Key Takeaways

Inverter Manufacturer and Relay Manufacturer Coordination Meeting
April 2019

NERC facilitated an in-depth technical discussion between inverter manufacturers, protective relay manufacturers, and industry experts related to current injection of bulk power system (BPS)-connected inverters during fault conditions and potential impacts and solutions for BPS protection schemes.[1] The following key takeaways, recommendations, and next steps were an outcome of this discussion.

General Takeaways

- Industry needs to collectively speak in terms of phase unbalance rather than sequence components, to better understand the underlying issues regarding current injection during faults. Sequence components are a tool for analyzing unbalanced three-phase power systems, and are derived from phase quantities.
- Protection engineers setting protective relay settings do not generally use electromagnetic transient (EMT) simulation programs. Short-circuit programs typically used by protection engineers do not accurately represent the dynamic response of inverter-based resources during the first few cycles after fault inception as the phase and sequence components may not stabilize.
- The injection of negative sequence current (I2) from generating resources during unbalanced fault events is beneficial for existing protection schemes and BPS reliability.[2] All resources, where possible, and in the future, should maintain the correct phase relationship between the unfaulted phases and faulted phases both in voltage and current. This ensures predictable phase relationship between sequence voltages and currents, and consequently operation and protection behavior that is consistent with conventional power system operation.
- Inverter-based resources respond to faults based on the controls programmed into the inverter. Controlled inverter response generally does not start to occur earlier than one electrical cycle (measurement and processing time delay) from fault inception. During the first couple of electrical cycles of a severe[3] fault, the response from inverters may not be controlled in a way that provides necessary sequence currents for protective relaying.[4] This may pose a significant challenge when setting primary protection in a heavily inverter-dominated part of the BPS.
- The concept of critical clearing time may need to be reconsidered and studied fairly frequently as inverter-based resources continue to displace synchronous generation. As synchronous generation

---

[1] This was a follow-up to the work related to the *IEEE Technical Report: Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance*. Available: http://resourcecenter.ieee-pes.org/pes/product/technical-publications/PES_TR_7-18_0068.

[2] Negative sequence current supports reliable BPS operation. For example, it helps balance voltages and provides voltage support to unfaulted phases (avoiding overvoltage).

[3] Typically either a very low terminal voltage, severe voltage distortion, or large change in phase angle.

[4] The inverter response is highly dependent on factors including fault timing, pre-fault condition, fault type, and fault depth. Therefore, it may be difficult to predict

retires, there may be opportunities to slow down protection system operation. This is particularly needed where the system is dominated by inverter-based resources, which require some time (cycles) to determine the appropriate response based on observed (measured) terminal conditions. The impact of slowing down protection system operation on critical clearing time of remaining synchronous machines (that may have a faster acceleration/deceleration behavior) should be studied.

Existing Inverter Technology

- While some STATCOMs, HVDC circuits, and Type 3 wind turbine generators (WTGs) may inject I2, some existing solar photovoltaic (PV) inverters and Type 4 WTGs do not have the capability to provide I2 (unbalanced) currents without modifying their controls.[5] These inverter controls maintain a pre-established[6] angular relationship between phase voltage and current during normal and fault conditions. Their controls are configured and programmed to inject positive sequence (balanced) currents only.
    - The inverter phase lock loop (PLL) typically provides a balanced phase angle value to each of the three individual phase currents. Therefore, while these resources may be able to provide current with unbalanced magnitude they generally cannot provide an unbalanced phase relationship between individual phases.
- For inverters with controls that inject I2, detailed EMT studies using real-code models and historical grid events analyses have shown that the I2 injection is not repeatable across technologies, vendors, and vintages of inverters.
- These studies have shown that the I2 injection from some inverter-based resources has rotated phase relative to negative sequence voltage (V2), indicative that the I2 injection is not matched to the impedance of the grid (which is not consistent with protective relay assumptions). Inconsistency in phase relationship between I2 and V2 poses a significant challenge to certain types of protection applications, and is potentially more important than the reduced (or zero) I2 magnitude from inverter-based resources.
- There is currently no standardization of I2 injection from inverter-based resources (other than the German VDE grid code requirement).
- The response of synchronous machines to fault events is fundamentally based on the physical and electrical characteristics of the machine. Therefore, the current injected by these resources can be modeled using standardized, generic models. On the other hand, inverter-based resources inject current based on controls programmed in the inverter and are not based on any inherent characteristics of the resource. Due to the lack of standardization, the response from inverters is less repeatable and generic library models used in simulations are developed based on various I2

---

[5] Existing inverter designs can provide unbalanced current within certain limits of the design. Putting a different control or new firmware into the control without replacing the inverter itself may be possible (although with some cost associated). Retrofitting existing inverters may not be economically practical. If controls can be reprogrammed or new firmware added, this will likely be much more economical than fully replacing inverters.

[6] This pre-established angular relationship from existing inverters may not be the angular relationship needed for protective relaying needs.

injection schemes that have been proposed in the literature and do not necessarily represent the actual controls of inverters.

- It is not practical at present time[7] to conduct an EMT simulation for every relay setting, nor should this become the new expectation. However, without some assurance on the angular relationship of I2 with respect to V2 from inverter-based resources, potential misoperation challenges may exist.
- Actual grid disturbances with relay misoperation or near-miss conditions are starting to occur more frequently. Under the current paradigm and with growing penetration of inverter-based resources, the industry will be (and already is) facing challenges with conventional protective relaying in pockets of high inverter-based resource penetration.
- Since the I2 injection during faults can vary widely and is not effectively modeled, protection engineers cannot rely on an expected performance from inverter-based resources (related to negative sequence) and may run into challenges with the application of certain types of protection schemes. In particular, distance protection, negative sequence directional elements, and polarizing elements may be a challenge. These are considered fairly "conventional protection systems" that may need to be replaced with more advanced forms of protection in some situations.
  - In pockets of high penetration of inverter-based resources or specific applications where issues are identified, more robust forms of protection are likely need and should be considered the new norm. For example, the use of current differential (87L) protection for circuits radially connecting inverter-based resources to the BPS might be standardized in many cases.
  - This is primarily a concern for high-speed primary protection rather than backup protection. Similar issues do not exist for backup distance protection (e.g., Zone 2) due to the inherent operating time delay.
- There are a number of mitigation options related to lack of I2 injection and the unpredictable phase relationship of I2 and V2. Options may include, but are not limited to, the following:[8]
  - Synchronous condensers can be installed to maintain fault current levels, synchronizing torque, system inertia, and conventional current injection expected during faults for the purposes of reliable protective relaying.
  - Existing protection schemes can be replaced or supplemented with other types of relaying (e.g., current differential and other advanced protection schemes).
  - Future inverter-based resources can be programmed to inject some amount of negative sequence current in a standardized way to support conventional protective relaying schemes.

---

[7] EMT modeling and simulation capabilities are quickly evolving as computational power and expertise in this area continues to grow. Software tools are being developed to keep up with the rapidly increasing size and volume of EMT studies being requested. Protection studies using EMT modeling and simulation tools is becoming more common. Concerns about specific relay applications or breaker duties are realizing that conventional fault study tools may be inadequate near inverter-based resource and need confirmation using EMT tools. This is not standardized for every interconnection or relay study, but it is becoming more common.

[8] The selection of these options is system-specific and application-specific. Each protective relaying issue should be considered in its entirety, with the most appropriate and cost effective solution identified.

Future Inverter Technology

- New protection schemes may be able to adapt once standardization of fault current injection from inverter-based resources is achieved. Standardization should occur within the IEEE P2800 effort, and developing I2 injection capability and performance specifications in IEEE P2800 is warranted.
  - Standardization should include the magnitude, phase angle relationship, timing (rise time, settling time, etc.), and current priority for I2 injection (coordinated with I1 and with Ip and Iq priorities). A minimum threshold (i.e., minimum V2 measurement) where I2 would be injected should also be considered, yet may be system-specific in most cases.
  - Performance and capability standardization should consider the elements of the table shown below. The concepts and performance targets are still a work in progress, and should be further vetted and explored in IEEE P2800. The table is intended to be used as a starting.

Table: Negative Sequence Current Injection Performance

Parameter	**Description**	**Possible Performance Target**
For a step change in fundamental frequency negative sequence voltage, the negative sequence current response from the inverter should meet the following performance specifications…		
Magnitude	Negative sequence current should be proportional to the measured negative sequence voltage, programmable using a K-factor adjustable between 1 and 6	Proportional response (K factor)
Angle	The negative sequence current injected to the BPS should lead the negative sequence voltage by a minimum of 90 degrees (reactive negative sequence)[9]	I2 leads V2 by 90 degrees (reactive)
Timing	The negative sequence current injected to the BPS should meet the following timing specifications to support BPS protective relaying	
Reaction Time	Time between the step change in voltage and when the inverter negative sequence current begins responding to the change[10]	< 16 ms
Rise Time	Time between the step change in voltage and when the inverter negative sequence current reaches 90% of the new steady-state output	< 100 ms[11]
Overshoot	Percentage of rated negative sequence current that the inverter can exceed while reaching the settling band	TBD

---

[9] Ideally, I2 would lead V2 by 180° minus the Thevenin equivalent impedance angle to the fault.

[10] Time between the step change in voltage and reaching 10% of new steady-state value can be used as a proxy for determining this time.

[11] This timing may be considered to slow for conventional primary protection schemes. This should be further analyzed in detail in IEEE P2800 activities.

  - Performance specifications for I2 should consider the upwards response (I2 injection during fault inception) as well as the downward response (I2 injection withdrawal upon fault clearing).
  - The German grid code (VDE) requirements are generally well accepted, and should be considered a starting point for further discussion in the P2800 activities. Specifically, the aspects related to timing[12] of current injection to support protective relaying should be further explored.[13] It should also be more clearly articulated that the phase angle relationship between I2 and V2 should be a minimum of 90 degrees leading (reactive).
- Continued research and EMT simulations are needed in this area to continue exploring the optimal injection and prioritization of currents from inverter-based resources, and to better understand the possible inverter-level transient conditions seen during actual grid disturbances that have caused inverter tripping. Another area of research should focus on situations where conventional protective relaying may fail (either falsely trip or fail to operate), which should lead to recommendations regarding protection practices in areas of increasing inverter-based resource penetration.

Next Steps

- Inverter manufacturers should provide review and feedback on the above recommendations and on the specific elements of the German grid code which are concerning to them. This feedback can be integrated into early drafts of the upcoming IEEE P2800 and IRPTF documents.
- The takeaways and recommendations presented here should be integrated into the NERC Reliability Guideline: BPS-Connected Inverter-Based Resource Performance.
- The IEEE P2800 effort should also integrate aspects of these key takeaways into the standard for newly interconnecting inverter-based resources.
- IEEE Power System Relaying and Control (PSRC) Committee should continue examining the impacts of changing fault currents on the BPS, and develop guides to address existing protection systems that may be adversely impacted. IEEE PSRC should also continue developing short circuit models and modeling practices to address the need for modeling improvements in this area.

---

[12] The limitations for response times related to negative sequence current injection include: 1) time to calculate negative sequence voltage from the phase quantities (about 1 cycle), and 2) time for controls to respond to the calculated negative sequence voltage (1-2 cycles).

[13] Further discussion related to manufacturer perspectives and technical challenges in meeting the VDE requirements should occur. This should focus on the technical considerations related to generating negative sequence current to meet the specifications. Some engagement from European experts would be useful in this area.

Attendee List

Rich Bauer	North American Electric Reliability Corporation
Ryan Quint	North American Electric Reliability Corporation
Ritwik Chowdhury	Schweitzer Engineering Laboratory
Gary Custer	SMA America
Ratan Das	General Electric
Normann Fischer	Schweitzer Engineering Laboratory
Ross Guttromson	Sandia National Laboratories
Andrew Isaacs	Electranix
Atiqul Islam	Siemens Gamesa
Prashant Kansal	Tesla
Amir Kazemi	General Electric
Gary Kobet	Tennessee Valley Authority
Mike Kockott	ABB
Venkat Konala Reddy	First Solar
Sergey Kynev	Siemens FACTS
Tony Liu	American Superconductor
Chris Milan	First Solar
Nian’an Pan	Sungrow
Sid Pant	General Electric
Manish Patel	Southern Company
Russ Patterson	Patterson Engineers
Deepak Ramasubramanian	Electric Power Research Institute
Steve Saylors	Vestas
Sanket Shah	Power Electronics
Sachin Soni	First Solar
Mike Thompson	Schweitzer Engineering Laboratory Engineering Services
Ilia Voloh	General Electric
Mahammad Zadeh	ETAP