International Journal of Advance Research and Innovation

Solar Photovoltaic Inverter Current Distribution during Fault on Distribution and Transmission System

Rishabh Pandey, Uttam Singh, Varun Sachdeva, Jaikaran Singh

Department of Electronic and Communication Engineering, MIT, Moradabad, Uttar Pradesh, India

Abstract

To facilitate more extensive adoption of renewable distributed electric generation, the U.S. Department of Energy launched the Renewable Systems Interconnection (RSI) study during the spring of 2007. The study addressed the technical and analytical challenges that must be addressed to enable high penetration levels of distributed renewable energy technologies. Interest in PV systems is increasing and the installation of large PV systems or large groups of PV systems that are interactive with the utility grid is accelerating, so the compatibility of higher levels of distributed generation needs to be ensured and the grid infrastructure protected. The variability and non dispatch ability of today's PV systems affect the stability of the utility grid and the economics of the PV and energy distribution systems. Integration issues need to be addressed from the distributed PV system side and from the utility side. Advanced inverter, controller, and interconnection technology development must produce hardware that allows PV to operate safely with the utility and act as a grid resource that provides benefits to both the grid and the owner.

1. Introduction

Proliferation of power electronic-based distributed generation units at transmission and distribution systems has introduced new challenges for utility engineers to determine changes in the short-circuit capacity of a system and potential impact on interruption rating of switching devices. As part of an interconnection study for a new generation facility, utilities require detailed information on fault characteristics of the generation sources. Yet, there is limited knowledge or contradictory conclusions regarding the behavior of power electronic-based distributed energy resources (wind and solar photovoltaic plants) during faults on distribution or transmission systems. The issue is more complex in nature when several renewable generation sources are connected to the same system (e.g., a distribution feeder or a circuit) as the aggregated effect of the contributing sources to the fault and interaction among the electronically controlled generation units are unknown. Recently, Quanta Technology completed a third-party study for CanSIA (an organization that represents PV solution providers in

Ontario, Canada) and Hydro One, along with participation from other industry stakeholders, including Toronto Hydro and several photovoltaic (PV) inverter manufacturers and plant developers. The study addresses various technical issues regarding the connection of solar PV to the Ontario electrical grid with specific focus on short-circuit current impacts. Concern is currently widespread throughout Ontario regarding the constraint limiting solar pv from connecting to the electrical grid system for projects equal to or less than 500 kW. Many solar industry participants have had connection applications rejected or are experiencing delays regarding the connection of their project This paper reports on the study approach and major findings from a series of extensive impact studies and sensitivity analyses that were performed to determine the level of contribution of PV inverters to system fault. A combination of simulation studies and analytical methods were applied to investigate the impact of additional current contribution from PV inverters on circuit breaker interruption ratings including: Close & Latch rating (in the first half cycle after a fault), and asymmetrical/symmetrical current rating (at contact parting time). The study suggested improvement in

Corresponding Author,
E-mail address: pandeyrishabh350@gmail.com

fault calculation methods and changes to the standard formulas used.

2. Study Approach

The specific focus of this joint CanSIA and Hydro One study was to determine characteristics of commercial PV inverters under short-circuit conditions and to investigate the potential contribution of the PV inverters to short-circuit current levels when there are faults on the distribution and transmission systems. This study took a systematic approach to examining the PV inverter transient short-circuit characteristics and their short-circuit contributions to the electrical grid that a distribution or transmission utility needs to reflect in impact assessments. The overall approach of the study was to:

- Obtain detailed modeling information from manufacturers of PV inverters that were likely to be utilized for solar PV projects equal to or less than 500 kW in Ontario
- Develop the necessary mathematical and software simulation models that provide the representative response of such inverters, and then conduct simulations of these devices on an electrical system that is reflective of the distribution and transmission network where currently short circuit-constraints exist
- Perform simulations based on several fault cases and investigate the sensitivity of changing system parameters to assess the short-circuit impact of the single and multiple PV inverters for a wide range of system fault capacities and impedance characteristics In addition, a literature survey was also conducted to further inform the development of the study approach, understand issues identified by others and incorporate findings from previous investigations., The survey also provides insight on the state-of-the-art with respect to modeling of PV inverters and their potential impacts on system short-circuit levels.

3. PV Inverter Behavior During Faults

The short-circuit phenomenon, as they apply to the operation of power system equipment, takes place typically from a few to 10 cycles (within the PV inverter maximum interruption timeframe), which translates into a timeframe of up to 170 milliseconds. During this period, circuit breakers must operate and be able to interrupt the short-circuit current, which can be in the order of thousands to tens of thousands of amps and represent tremendous levels of energy. The electrical behavior of inverter-based generation units and their controls during this transient timeframe

are extremely complex and different than the conventional synchronous generator-based systems. As a result, advanced simulation tools to conduct switching transient analysis, such as PSCAD/EMTDC, were required to examine the complex control systems of PV inverters and their impacts to the system. More conventional programs used for "production level" connection impact studies by utilities such as PSS/E and CYMDIST are referred to as "steady state" programs. Both the analysis capability and the associated simulation models of such programs are not suitable to properly assess the dynamic three-phase analysis required in this study. Significant effort was required to consult with PV manufacturers to obtain and assess models that simulate inverters in the 60 Hz to 5 kHz time frame and their corresponding data. A total of eight PV manufacturers were consulted in an effort to cover as much of the Ontario market share as possible. Ultimately, six manufacturer models were obtained, verified, and their short-circuit characteristics analyzed. These six models represent more than 80% of the PV inverters being installed in Ontario. A summary of the fault simulation analysis for the six vendor models is shown in Table 1.

Fault	Peak current (instantaneous) in time increment after fault					Inverter Tripping	
	First ½ cycle	2nd ½ cycle	In 2nd cycle	In 3rd cycle	In 5th cycle	time	Current
M1 TPH	180%	0	0	0	0	4 ms	180%
M1 SLG	146%	0	0	0	0	4ms	146%
M2 TPH	Large spike	100%	100%	100%	100%	11 cycles	100%
M2 SLG	100%	100%	100%	100%	100%	11 cycles	100%
M3 TPH	155%	107%	110%	110%	110%	10 cycles	110%
M3 SLG	105%	110%	110%	0	0	1.8 cycles	110%
M4 TPH	Large spike	110%	115%	115%	115%	8.5 cycles	115%
M4 SLG	120%	110%	110%	110%	110%	Inf.	110%
M5 TPH	Large Spike	110%	110%	110%	0	4.5 cycles	110%
M5 SLG	Large Spike	110%	110%	110%	110%	Inf.	110%
M6 TPH	210%	120%	100%	100%	100%	10.5 cycles	100%
M6 SLG (Delta XFMR)	200%A. 110%B&C	150%A. 100%B&C	150%A. 100%B&C	150%A. 100%B&C	150%A. 100%B&C	10.5 cycle	150%

Table: 1. Summary of Fault analysis for the vendor models

Following further analysis and verification of the transient behavior of the six models under short-circuit conditions, it was determined that these models could be grouped into two categories:
Model: 1. Fast disconnection (i.e., in less than one cycle); interrupts the inverter current contribution immediately during a fault event if the PCC voltage drop is beyond 50%.

Generic Model: Continued operation for upto 10 cylces; continues the inverter current for a few

cycles (maximum of 10 cycles) after a fault incident, even if the voltage reduction at the terminal of the generic PV inverter model is below 50%.
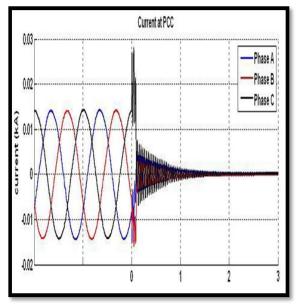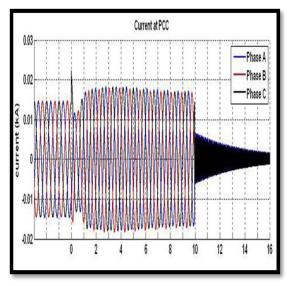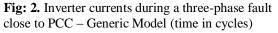

Fig: 1. Inverter currents during a three-phase fault close to PCC – Model 1 (time in cycles)

Fig: 2. Inverter currents during a three-phase fault close to PCC – Generic Model (time in cycles)

4. Study Benchmark

Once the inverter models were established, a PSCAD/EMTDC model of a benchmark system was developed in consultation with Hydro One. The benchmark model reflects a 115 kV transmission system supplying typical step-down transformer stations (TS) connecting a distribution system. The distribution system includes the TS, downstream distribution stations (DS), reclosers, and lower voltage distribution feeders to represent the system levels that supply typical end-user customers and where PV installations may be found. The transmission and distribution system includes modeling details, such as transformer winding configurations and grounding devices that may impact short-circuit levels. This system represents an actual portion of the Hydro One distribution and transmission system where short circuit constraints presently exist. Single or multiple PV inverters with individual sizes equal to or smaller than 500 kW were connected at various points along the Feeder 1 and 2 (Points A to D) to investigate the change in fault currents and aggregated contribution up to 16 MW distributed PV systems.

A large number of simulations were then performed looking at the short-circuit impact with various permutations of:

- PV inverters at four different locations
- One, two and four inverters at each location
- Applying faults at five locations along the feeders
- Applying three types of faults: line-to-ground, line-to-line-ground and 3-phase

More than 840 simulation case studies were conducted to cover a wide range of conditions and scenarios. Both the inverter behavior and the impact of the inverters on the system short circuit levels were reviewed. Further sensitivity analysis was conducted looking at the short circuit impact of PV inverters to various system parameters including line/feeder length, transformer impedance, X/R ratios and system strength.

An assessment of the impact of PV inverters on the close-and-latch capability of circuit breakers was also conducted. The IEEE standard C37.04-1999 establishes the close-and-latch requirement for circuit breakers and maximum instantaneous current levels must not exceed these requirements to ensure the integrity of the breaker operation. Simulations were conducted for different scenarios and fault conditions to assess the impact of the PV inverters during the short-circuit period.

Based on the simulation studies and analytical investigation, a modification for the formula introduced by IEEE C37.04 standard was also proposed for precise calculation of the asymmetrical rating.

5. Conclusions

The study showed that variations in the PV inverter design among various vendors can introduce

major difficulties in precise calculation of the fault current. However, in most cases, a generalized approach can be applied and used during the typical short-circuit studies performed by utility engineers. Some modifications in the standard equations used to calculate symmetrical and asymmetrical current ratings of circuit breakers were also proposed and evaluated.
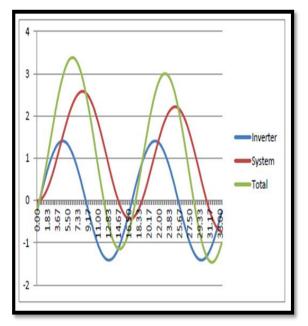

Fig: 4. Example of total fault current comparison (assuming one per unit rated inverter current on system base)

From the simulation results and analytical analysis, it was concluded that the PV inverter current and the system contribution to the fault have their maximum values during the first cycle, but at different time instances. Figure 4 shows how the contribution of the PV inverter current will change the location and the value of the first cycle peak of the system fault current. For demonstration purposes both currents are assumed at 1 pu.

The main findings and conclusions from the study are outlined below:

1. The PV inverter current contribution during a fault is not zero and varies by design.

a. It was observed that, for most fault conditions, several PV inverters continued supplying current to the feeder, subsequent to a fault for a period ranging from four to 10 cycles.

b. The current contribution level is a function of the voltage at the terminal of the PV inverter during a fault, which is determined by the type and location of a fault.

c. For most vendor-specific PV inverter models, the PV inverter current during the fault was above the rated inverter current and may reach up to 120% of the inverter-rated current.

d. For a few PV inverter models, the inverter current during faults was maintained at the pre-fault inverter current.

e. In one inverter model, the inverter current was dropped to zero and the inverter was disconnected in less than 0.5 cycles for a fault case in which the terminal voltage reached below 50% on any phase.

2. In computing the short-circuit level seen by a circuit breaker, the rated current of the PV inverter (aggregate size) with an adjustment factor of 1.2 (maximum) may be used and arithmetically added to the system fault current, as calculated from conventional distribution short-circuit study tools (without incorporating PV inverters).

a. Applying an arithmetic summation is a generalization approach for the worst case scenario. The accurate calculation by using the phase-angle difference between the two current vectors contributing to the fault at the contact parting time of a circuit breaker requires a complex transient study, but can result in smaller values.

b. Depending on the vendor-specific inverter models, the adjustment factor may vary in the range of 1.0 to 1.2 per unit. However, the aggregate aspects of multiple inverters from various vendors with potentially different adjustment factors complicate the consideration of a lower factor.

c. In one specific vendor model (and only for the faults causing a voltage drop more than 50% at the PV inverter terminal) there was no current contribution (i.e., adjustment factor of zero).

3. In PV project site cases, where system fault current levels are close to upstream breaker performing electromagnetic transient simulation studies.

a. In order to apply vector summation of the two contributing current components, one needs to determine the phase-angle difference between the two currents at the contact parting time of a circuit breaker.

b. Typically, there is an initial phase-angle difference of 72 to 90 degrees between the two currents. However, under some fault conditions, the phase angle of the inverter current may vary with time.

c. Five out of the six selected inverter models showed changes in the phase angle of the inverter current during the fault, due to specific inverter control behavior associated with design of the Phase Locked Loop block. The frequency of the PV inverter current during a three-phase bolted fault at the PV inverter terminal may be different than the pre-fault grid frequency. This introduces a time-varying phase angle with the potential of two current vectors gradually becoming in phase at some point in time.

d. A relatively complex transient simulation study will be needed to model the PV inverter's control behavior and properly symmetrical/interrupt rating, the computation of the fault current level increment, due to PV inverter units addition/connection, can be better estimated

References

[1] C2000 Solar Workshop: http://processors.wiki.t i.com/index.php /C2000_SolarWorkshop

[2] Microcontrollers Data Sheet (SPRS742) Concerto F28M35x Technical Reference Manual (SPRUH22)

[3] Soeren Baekhoej Kjaer, John K. Pedersen, Frede Blaabjerg, A review of Single – phase grid connected inverters for photovoltaic systems, IEEE transactions on industry applications, 41(5), 2005

[4] Remus Teodorescu, Marco Liserre, Pedro Rodriguez, Gird Converters for Photovoltaic and Wind Power Systems, John Wiley and Sons, 2011

[5] Tamas Kerekes, Analysis and Modeling of Transformerless Photovoltaic Inverter Systems,

through investigate the PV inverter's current contribution to the system fault and its impact on the symmetrical rating of a circuit breaker.

4. From the circuit breaker close-and-latch viewpoint, the PV inverter current contribution during the fault is not a limiting factor, if the symmetrical rating requirements are properly met. The close-and-latch rating can be estimated based on the findings stated below:

a. The PV inverter current contribution to the peak of the first cycle fault (base for the calculation of the CB close and latch rating) is about 20% of the aggregated PV inverter-rated current.

b. The PV inverter current does not have any direct current component (DC offset) that would cause any shift in the output current.

Department of Energy Technology, Aalborg University, 2009

[6] Zhang Housheng; Zhao Yanlei, "Research on a Novel Digital Photovoltaic Array Simulator," Intelligent Computation Technology and Automation (ICICTA), 2010 International Conference on , 2, 1077-1080, 11-12, 2010

[7] Britton, Lunscher, Tanju, A 9KW High-Performance Solar Array Simulator", Proceedings of the European Space Power Conference, 1993

[8] Soeren Baekhoej Kjaer, Design and Control of an Inverter for Photovoltaic Applications, Department of Energy Technology, Aalborg University, 2009

[9] Francisco D. Freijedo et al, Robust Phase Locked Loops Optimized for DSP implementation in Power Quality Applications, IECON 2008, 3052-3057