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Photovoltaic Inverter Momentary Cessation: Recovery Process is Key

PRESENTED BY

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Momentary cessation

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.

Inverter reaction to a fault

- Disconnect: completely stop injecting power and take a long time to reconnect (typically 5 min.).

- Full ride-through: stay connected and inject current.

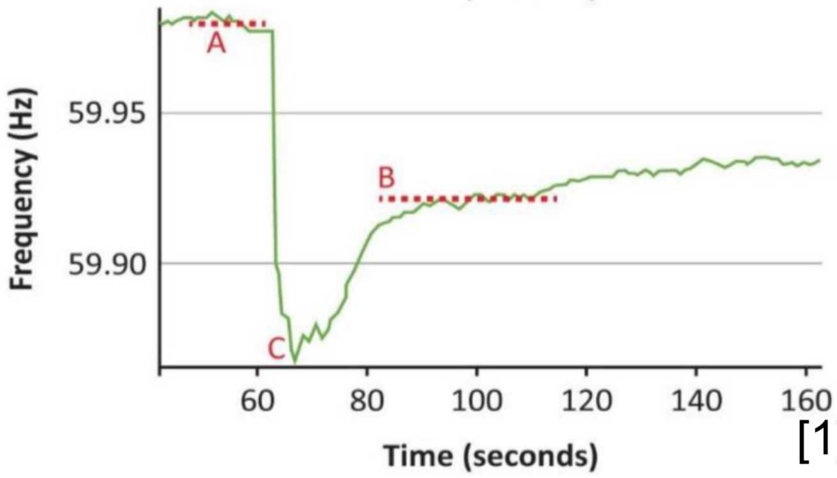
- Momentary cessation: cease to inject current but attempt to maintain phase-locked loop (PLL) synchronism and start to inject current again quickly after the voltage recovers.

Motivation – Large California disturbances due to momentary cessation

- Two NERC reports
  - 1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance report [1].
  - 900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance report [2].

Table 1.1: Solar Photovoltaic Generation Loss						
Event No.	Date/Time	Fault Location	Fault Type	Clearing Time (cycles)	Lost Generation (MW)	Geographic Impact
1	8/16/2016 11:45	500 kV line	Line to Line (AB)	2.49	1,178	Widespread
2	8/16/2016 14:04	500 kV line	Line to Ground (AG)	2.93	234	Somewhat Localized
3	8/16/2016 15:13	500 kV line	Line to Ground (AG)	3.45	311	Widespread
4	8/16/2016 15:19	500 kV line	Line to Ground (AG)	3.05	30	Localized

[1]

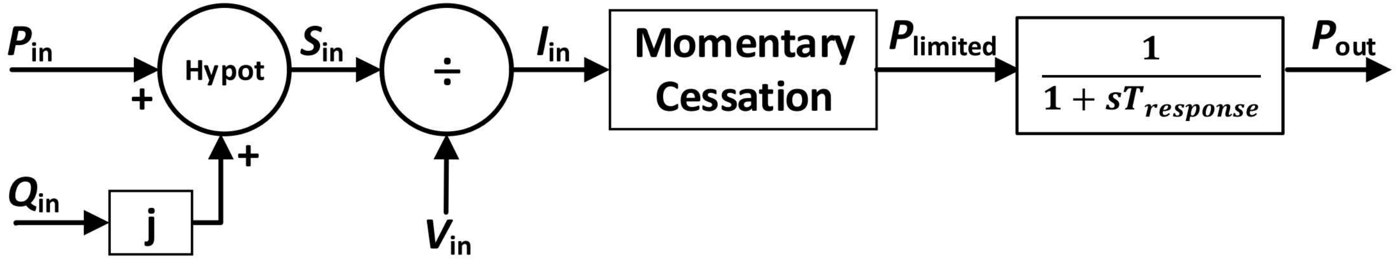


[1]

Lack of momentary cessation included in bulk system models

- The existing bulk system models in PSS/E and PSLF did not include momentary cessation.

- Developed a custom PSS/E model to help Hawaiian Electric Company study the effects momentary cessation may have on their system.



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

Momentary cessation algorithm and parameters

- IEEE 1547-2018 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.

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

Algorithm 1. Momentary cessation algorithm.

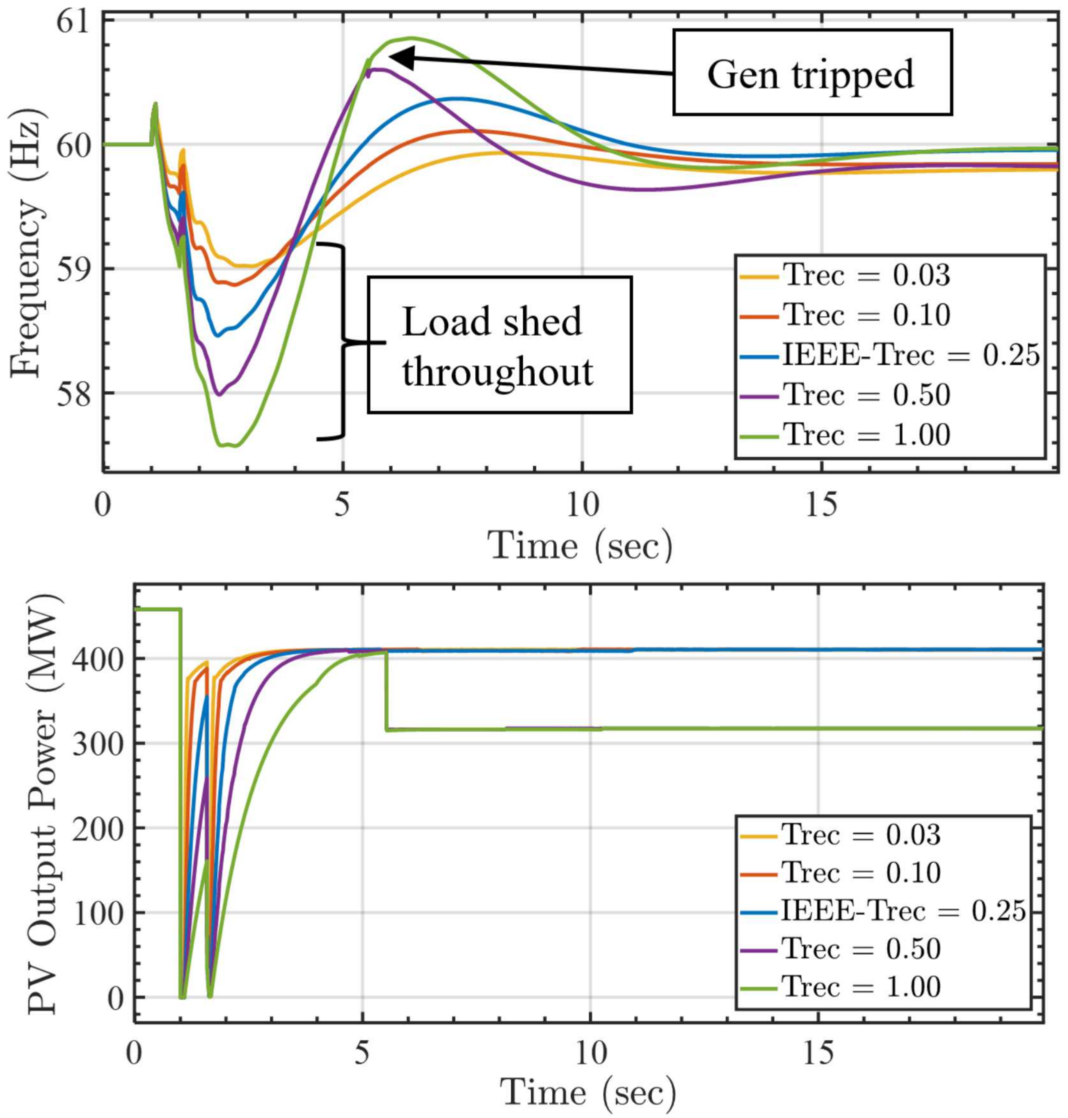
if $I_{in} > I_{max}$ **then** — Case 1
    $T_{response} = T_{limiter}$;
    $P_{out} = \sqrt{(I_{max} * |V_{in}|)^2 - {Q_{in}}^2}$;
    $I_{limit} = 1$;
end if
if $I_{in} < I_{max}$ & $I_{limit} = 1$ **then** — Case 2
    $T_{response} = T_{rec}$;
    $P_{out} = P_{limited}$;
    if $P_{out} > P_{rec}$ **then**
        $I_{limit} = 0$;
    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
$P_{out} = P_{limited}$;

Simulation results on Oahu, Hawaii system.

- Validated PSS/E model of Oahu from Hawaiian Electric Company
- 40% PV penetration
- 89% of PV includes momentary cessation
- 11% is legacy PV that includes complete disconnect during low voltage event
- Model includes Oahu under-frequency load shed settings and generation protection settings
- Simulation shown in the next slides is a high voltage transmission line three phase fault. 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.

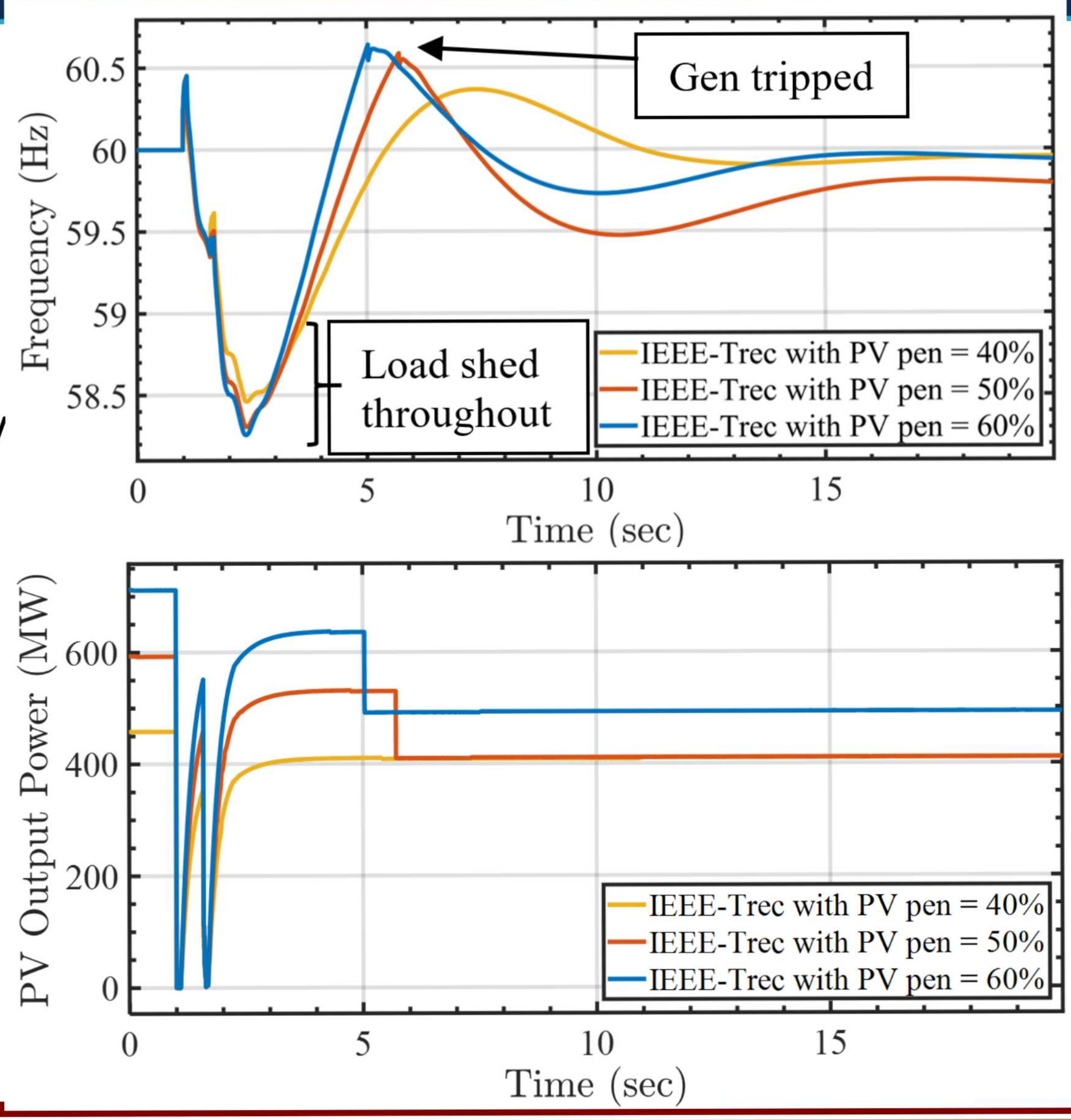
Momentary cessation ramp time

- If the recovery from momentary cessation takes too long, severe under-frequency events can occur, causing load shedding.
- In addition, if the ramp takes too long, an over-frequency event may occur causing generation to trip offline.
- This indicates the ramp rate after momentary cessation should be very fast.
  - Two exceptions exist. 1) if a fast ramp is shown to be problematic from a local transient stability perspective. 2) if momentary cessation has been active for a long period, the frequency may have already recovered, and an immediate connection of large amounts of PV may cause an over-frequency event.



Momentary cessation with higher penetration levels

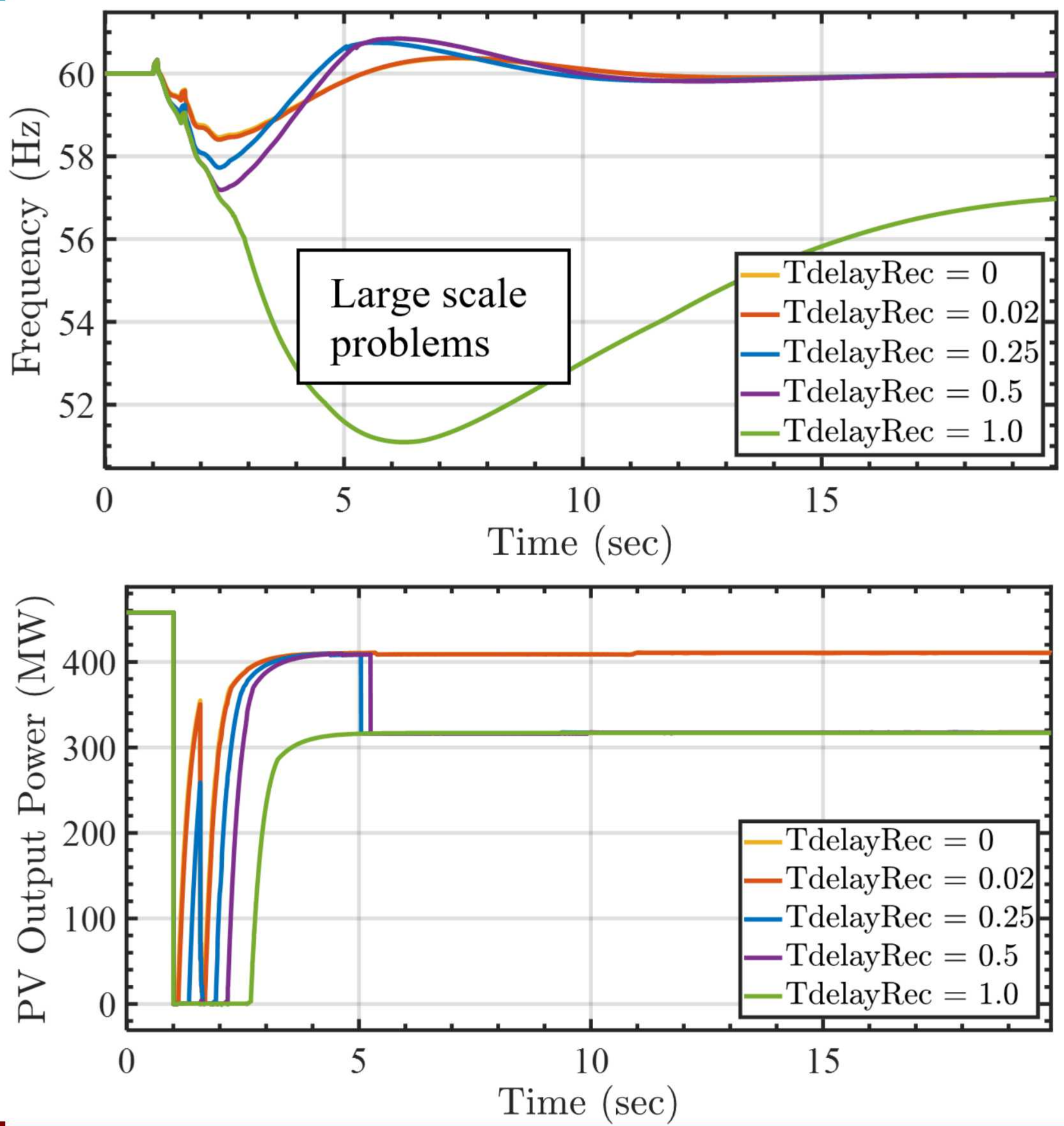
- As PV penetration increases, the problem is exacerbated.
- With 50% or 60% penetration, and 89% of the PV including momentary cessation, even with a ramp time as specified by IEEE 2018-1547, severe under-frequency occurs, with load shedding, and followed by over-frequency and generation tripping.



*50% and 60% cases are not validated Hawaiian Electric models, but rather built from the 40% case.

Momentary cessation with delay before recovery

- If delay is included in the recovery process the under-frequency event can be even worse.
- For this reason delay before recovery should be kept as minimal as possible.



Conclusions and future work

- Recovery time after momentary cessation should be very fast with minimal (close to 0) delay before recovery.
  - At least two exceptions exist: 1) if the PV is in momentary cessation for an extended period, the frequency may have already recovered while momentary cessation was active, therefore an immediate ramp of the PV may cause an over-frequency event. 2) if studies indicate that too fast of a recovery can cause local transient stability problems.
- Recovery process after momentary cessation will become exceedingly more important as inverter-based generation penetration levels grow.
- There may come a point where momentary cessation needs to be eliminated even in some scenarios where it is allowed or required today.
- Future work should look into this further, and come up with the optimal momentary cessation recovery process based on the system, penetration levels, and amount of time in momentary cessation.

Thank you

Questions?

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References

1. North American Electric Reliability Corporation, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report: Southern California 8/16/2016 Event," NERC, Atlanta, GA, June 2017.
2. North American Electric Reliability Corporation, "900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report: Southern California Event: October 9, 2017 Joint NERC and WECC Staff Report," NERC, Atlanta, GA, Feb. 2018.