Photovoltaic Inverter Momentary Cessation: Recovery Process is Key

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***Abstract* — Momentary cessation refers to an inverter control mode. When the inverter terminal voltage falls below (or exceeds) a certain level, the inverter ceases to output any current, but attempts to maintain (or quickly regain) phase-locked loop synchronization to allow for quick reinjection of current when the voltage recovers to a certain point. This paper presents a photovoltaic (PV) momentary cessation model developed in PSS/E. Simulations are presented for a high voltage transmission line fault contingency in the Hawaiian island of Oahu power system on a validated PSS/E model, modified to include a custom distributed PV inverter model, and different near-future distributed PV penetration levels. Simulations for the island power system include different penetration levels of PV, and different recovery times (ramp rates and delays) after momentary cessation. The results indicate that during low voltage events, such as faults, momentary cessation can produce severe under frequency events, causing significant load shed and shortly thereafter, in some cases, over frequency events that cause generation to trip offline. The problem is exacerbated with higher penetration levels of PV. If momentary cessation is used (as is typically the case for distribution-connected resources), the recovery process after momentary cessation should be carefully considered to minimize impacts to bulk power system stability.**

***Index Terms* — Frequency control, inverter control, momentary cessation, photovoltaic, PV, smart inverter.**

I. Introduction

Renewable generation is increasing across the world, driven by renewable portfolio standards from states and countries, and decreasing costs for renewable generation such as photovoltaic (PV) solar power. As PV increases in penetration levels, PV inverter control actions during abnormal grid conditions such as faults need careful consideration; the same is true for other asynchronous and inverter-based resources such as battery energy storage and wind generation. In response to this, inverter vendors have started to include grid support functionality, and grid interconnection rules and standards have started to require that functionality. Recently, Hawaii now requires frequency-watt control functionality [1]-[2] on all new PV inverters [3], as recommended by a U.S. DOE-funded report [4]. California's Rule 21 interconnection regulation contains similar requirements. In addition, the IEEE 1547-2018 interconnection standard for distributed energy resources (DERs) requires DERs to include functions such as frequency-watt control and momentary cessation [5]. Momentary cessation, a type of inverter response to abnormal grid conditions, is discussed further below.

When a fault occurs, and the voltage drops at the inverter, the inverters connected today have three control options:

1. Disconnect: completely stop injecting power and take a long time to reconnect (typically 5 min.).
2. Full ride-through: stay connected and inject current.
3. Momentary cessation: cease to inject current but attempt to maintain phase-locked loop (PLL) synchronism and start to inject current again quickly after the voltage recovers.

From the bulk power systems perspective, the first option is the least favorable; disconnecting completely when there is a high penetration of PV can cause extreme under frequency events. The second option is often not preferred by distribution system operators, who may favor that the PV trip offline due to islanding and protection concerns. In addition, manufacturers may have a difficult time implementing full ride through. However, the second option is likely the best option from a bulk system stability perspective. The third option, momentary cessation, is a compromise between the first two where the PV will cease its output during the low voltage event, but quickly come back online once the voltage recovers.

Notably, a recent performance guideline for inverter-based resources on the U.S. bulk power system published by the North America Electric Reliability Corporation (NERC) calls for full ride through without momentary cessation [6], though the NERC task force responsible for the guideline recognized that it may not be feasible to eliminate momentary cessation in some existing inverters. In contrast, IEEE 1547-2018 *requires* momentary cessation for Category III DERs and allows momentary cessation for Categories I and II DERs [5], so for distribution-connected inverters momentary cessation is the expected behavior.

The primary goal of this paper is to present a momentary cessation model and illustrate the impact of momentary cessation recovery time through a realistic example with a validated model of Oahu, Hawaii and various renewable generation scenarios. The results indicate that *if* PV inverter

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momentary cessation is utilized during under voltage events, the recovery time after momentary cessation must be fast enough to prevent large frequency events. In addition, the simulation results show that the recovery time is increasingly important as PV penetration levels increase. Recent NERC documents based on California events [7]-[10] show that momentary cessation can cause bulk system stability issues. The advice to mitigate bulk system problems associated with momentary cessation are [7]:

1. Use full ride-through instead of momentary cessation if possible. Preferred from bulk-system stability perspective.
2. If full ride-through is not possible, lower the voltage thresholds before momentary cessation occurs.
3. Significantly reduce the recovery delay to milliseconds, or close to zero.
4. Recover quickly to pre-disturbance power output (ramp quickly).

Note that ramping too quickly could cause an undesirable transient event or local stability issues. A detailed model of the local inverter area would be needed to fully capture the impact of faster momentary cessation on local transient issues such as transient voltage recovery. In addition, if there is a longer low voltage event, i.e. the voltage at the inverter is suppressed for an extended period of time (seconds or longer), then a quick (or instantaneous) ramp may not be in the best interest for the bulk system (for this specific case); it may cause an over-frequency event. Our hypothesis is that the optimal momentary cessation ramp time is dependent on the system, the PV penetration level, and the amount of time the PV has been in momentary cessation. This optimal momentary cessation ramp time analysis is left to future work. This paper does indicate initial results that the recovery after momentary cessation should be as fast as possible unless, 1) it is shown that very fast recovery (ramp) causes undesired transients or stability issues, or 2) the momentary cessation event was longer than a typical fault event, e.g. if momentary cessation is seconds long, under-frequency load shedding may have already occurred, and/or the frequency is already recovering to the pre-disturbance level; a fast recovery from momentary cessation may then cause an over-frequency event.

II. Current Limiter and Momentary Cessation Logic

The PV inverter model presented here includes low-voltage response dynamics including momentary cessation. Note that although this paper simulates momentary cessation with PV, similar analysis is valid on all inverter-based generation. If the terminal voltage falls below a certain level, the inverter ceases to output any current, but attempts to maintain (or quickly regain) PLL to allow for quick reinjection of current when the voltage recovers to a certain point; this is the inverter behavior known as momentary cessation [5]. If the terminal voltage drops too low, the inverter model limits current to avoid violating the transistors' current limits.

Fig. 1 shows the inverter controls including momentary cessation. The variables for the momentary cessation algorithm are in Table I. The parameters and their values used in the presented simulations for the momentary cessation algorithm are in Table II. The momentary cessation algorithm is explained in Algorithm 1.

This model does not prioritize reactive or active power recovery, but rather allows the system to dictate what is needed. It has been shown [10] that if active power priority is given during recovery, while recovering, the active power priority may reduce needed reactive power driving the voltage lower, and tripping the PV back into momentary cessation, this causes an oscillation, where the PV plant is going in and out of momentary cessation. If reactive power priority is given, during a fault that does not cause the PV to enter momentary cessation, reactive power may spike during the fault to raise the suppressed voltage, and once the fault clears, the voltage may become too high triggering momentary cessation [10]. The custom model in Fig. 1 and Tables I and II, was developed and implemented in PSS/E.

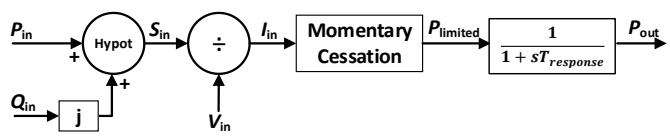

Fig. 1. The current limiter and momentary cessation block diagram

TABLE I
THE VARIABLES NEEDED FOR THE MOMENTARY CESSATION ALGORITHM

Name	Description
V_{in}	The measured AC voltage
P_{in}	The requested real power level
Q_{in}	The requested reactive power level
I_{in}	The current requested that may need to be limited
$P_{limited}$	The power output after momentary cessation
P_{out}	The final output power of the smart inverter
I_{limit}	Boolean to determine if the current was limited
V_{dip}	Boolean to determine if the voltage is below the threshold

The current limiter (momentary cessation) logic in Fig. 1 is broken into five cases [2]. Case 5 is normal operation.

Algorithm 1. Momentary cessation algorithm.

if $I_{in} > I_{max}$ **then** — Case 1
  $T_{response} = T_{limiter}$;
  $P_{out} = \sqrt{(I_{max} * |V_{in}|)^2 - Q_{in}{}^2}$;
  $I_{limit} = 1$;
end if
if $I_{in} < I_{max}$ & $I_{limit} = 1$ **then** — Case 2
  $T_{response} = T_{rec}$;
  $P_{out} = P_{limited}$;
  if $P_{out} > P_{rec}$ **then**

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                $I_{limit}$ = 0;
        end if
end if
if $V_{in}$ < $V_{lv}$ then                                  Case 3
        $T_{response}$ = $T_{limiter}$;
        $P_{out}$ = 0;
        $V_{dip}$ = 1;
end if
if $V_{in}$ > $V_{lv}$ & $V_{dip}$ = 1 then                  Case 4
        wait $T_{delayRec}$, then
                $T_{response}$ = $T_{rec}$;
                $P_{out}$ = $P_{limited}$;
                if $P_{out}$ > $P_{rec}$
                        $V_{dip}$ = 0;
                end if
end if
$T_{response}$ = $T_{response}$;                             Case 5
$P_{out}$ = $P_{limited}$;
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TABLE II
MOMENTARY CESSATION PARAMETERS AND THEIR VALUES USED IN THE PRESENTED SIMULATIONS

Name	Value	Description
$T_{response}$	0.5	Inverter power time constant (normal operation)
I_{max}	1.1	Maximum inverter current (pu)
V_{lv}	0.5	Low voltage limit (if $V < V_{lv}$: inverter will cease to inject power but stay connected)
$T_{limiter}$	0	Current limiter time constant (If $I > I_{max}$, the inverter will be modelled using this time constant) typically much faster than T_{rec}
T_{rec}	0.25	Inverter recovery time constant: when I becomes < I_{max} after voltage recovery, inverter output is controlled using this time constant until power reaches P_{rec}
P_{rec}	0.9	Inverter recovery power limit (once the inverter output recovers above this value, the inverter is controlled by the time $T_{response}$ time constant)
$T_{delayRec}$	0	Time delay before inverter starts recovering from voltage dip after the voltage has recovered

III. PSS/E SIMULATIONS WITH MOMENTARY CESSATION

The recovery of the PV output power after momentary cessation is extremely important and should be fast to minimize impacts on system stability (unless the momentary cessation event was an extended period, or an extremely fast recovery ramp could cause stability issues). Many inverter manufacturers used momentary cessation voltage thresholds of 0.9 pu, which is found to be too high, and NERC recommendations have changed this to 0.5 pu [6]. In IEEE 1547-2018 [5] on page 53 indicates after momentary cessation current must recover to 80% of pre-undervoltage level within 0.4 sec. This is satisfied for the case of full voltage recovery, if $T_{delayRec}$=0 and T_{rec}=0.25 sec. in the model in Section II and Table I. Too slow a recovery can have a major impact on the system frequency response and can lead to increased load shedding, and possible generation loss.

A full scale, Hawaiian Electric Company validated PSS/E dynamic model of Oahu is utilized for simulation analysis, modified to include the custom inverter model developed from Section II, and different PV penetration levels. PV penetration levels are defined in this paper as the percent of total generation that is being supplied by PV at the moment this simulation takes place. The custom inverter model replaces the original model in the base case for all the controllable PV in the Hawaiian system. The 2019 base case includes ~40% PV penetration and the dynamic base case includes generation protection relays. Over-frequency, under-frequency, over-voltage, and under-voltage generation protection relays are included. In addition, under-frequency load shedding relays are included with Hawaiian load shedding schemes enabled. The base case includes distinct types of models for the PV, in an attempt to represent the many types and ages of the PV in the Hawaiian system. The 40% PV penetration in the system made up of two types of PV: 11% legacy PV which trips immediately during the fault and does not recover during the simulation, and 89% controllable PV which performs momentary cessation.

Simulations are analyzed during a high voltage transmission line three phase fault shown in Figs. 2-7. The fault starts a t=1 sec., trips at t=1.083 sec., recloses at t=1.583 sec., and opens permanently at t=1.667 sec. For Fig. 2-3 the recovery time constant, T_{rec}, is varied, and results show that as the recovery time constant increases, a more severe under-frequency event occurs with significant load shedding, and as the PV recovers, an over-frequency event occurs causing some generation to trip offline (both conventional and PV), seen with a recovery time constant (T_{rec}) value of 0.5 sec. and 1.0 sec.

For Fig. 4-5, the PV penetration level is varied by evenly increasing PV generation and decreasing conventional generation. The results show that as PV penetration increases the recovery time becomes increasingly important.

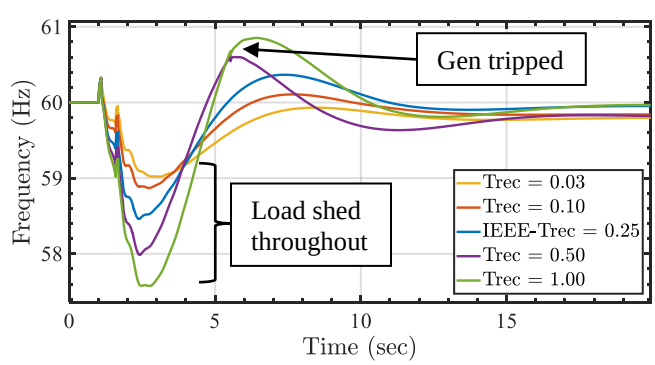

Fig. 2 The Oahu system frequency response during a transmission line three-phase fault when PV includes momentary cessation, with different recovery times (ramp rates).

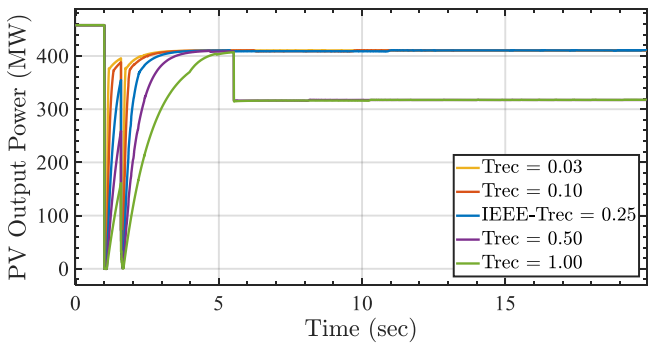

Fig. 3. The total Oahu system PV output power during a transmission line three-phase fault when PV includes momentary cessation, with different recovery times (ramp rates).

Following load shed, similar to Fig. 2, the frequency rebound results in additional PV tripping on over-frequency. Note that when the PV penetration levels were changed, it does not qualify as a Hawaiian Electric Company base case, i.e. the 50% and 60% cases are not validated.

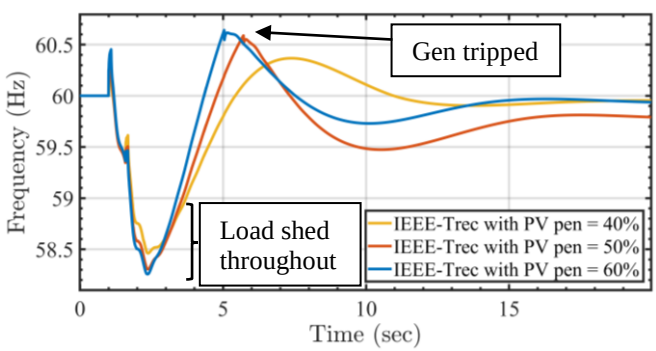

Fig. 4. The Oahu system frequency response during a transmission line three-phase fault when PV includes momentary cessation, with different PV penetration levels.

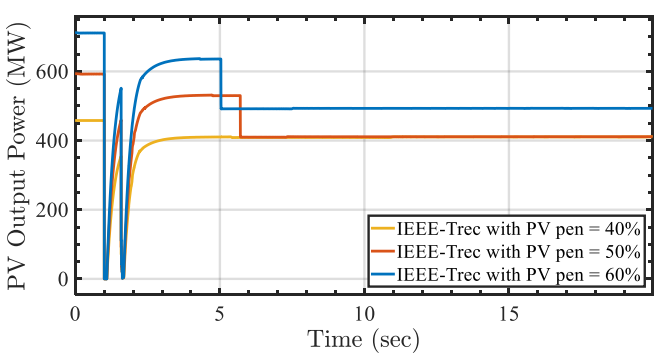

Fig. 5. The Oahu total aggregate PV output power during a transmission line three-phase fault when PV includes momentary cessation, with different PV penetration levels.

Figure 6-7 show that if T_{delayRec} (time delay before inverter starts recovering from voltage dip after the voltage has recovered) were non-zero, the disturbance due to momentary cessation can become very severe. For this reason, it is recommended that T_{delayRec} should be small (a few milliseconds or less). Note that in Figs. 6-7, the recovery time constant (T_{rec}) is held at the IEEE 1547 level of 0.25 sec., and with a slight delay recovery (T_{delayRec}), can cause a large under-frequency event.

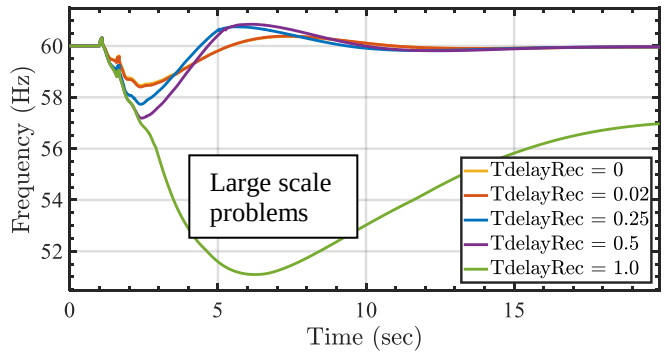

Fig. 6. The Oahu system frequency response during a transmission line three-phase fault when PV includes momentary cessation, with different momentary cessation delay recovery times. Note when T_{delayRec} is 1.0, system blackouts would likely occur.

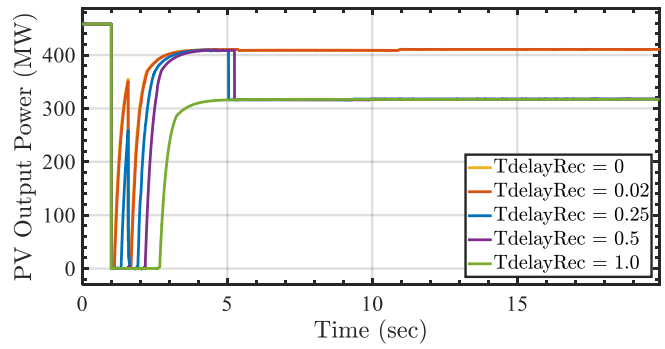

Fig. 7. The Oahu total aggregate PV output power during a transmission line three-phase fault when PV includes momentary cessation, with different momentary cessation delay recovery times.

IV. Conclusion

This paper presents an inverter model including momentary cessation developed in PSS/E. Simulation results on the validated PSS/E model of Oahu, Hawaii, indicate that if momentary cessation is used, a fast recovery time is critical to mitigating under/over frequency events during faults and low voltage conditions. While this analysis focuses on Oahu, similar results are expected on larger systems as PV levels increase. In addition, the recovery time is more critical as inverter-based generation increases on Oahu. Findings indicate that if momentary cessation is necessary, inverter-based generation should recover as quickly as possible to the pre-disturbance power output once the voltage recovers in most circumstances. Two possible exceptions are: 1) if the momentary cessation event lasts longer than a typical fault, e.g. seconds, a fast ramp recovery may cause an over-frequency event, 2) if a fast ramp recovery is shown to cause a large transient or stability issues.

Future work should continue to examine the implications of momentary cessation for grid voltage and frequency stability, impacts of momentary cessation on protection systems, coordination of momentary cessation with other grid support

functions such as frequency support and dynamic voltage support, and other emerging topics. This will become especially important as power systems continue to transition to higher and higher levels of inverter-based generation. There may come a point where momentary cessation needs to be eliminated even in some scenarios where it is allowed or required today.

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