Modeling of Inverter-Based Resources for Protection Studies Considering Momentary Cessation

Ali Bidram
Electrical & Computer Engineering
University of New Mexico
Albuquerque, NM
bidram@unm.edu

Matthew J. Reno
Electric Power System Research
Sandia National Laboratories
Albuquerque, NM
mjreno@sandia.gov

Trupal Patel
Electric Power System Research
Sandia National Laboratories
Albuquerque, NM
tpatel@sandia.gov

Daniel J. Kelly
Electric Power System Research
Sandia National Laboratories
Albuquerque, NM
djkell@sandia.gov

Yazid Alkraimeen
Siemens Grid Software
Siemens Industry, Inc.
Ann Arbor, MI
yazid.alkraimeen@siemens.com

***Abstract*—This paper addresses the impact of the momentary cessation of Inverter-Based Resources (IBRs) on the protection of distribution systems. Momentary cessation is one of the requirements in IEEE 1547 standard that requires IBRs to momentarily cease the energization when a severe disturbance (e.g., fault) occurs and large deviations in the system voltage or frequency are observed. This will enable IBRs to also accommodate the voltage-ride-through requirements since they can be energized again if the fault is cleared before the ride-through time. The momentary cessation modeling in PSS®CAPE and Matlab/Simulink is elaborated. The paper highlights the impact of momentary cessation on the fault current and operation of time over current elements by simulating a modified version of the IEEE 123 node system in PSS®CAPE.**

***Index Terms*—IEEE 1547, Inverter-based resources, Momentary cessation, protection system**

I. Introduction

The proliferation of inverter-based resources (IBRs) in distribution systems has created new challenges for the reliable, secure, and selective operation of the protection system [1]–[5]. Due to the utilization of semiconductor switching devices that are not tolerant with respect to high fault currents, IBRs' fault current contribution is typically limited to 1.1-1.5 pu. Moreover, the fault response of IBRs highly depends on their pre-fault operating mode and control system (e.g., grid-forming versus grid-following IBRs) [6]. To effectively study the fault response of IBRs, IEEE Power System Relaying Committee's (PSRC) working group C24 report has addressed the modeling requirement of wind turbine generators for commercial fault calculation programs. The proposed solutions for Type IV models can be also applied to IBRs used for the integration of photovoltaic or battery energy storage systems in discharging mode [5].

IEEE 1547 standard addresses the interconnection and interoperability of Distributed Energy Resources (DERs) to electric power systems. The voltage ride-through requirements of the IEEE 1547 standard require the momentary cessation of IBR's current when the voltage at its terminal falls below a specific threshold. Momentary cessation requires IBRs to temporarily get de-energized when a severe disturbance (e.g., fault) occurs and large deviations in the system voltage or frequency are observed. The momentary cessation allows for the instantaneous restoration of IBR when the system voltage and frequency return to allowable ranges [3]. Since the momentary cessation forces IBRs to stop injecting current in the event of severe faults, the fault currents flowing through the time overcurrent (TOC) elements can change compared to the case that momentary cessation is not in place. Therefore, it is of paramount value to study the impact of momentary cessation on the performance of the protection system in distribution systems. This paper discusses the modeling of momentary cessation on IBRs in both PSS®CAPE and Matlab/Simulink. The impact of momentary cessation on the protection of TOC elements in the modified IEEE 123 node system is studied in PSS®CAPE.

II. Voltage Requirements of IEEE 1547 Standard

The IEEE 1547 standard's requirement regarding mandatory voltage tripping is based on three categories related to the response of IBR under abnormal conditions [3]. Among these categories, the abnormal operating performance Category III accounts for the stability and reliability requirements of both bulk power systems and distribution systems, and was amended in 1547a-2020. According to this standard, the IBR response to the abnormal voltages under Category III should be based on the settings provided in Table I.

In addition to the above requirements, the voltage ride-through requirements of IEEE 1547a-2020 standard for Category III requires the momentary cessation of IBR's current when the voltage at its terminal falls below 0.5 pu with a

TABLE I: IEEE 1547a-2020 amended requirements regarding mandatory voltage tripping (the range of allowable settings) [3]

Element	Voltage Threshold (pu)	Clearing Time (s)
OV2	1.2	0.16
OV1	1.1-1.2	1-13
UV1	0-0.88	2-50
UV2	0-0.5	0.16-21

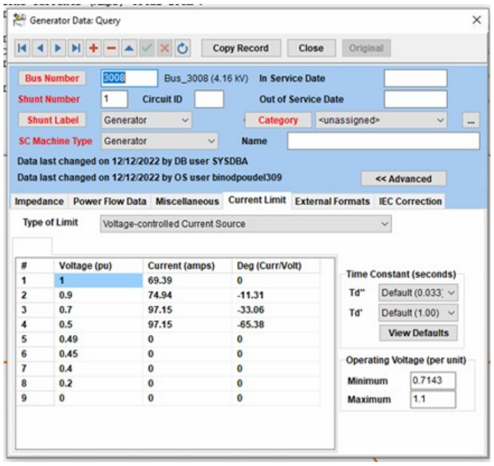

Fig. 1: Incorporating momentary cessation into IBR model.

maximum response time of 5 cycles. However, the minimum ride-through time is equal to 1 s. Momentary cessation is defined as the temporary cessation of the energization of an IBR when a severe disturbance (e.g., fault) occurs and large deviations in the system voltage or frequency are observed. The momentary cessation however allows for the instantaneous restoration of IBR when the system voltage and frequency return to allowable ranges. If the temporary disturbance is cleared before the ride-through minimum time (the ride-through minimum time should be $\geq$ 1 s), the IBR can instantaneously restore supply power to the rest of the power grid.

III. Momentary Cessation Modeling in PSS®CAPE

A. Momentary Cessation Modeling for Short Circuit Studies

For the purpose of short circuit studies of a DS in the presence of IBRs, the short circuit software package should be able to stop IBRs from injecting current when their terminal voltage after fault drops below 0.5 pu. For example, in PSS®CAPE model, the voltage-controlled current source (VCCS) model can be utilized to force an IBR to stop injecting current when its voltage falls below 0.5 pu. In Fig. 1, the utilized values for accommodating momentary cessation in a tabular format for the voltage-controlled current source model are summarized.

B. Momentary Cessation Modeling for Coordination Studies

The coordination study is referred to as evaluating the selectivity of the protection system by applying different types of faults at different locations of the distribution system and verifying the coordinated operation of protection relays for all of the studied fault scenarios. To this end, each primary/backup protection relay pair should satisfy a minimum coordination time interval (CTI) determined by the utility standards (e.g., 0.3 s). The coordination study should account for the sequence of actions by different relays in response to a fault scenario. To accommodate the requirements of IEEE 1547 regarding IBR's response to abnormal voltages and momentary cessation, one can create a generic under-voltage relay model in PSS®CAPE and add them to the tie-breakers interconnecting IBRs to the rest of the system. The created under-voltage relay model is shown in Fig. 2.

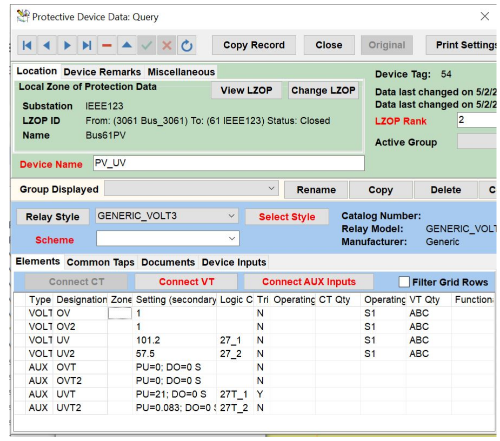

Fig. 2: Generic voltage relay in CAPE.

IV. Momentary Cessation Modeling in MATLAB/Simulink

In MATLAB Simulink, the momentary cessation is modeled similarly to PSS@CAPE. When the IBR terminal voltage drops below 0.9, the inverter control switches the current reference to mimic a voltage-controlled current source based on the values in Fig. 1. Fig. 1 is represented in the Simulink as a lookup table, which outputs the appropriate current magnitude and angle for the corresponding voltage level during a fault. Therefore when the voltage reduces below 0.5 pu, the current reference is set to 0, and the IBR enters cessation in less than five cycles. Additionally, several voltage comparators are used to create the mandatory voltage-tripping function. The output of each comparator is then delayed based on the voltage level, with their associated delay times shown in Table I. The on-delay only allows the voltage trip to trigger if the comparator output remains on for the duration of the delay. The outputs of the four comparators are combined to set the breaker trip. A block diagram of the tripping logic is shown in Fig. 3. When triggered, the IBR breaker is tripped disconnecting the IBR from the system.

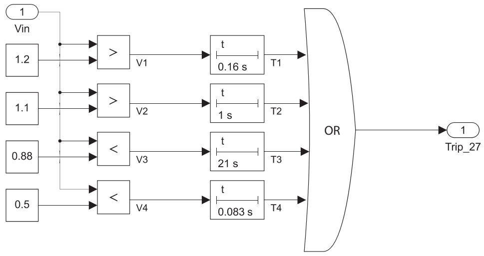

Fig. 3: Mandatory voltage tripping logic modeled in Simulink.

V. Simulation Results

A. Impact of Momentary Cessation on the Distribution System Protection

High penetration of IBRs in a distribution system can impact the coordination of time overcurrent (TOC) relays. For the protection engineers, it is of particular importance to properly model IBRs in the simulation model to consider their impacts when setting TOC relays. However, one more factor that should be accounted for is the possibility of momentary cessation of IBRs for some fault scenarios. Especially for bolted faults that are close to the IBR terminal, the momentary cessation of IBR is very probable. To show the impact of momentary cessation, a modified version of IEEE 123 node test system is simulated in PSS®CAPE. This paper uses a portion of this system for studying the impact of momentary cessation which is shown in Fig. 6 [7]. It is assumed that a large IBR (5 MW) is placed at node 61. The VCCS model of this PV IBR is shown in Fig. 7. Our goal is to study the impact of momentary cessation at this IBR on the TOC elements of R4, RTL4, and R5 relays. The considered primary/backup pairs are R4/RTL4 and RTL4/R5. The settings of these elements (secondary amps pickup current, time dial setting (TDS), and curve) are provided in Table II. The impact of momentary cessation on the fault currents flowing through RTL4/R5 pair for a three-phase fault in front of R5 is highlighted in Figs 8 and 9. The impact of momentary cessation on the fault currents flowing through R4/RTL4 pair for a three-phase fault in front of RTL4 is highlighted in Figs 10 and 11. As seen, with momentary cessation, a lower amount of fault current will flow through RTL4 compared to the case where momentary cessation is not active.

If the large IBR is behind the primary/backup pair, the momentary cessation results in the slower operation of TOC elements. This can create CTI violations when the relay settings are adjusted considering momentary cessation and the momentary cessation on IBRs is deactivated. For a fault in front of R5, the TOC element at RTL4 acts as a backup protection and should comply with a minimum CTI requirement (e.g., 0.2 s). This minimum CTI requirement depends on the utility practice. The operating time of TOC elements at RTL4 and R5 for a three-phase fault in front of R5 is summarized in Table III. As seen, the operating times are provided for two cases considering the momentary cessation. With the momentary cessation in service, as seen in Fig. 8, less fault current goes through the backup relay RTL4. As seen in Table III, the CTI between RTL4 and R5 in this case is equal to 0.2 sec. However, if the momentary cessation on IBR is deactivated, more fault current can go through RTL4. Comparing Figs 8 and 9, the magnitude of fault current flowing through RTL4 increases from 3713 A to 4557 A when the momentary cessation is deactivated on IBR at node 61. This results in the faster operation of RTL4 where the CTI decreases to 0.18 s. It should be noted that either of the modeling practices discussed in Section III results in the same amount of fault currents. However, if one requires to perform coordination studies, the addition of the undervoltage relay is preferred to effectively incorporate momentary cessation into the sequence of operations. One important factor that can impact the fault current levels in the system is the phase angle of fault current contribution by IBR. If this phase angle is close to the phase angle of the fault current flowing through the relay that is supplied by the upstream grid, then the IBR fault current can change the current flowing through the relays more significantly.

If the large IBR is between the primary and backup relays, the momentary cessation results in the slower operation of the primary TOC while not impacting the operating time of the backup element. This can create CTI violations when the relay settings are adjusted without considering momentary cessation in place and the momentary cessation on IBRs is activated. For a fault in front of RTL4, the TOC element at RTL4 acts as a backup protection. The operating time of TOC elements at R4 and RTL4 for a three-phase fault in front of RTL4 is summarized in Table IV. Without the momentary cessation in service, as seen in Fig. 11, less fault current goes through the backup relay RTL4. As seen in Table IV, the CTI between R4 and RTL4, in this case, is equal to 0.2 sec. However, if the momentary cessation on IBR is activated, less amount of fault current can go through RTL4. Comparing Figs 10 and 11, the magnitude of fault current flowing through RTL4 decreases from 4880 A to 4010 A when the momentary cessation is activated on IBR at node 61. This results in the slower operation of RTL4 where the CTI decreases to 0.17 s.

B. IBR Response to Fault in Matlab/Simulink Considering Momentary Cessation

For a bolted 3-phase fault just after R5, the voltages and currents observed at the IBR terminal on Bus 61 of IEEE 123 nide system are shown in Fig. 4. The fault occurs at 1.0s, and the IBR detects the fault at 1.005s. At this point, the IBR begins to output fault currents based on the table in Fig. 1. However, the voltage decreases and drops below 0.5 pu at 1.02s, triggering momentary cessation and reducing the current output to zero at 1.07s. The voltage remains below 0.5 for 0.16s, which triggers the mandatory voltage tripping at 1.104s. The fault currents observed at the relays R5 and RTL5 for the fault in front of relay R5 are shown in Figure 5. For this fault, R5 observes a fault current of 4252 A resulting in a trip time of 0.06s. RTL4 observes a fault current of 4142 A before the IBR

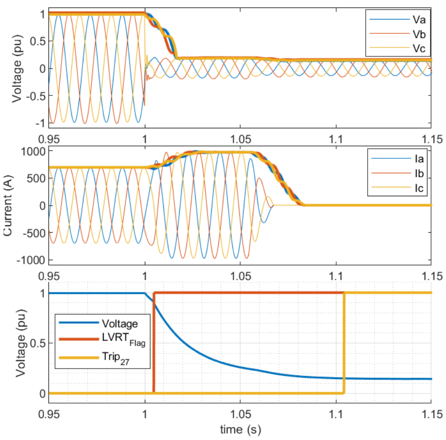

Fig. 4: IBR behavior for a 3-phase bolted fault.

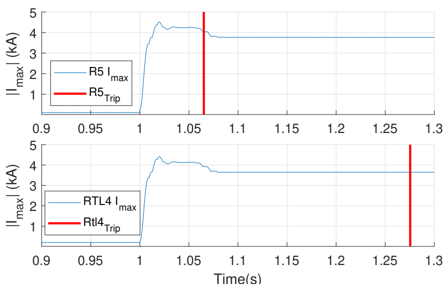

Fig. 5: Relay fault currents and trip times for a 3ph fault.

at bus 61 enters momentary cessation at 1.07s, afterwords the current observed by RTL4 reduces to 3648 A. Therefore, RTL4 trips after 0.28s. Trip times and the sequence of operations for faults in front of relay RTL4 and R5 are shown in Table III and IV.

TABLE II: Directional Forward TOC Settings in RTL4 and R5.

Relay	Pickup	TDS	Curve
R4	2.8	5.6	U.S. Extremely Inverse
RTL4	1.7	5	U.S. Extremely Inverse
R5	1.44	1.2	U.S. Extremely Inverse

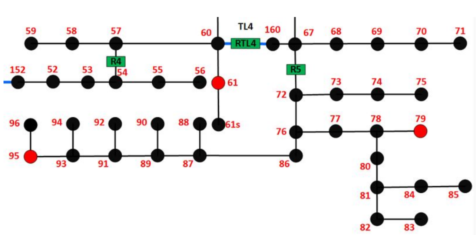

Fig. 6: A portion of IEEE 123 node system used for studying the impact of momentary cessation on the protection system.

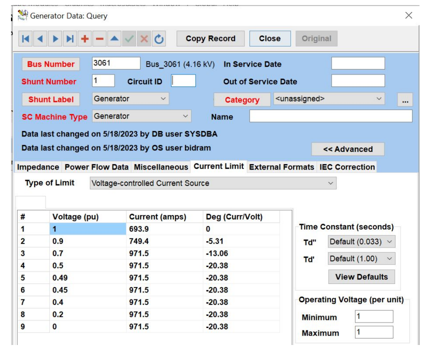

Fig. 7: The VCCS table for PV IBR at Bus 61.

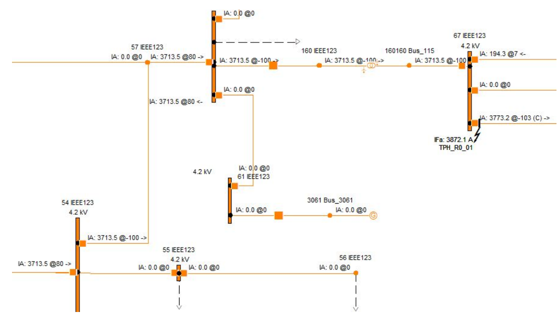

Fig. 8: System fault currents for a three-phase fault in front of Relay R5 when momentary cessation is in place.

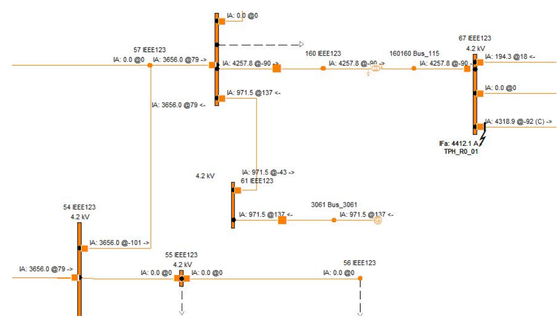

Fig. 9: System fault currents for a three-phase fault in front of Relay R5 when momentary cessation is not active.

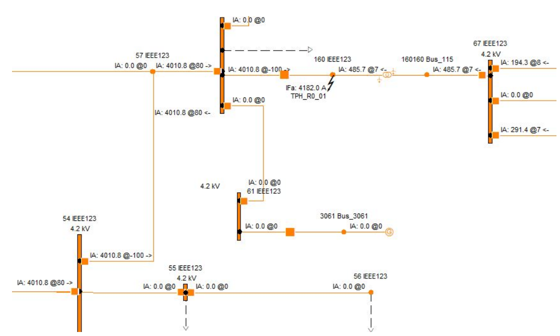

Fig. 10: System fault currents for a three-phase fault in front of Relay RTL4 when momentary cessation is in place.

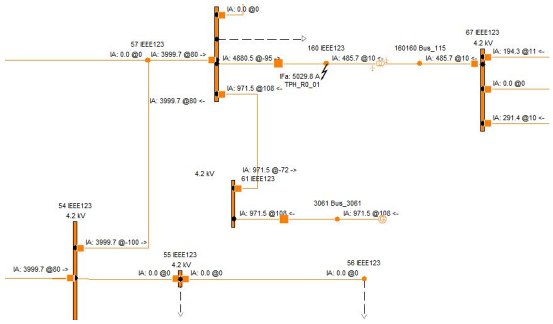

Fig. 11: System fault currents for a three-phase fault in front of Relay RTL4 when momentary cessation is not active.

TABLE III: Sequence of operations and operating times of relays for a fault in front of R5 with and without momentary cessation (MC).

Operation	With MC	Without MC
	CAPE	
1	R5 = 0.06s	R5 = 0.06s
2	PV61 = 0.083	RTL4 = 0.24
3	RTL4 = 0.26s	
	MATLAB Simulink	
1	R5 = 0.066s	R5 = 0.064s
2	PV61 = 0.07s	RTL4 = 0.25s
3	RTL4 = 0.28s	

TABLE IV: Sequence of operations and operating times of relays for a fault in front of RTL4 with and without momentary cessation.

Operation	With MC	Without MC
	CAPE	
1	PV61 = 0.083s	RTL4 = 0.22s
2	RTL4 = 0.25s	R4 = 0.42s
3	R4 = 0.42s	
	MATLAB Simulink	
1	PV61 = 0.07s	RTL4 = 0.23s
2	RTL4 = 0.25s	R4 = 0.41s
3	R4 = 0.40s	

VI. Conclusion

This paper addressed the impact of the momentary cessation of IBRs on the protection of distribution systems. Momentary cessation is one of the requirements in IEEE 1547 standard which requires IBRs to momentarily cease the energization of IBR when a severe disturbance (e.g., fault) occurs and large deviations in the system voltage or frequency are observed. The momentary cessation modeling in PSS®CAPE and Matlab/Simulink was elaborated. The paper highlighted the impact of momentary cessation on the fault current and operation of TOC elements by simulating a modified version of the IEEE 123 node system in PSS®CAPE. It was shown that depending on the location of IBR with respect to the primary/backup relays, the momentary cessation can increase or decrease CTI.

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