short circuit programs

Fault	**SLG**	One IBR Case - SC Program A		One IBR Case - SC Program B		
Bus No	Bus	3I0 A	Phase angle	3I0 A	Phase Angle	Percent Change
5	Load A	1874	-82	1931	-77	3.04
6	Load B	1524	-77	1727	-86	13.32
8	Load C	1518	-77	1743	-89	14.82
4	Station 1	3119	-85	3383	-90	8.46
7	Station 2	2518	-83	2765	-89	9.81
9	Station 3	1149	-71	1388	-90	20.80

Fault	**L-L**	One IBR Case - SC Program A		One IBR Case - SC Program B		
Bus No	Bus	I2 A	Phase angle	I2 A	Phase Angle	Percent Change
5	Load A	905	98	911	106	0.66
6	Load B	754	102	863	91	14.46
8	Load C	717	102	832	89	16.04
4	Station 1	1322	95	1441	90	9.00
7	Station 2	1033	97	1137	91	10.07
9	Station 3	574	109	705	85	22.82

Fault	**3LG**	One IBR Case - SC Program A		One IBR Case - SC Program B		
Bus No	Bus	I1 A	Phase angle	I1 A	Phase Angle	% Difference
5	Load A	1785	-83	1823	-74	2.13
6	Load B	1461	-80	1726	-89	18.14
8	Load C	1359	-81	1664	-91	22.44
4	Station 1	2595	-87	2882	-90	11.06
7	Station 2	2001	-85	2275	-89	13.69
9	Station 3	1029	-78	1410	-95	37.03

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

All Inverter Based Generation Test Case

Results

Short Circuit Program A

```
Error: Fault simulation aborted because the faulted bus or branch is in a network with no conventional generators.
Error: Fault simulation aborted because the faulted bus or branch is in a network with no conventional generators.
Error: Fault simulation aborted because the faulted bus or branch is in a network with no conventional generators.
```

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

All Inverter Based Generation Test Case

Results

Short Circuit Program B

```
==================================================================================================================================
 THREE_PHASE at bus "9 Station 1"
 ----------------------------------------------------------------------------------------------------------------------------------
 Substation AnF9 Station 1
 Bus      9 Station 1     CO              Base kV  230.00 Ph-Ph (  132.79 @0 deg A-Gnd)     Prefault 0.000 V (p.u.)   @    0.00
                        + seq              - seq           0 seq / 3Io         A phase          B phase          C phase
                       ---------------  ---------------  ---------------   ---------------  ---------------  ---------------
 Voltage (p.u.)      > 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0 | 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0
 Voltage (kV) Ph-Gnd > 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0 | 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0

 Thevenin (R, X)(p.u.)> INFINITE         INFINITE         ISOLATED
 Thevenin (R, X)(Ohms)> INFINITE         INFINITE         ISOLATED

 Fault Currents (Amps)> 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0 | 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0

 Line Currents (Amps) incremental from >
 AnF9 Load A  Line:  ST1_LBUSA
      5 Load Bus A    1 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0 | 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0
 AnF9 Load B  Line:  ST1_LBUSB
      6 Load Bus B    1 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0 | 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0

 Branch-Model Transformer Terminal Currents (Amps) incremental from >
 AnF9 Station 1
     10 Gen 1 Bus     1 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0 | 0.00000 @    0.0  0.00000 @    0.0  0.00000 @    0.0
```

MODELING OF IBR IN SHORT CIRCUIT PROGRAMS

EMTP Issues for Protection Analysis

- EMTP used for detailed studies of short circuit behavior of IBRs
- Feasible for small study area
- Setting up EMTP models requires detailed data for the control system – makes relay settings and coordination studies cumbersome
- IBR manufacturers have proprietary EMTP models
- Protection engineers have limited experience with EMTP programs

PROTECTION SCHEMES BEHAVIOR DUE TO HIGH IBR PENETRATION

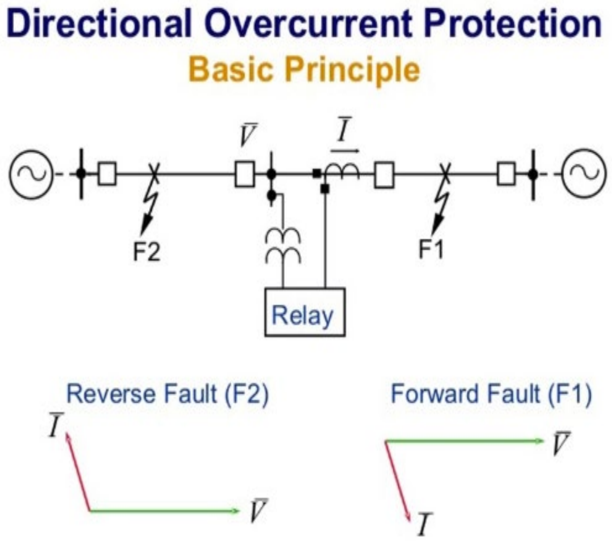
Overcurrent Scheme

- High IBR penetration will cause low fault currents in the system
- OC schemes use fault current magnitudes to detect faults
- Difficult for phase element to differentiate between normal load and fault currents
- Detection of Line-Line faults fed by IBRs will be difficult for negative sequence elements
- Zero sequence elements will face issues due to low ground currents in system with high IBR penetration

PROTECTION SCHEMES BEHAVIOR DUE TO HIGH IBR PENETRATION

Directional Elements

- Directional elements determines direction of the fault from relay location
- Supervision for overcurrent and distance elements
- Compares the phase shift between an operating quantity and a polarizing quantity
- Low sequence currents will cause issues in directional elements operation
- Unconventional phase angle relationship may cause unreliable operation of negative sequence polarized elements
- Zero sequence directional elements may face issues with insufficient zero sequence voltages and current magnitudes



PROTECTION SCHEMES BEHAVIOR DUE TO HIGH IBR PENETRATION

Impedance Relays

- Two popular types – mho and reactance
- Basic principle – sense voltage and current at relay location and perform phase comparison for directionality
- Self polarization, memory polarization
- In IBR dominated systems memory polarization techniques will suffer
- Self polarized relays may work correctly if voltage and current magnitudes are sufficient
- Phase angle relation between voltage and current will be influenced by IBR controls at relay location
- As such fault might lie outside the characteristics in the impedance plane

PROTECTION SCHEMES BEHAVIOR DUE TO HIGH IBR PENETRATION

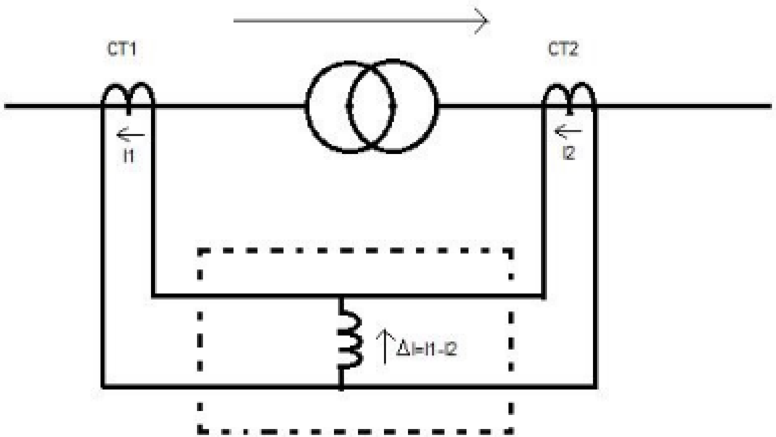
Pilot Protection Schemes

- Provides high speed detection of phase and ground faults
- Uses communication channel between terminals to provide instantaneous clearing of faults
- Common schemes – DCB, POTT, DCUB and PUTT
- These schemes are enabled by distance and overcurrent elements
- Issues with fault current detection, polarization, unconventional phase angle relationship for comparison

PROTECTION SCHEMES BEHAVIOR DUE TO HIGH IBR PENETRATION

Differential Protection

- Basic principle – Current in equals current out, violation of this property due to in section faults provides the operating current for trip
- Operation largely immune to low fault currents
- Even if the line terminals are weak source due to IBRs, the relay will see enough operating current
- Differential protection is reliable and sensitive compared to other schemes in IBR dominated systems



UNCONVENTIONAL SCHEMES FOR IBR DOMINATED SYSTEMS

- Traveling wave based protection schemes
- Voltage-Based fault detection techniques
- Synchronous condensers
- Setting-Less protection
- Uprated power electronics in inverter circuits
- Modification of inverter controls

CONCLUSIONS

Main Recommendations

- We can’t trust short circuit models with IBRs. May need transient study
- Conservative approach is to specify differential protection. Differential scheme is the most reliable

Additional Thoughts

- Blocks negative and zero sequence components
- Control strategy of IBRs regulates the contribution of fault currents
- Affects traditional protection in terms of polarization, fault detection and signal magnitudes
- IBR models that can be integrated into existing utility scale SC models are still an ongoing research topic

Questions?

MAKE A POWERFUL DIFFERENCE.

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REFERENCES

[1] Utility-Scale Solar : Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States – 2018 edition available at https://emp.lbl.gov/sites/default/files/lbnl_utility_scale_solar_2018_edition_report.pdf
[2] Utility Scale Wind Energy available at https://windexchange.energy.gov/markets/utility-scale
[3] RE100,"193 RE100 companies have made a commitment to go '100% renewable'. Read about the action they are taking and why," available at: http://there100.org/companies
[4] IEEE PES Report, "Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance", July 2018, Technical Report, PES-TR68
[5] IEEE PES Report, "Impact of IEEE 1547 Standard on Smart Inverters," May 2018, Technical Report, PES-TR67
[6] IEEE PES Report, "Fault Current Contributions from Wind Plants", A report to the Transmission & Distribution Committee, Electric Machinery Committee and Power System Relaying Committee.
[7] J. D. Glover, et al, "Power System Analysis & Design", Cengage Learning, Fifth Edition, 2012.
[8] Siemens, "Inverter-Based Generator Models with Controlled Power and Current," Presented at the 2019 PSS®CAPE User Group Meeting, Ann Arbor, Michigan, June 2019.
[9] Xiaolin Mao, Raja Ayyanar "Average and Phasor Models of Single Phase PV Generators for Analysis and Simulation of Large Power Distribution Systems," Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition, 15-19 Feb. 2009, Washington DC, USA
[10] K. Zimmerman and D. Costello, "Fundamentals and Improvements for Directional Relays," 63rd Annual Conference for Protective Relay Engineers, March 2010.
[11] NERC, "Key Takeaways" Inverter Manufacturer and Reay Manufacturer Coordination Meeting, April 2019
[12] D. D. Fentie, "Understanding the Dynamic Mho Distance Characteristics", Schweitzer Engineering Laboratories, Inc, 42nd Annual WPRC, Oct 2015, Revised April 2017.

REFERENCES

[13] S. Marx, et al, “Traveling Wave Fault Location in Protective Relays: Design, Testing, and Results,” 16th GTPE Conference, Atlanta, Georgia, May 2013.
[14] R. M. Tumilty, et al, “Approaches to network protection for inverter dominated electrical distribution systems,” 3rd IET International Conference on PEMD, Dublin, Ireland, April 2006.
[15] A. Sannino, “Static transfer switch: analysis of switching conditions and actual transfer time,” IEEE PES Winter Meeting. Conference Proceedings, Columbus, Ohio, Jan-Feb. 2001.
[16] J. Jia, et al, “Synchronous Condenser Allocation for Improving System Short Circuit Ratio,” 2018 5th EPECS, Japan, April 2018.
[17] M. Ned, et al, “Application of synchronous compensators in the gb transmission network to address protection challenges from increasing renewable generation,” in Proc. CIGRE Study Committee B5 Colloquium, Auckland, New Zealand, Sep 2016, pp. 1-6.
[18] F. O. Igbinovia, et al, “Cost Implication and Reactive Power Generating Potential of the Synchronous Condenser,” 2nd International Conference on IGBSG, June 2016
[19] A. P. Meliopoulos, et al, “Setting-Less Protection: Laboratory Experiments and Field Trials,” CIGRE US National Committee: 2015 Grid of the Future Symposium.
[20] J. A. P. Lopes, A. G. Madureira, C. L. Moreira, “Defining Control Strategies for MicroGrids Islanded Operation,” IEEE Transactions on Power Systems, June 2006.
[21] VDE-AR-N 4120, “Technical Requirements for the Connection and Operation of Customer Installations to the High Voltage Network (TCC High Voltage), Jan. 2015.