Abstract—In 2017 and 2018, bulk power system (BPS) connected solar photovoltaic (PV) inverters tripped after grid disturbances in South California, causing large-scale power loss. One cause of PV tripping is subcycle overvoltage experienced by PV inverters when the grid suffers voltage dip and PVS enter into momentary cessation. This paper examines the underlying mechanism of the subcycle overvoltage dynamics. A \(dq\)-frame analytical model is built for a PV grid-integration system with a focus on the grid side converter (GSC) and grid interaction. PV’s dc circuit dynamics and controls are ignored. Eigenvalue analysis indicates that two modes cause the subcycle overvoltage. The modes are associated with shunt compensation, grid electromagnetic dynamics, and PV inverter controls. Furthermore, a more insightful explanation of subcycle overvoltage is offered relying on \(s\)-domain admittance models. The \(dq\)-frame admittance is derived for the PV viewed from the point of common coupling (PCC). A circuit model relying on the derived admittance can demonstrate subcycle overvoltage due to momentary cessation. Impacts of grid strength, phase-locked-loop (PLL) parameters and converter current control parameters are all examined. It is found that the inherent LC dynamics due to shunt compensation and grid inductance are the main dynamics that cause overvoltage, and momentary cessation excites overvoltage dynamics.

Index Terms—Solar Photovoltaic (PV) grid integration; voltage source converter (VSC); subcycle overvoltage dynamics; admittance model

I. INTRODUCTION

Solar PV penetration in power grids increases over time. PV systems experience various dynamics due to transmission grid disturbances. From 2016 to 2018, bulk power system (BPS) connected solar photovoltaic (PV) inverters tripped after large grid disturbances in South California [1]–[3]. The major cause for PV tripping in the 2017 Cayon 2 fire event is identified as overvoltage experienced by PV inverters within subcycle when the transmission grid experienced voltage dip due to faults. Inverter protection devices are suggested to have filters to filter out transient overvoltage and avoid such tripping.

The subcycle dynamics in PV farms during large transmission grid disturbances, are not well understood according to the NERC reports (page 6 of [2]). Recommendations have been given in [2] to industry to conduct more studies to better understand subcycle transient overvoltage.

The objective of this paper is to investigate the mechanism of subcycle overvoltage dynamics. To the authors’ best knowledge, this is the first research paper to address the particular dynamics.

The investigation employs large-signal simulation and the classical linear system analysis. First, we demonstrate the dynamics using two electromagnetic transient (EMT) testbeds with full details. While the EMT testbeds are suitable for demonstration and validation, they are not feasible for small-signal analysis which can offer invaluable insights [4], [5]. Thus, a nonlinear analytical model is built with the capability of both large-signal simulation and small-signal analysis.

In the literature, nonlinear state-space model of PV systems has been constructed in [6], [7]. The PV system model in [6], [7] includes grid-connected voltage source converter (VSC) feedback controls, DC/DC boost converter controls, maximum power point tracking (MPPT) and irradiance-driven dynamics.

This paper examines the underlying mechanism of the subcycle overvoltage dynamics. A \(dq\)-frame analytical model is built for a PV grid-integration system with a focus on the grid side converter (GSC) and grid interaction. PV’s dc circuit dynamics and controls are ignored. Eigenvalue analysis indicates that two modes cause the subcycle overvoltage. The modes are associated with shunt compensation, grid electromagnetic dynamics, and PV inverter controls. Furthermore, a more insightful explanation of subcycle overvoltage is offered relying on \(s\)-domain admittance models. The \(dq\)-frame admittance is derived for the PV viewed from the point of common coupling (PCC). A circuit model relying on the derived admittance can demonstrate subcycle overvoltage due to momentary cessation. Impacts of grid strength, phase-locked-loop (PLL) parameters and converter current control parameters are all examined. It is found that the inherent LC dynamics due to shunt compensation and grid inductance are the main dynamics that cause overvoltage, and momentary cessation excites overvoltage dynamics.

The analytical model built in the authors’ previous research for wind in weak grid [8]–[11] is adopted in this research. This model has the PV system dc side dynamics ignored but has the capability to consider the influence of grid strength by using two \(dq\)-frames: the grid frame and the PLL frame. Thus, grid strength effect and PLL dynamics’ influence can be adequately modeled. Also in the literature, linear state-space models of VSC grid integration systems were mathematically derived in [12], [13]. While those models can be used for eigenvalue and participation factor analysis, those models are not suitable for large-signal analysis. On the other hand, our analytical model can be used for both large-signal simulation and small-signal analysis.

Further, a more insightful explanation of subcycle overvoltage dynamics is sought, relying on the \(s\)-domain admittance model based circuit analysis. By viewing PV as a Norton circuit (a current source with a parallel \(s\)-domain admittance), a circuit model is built. The effect of momentary cessation can be captured by the circuit model and subcycle overvoltage can be demonstrated in the PCC voltage. Impacts of grid strength, PLL parameters and converter current control parameters are all examined.

\(s\)-domain impedance/admittance models for grid-connected inverters have been seen in the literature with PLL’s effect included, e.g., [14]–[16]. We adopt the same approach for admittance derivation. Nevertheless, using Norton equivalent to construct a circuit representing PV grid-integration system for subcycle overvoltage dynamic analysis is a unique contribution.

In summary, the contribution of this paper is twofold.

- Subcycle overvoltage dynamic phenomenon is successfully replicated and analyzed via a state-space nonlinear PV grid integration model. This model not only demonstrates subcycle overvoltage due to momentary cessation,
but also offers invaluable insights on the dynamic phenomenon via eigenvalue analysis and participation factor analysis.

- **s-domain admittance-based circuit analysis** leads to the discovery of subcycle overvoltage mechanism. Subcycle overvoltage is due to momentary cessation of PV inverters which excites the inherent LC dynamics of the system, where C is related to the PV shunt compensation and L is related to the grid’s Thevenin equivalent inductance.

The rest of this paper is organized as follows. Section II introduces two EMT testbeds: a 400-kW PV farm grid integration system (EMT testbed 1) and a 25-MW PV grid integration system (EMT testbed 2). The two testbeds employ different converter control parameters. In addition, EMT testbed 1 employs average model for converters while EMT testbed 2 includes power electronics switching details. The occurrence of subcycle overvoltage further indicates that control parameters have negligible influence on the occurrence of subcycle overvoltage dynamics.

The state-space nonlinear analytical model representing EMT testbed 1 is also described in Section II. Section III presents the subcycle overvoltage demonstration of the EMT testbeds, followed up with eigenvalue analysis and subcycle overvoltage demonstration using the analytical model. Section IV presents the s-domain admittance-based circuit model and the related analysis. Finally, conclusions are given in Section V.

## II. PV TESTBEDS AND ANALYTICAL MODEL

Two EMT testbeds are examined: one adopts average converter model while the other has full details of converter switching. While PV inverters in both testbeds are grid-following converters, they have different control parameters. Also the converters’ control structures have subtle difference.

Testbed 1 has voltage feedforward filter while Testbed 2’s feedforward has no filter. The utilization of the two testbeds is to examine how much influence converter control may have on subcycle overvoltage occurrence.

### A. EMT Testbed 1 in MATLAB/SimPowerSystems

A PV farm grid integration testbed, which is based on the 400-kW grid-connected PV farm demo in MATLAB/SimPowerSystems, is used for validation. The topology diagram is shown in Fig. 1. There are four PV arrays connected in parallel. Each array has a capability of delivering a maximum of 100 kW at 1000 W/m² sun irradiance. A single PV array block consists of 64 parallel strings, with each string having five SunPower SPR-315E modules connected in series.

The four PV arrays are connected to four DC/DC boost converters, respectively. Perturb and observe-based MPPT is implemented in the DC/DC boost converters to regulate the PV array voltage ($V_{pv}$) at 260 V level. The output voltage level of the DC/DC boost converters is 500 V dc. The dc voltage is converted to a three-phase 260 V ac voltage through a VSC, marked in the figure as grid-connected converter (GSC). Shunt compensation (notated as $C_1$) is employed at the PCC bus for reactive power compensation. The PV is connected to a 25 kV line through a step-up transformer, and further to a 120 kV grid through another step-up transformer. 25% shunt compensation is assumed. The parameters of Testbed 1 can be found in Table I.

This testbed has full EMT and control dynamics modeled, including DC/DC converter control for MPPT, VSC control, and grid dynamics. For converters, average models are adopted. In Sections III and IV, the simplified analytical model and derived admittance model are proposed based on this testbed’s parameters.

### B. EMT Testbed 2 in PSCAD

#### TABLE I: 25 MW PV farm testbed parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power base</td>
<td>$S_p$</td>
<td>400 kW</td>
</tr>
<tr>
<td>Voltage base</td>
<td>$V_{dc}$</td>
<td>260 V, 25 kV</td>
</tr>
<tr>
<td>Voltage base dc side</td>
<td>$P_{vdc}$</td>
<td>500 V</td>
</tr>
<tr>
<td>Power level</td>
<td>$P_{vdc}$</td>
<td>0.937 pu</td>
</tr>
<tr>
<td>Converter filter</td>
<td>$R_1$</td>
<td>0.15/50 pu</td>
</tr>
<tr>
<td></td>
<td>$X_1$</td>
<td>0.15 pu</td>
</tr>
<tr>
<td>Shunt Capacitor</td>
<td>$C_{dc}$</td>
<td>0.25 pu</td>
</tr>
<tr>
<td>DC-link Capacitor</td>
<td>$C_{dc}$</td>
<td>0.05 F</td>
</tr>
<tr>
<td>PV LC filter</td>
<td>$L_{pv}, C_{pv}$</td>
<td>5 mH, 100 μF</td>
</tr>
<tr>
<td>Transmission line</td>
<td>$R_{po}$</td>
<td>0.1 X_p</td>
</tr>
<tr>
<td>Current control loop</td>
<td>$K_{pp}, K_{i}p$</td>
<td>(0.3, 5) pu</td>
</tr>
<tr>
<td>DC-link control loop</td>
<td>$K_{pp}, K_{i}p$</td>
<td>(1, 100) pu</td>
</tr>
<tr>
<td>AC voltage control</td>
<td>$K_{pv}, K_{i}v$</td>
<td>(1, 100) pu</td>
</tr>
<tr>
<td>PLL</td>
<td>$K_{p, PLL}, K_{i, PLL}$</td>
<td>(60, 1400) pu</td>
</tr>
<tr>
<td>VFF filter</td>
<td>$V_{op}$</td>
<td>0.001 s</td>
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</table>

#### TABLE II: 25 MW PV farm PSCAD testbed parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching frequency</td>
<td>5 kHz (VSC)</td>
<td>5 kHz (DC/DC)</td>
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<tr>
<td>Power base</td>
<td>$S_p$</td>
<td>25 MW</td>
</tr>
<tr>
<td>Inverter power base</td>
<td>$S_p$</td>
<td>250 kW</td>
</tr>
<tr>
<td>Inverter dc voltage</td>
<td>$V_{dc}$</td>
<td>1 kV</td>
</tr>
<tr>
<td>PCC voltage base</td>
<td>$V_{pcc}$</td>
<td>0.35 kV</td>
</tr>
<tr>
<td>PCC voltage base</td>
<td>$V_{pcc}$</td>
<td>33 kV</td>
</tr>
<tr>
<td>Power level</td>
<td>$P_{vdc}$</td>
<td>1 pu</td>
</tr>
<tr>
<td>System frequency</td>
<td>$f_S$</td>
<td>60 Hz</td>
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<td>LCL filter</td>
<td>$L_{lcl}, C_{lcl}$</td>
<td>0.02 mH, 94.8 μF</td>
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<tr>
<td>Damp</td>
<td>$L_{damp}, C_{damp}$</td>
<td>1.76 mH, 22.40 μF, 750 μF</td>
</tr>
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<td>Shunt capacitor</td>
<td>$C_{sh}$</td>
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</tr>
<tr>
<td>DC-link capacitor</td>
<td>$C_{dc}$</td>
<td>10000 μF</td>
</tr>
<tr>
<td>PV LC filter</td>
<td>$L_{pvc}, C_{pvc}$</td>
<td>2.5 mH, 100 μF</td>
</tr>
<tr>
<td>Transformer impedance</td>
<td>$X_p, V_{op}$</td>
<td>0.05 pu</td>
</tr>
<tr>
<td>Transmission line</td>
<td>$X_p, V_{op}$</td>
<td>0.05 pu</td>
</tr>
<tr>
<td>Current control loop</td>
<td>$K_{pp}, K_{i}p$</td>
<td>(0.2, 20) pu</td>
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<tr>
<td>DC-link control loop</td>
<td>$K_{pp}, K_{i}p$</td>
<td>(1, 20) pu</td>
</tr>
<tr>
<td>Vcc control loop</td>
<td>$K_{pp}, K_{i}v$</td>
<td>(1, 10) pu</td>
</tr>
<tr>
<td>PLL</td>
<td>$K_{p, PLL}, K_{i, PLL}$</td>
<td>(600, 200) pu</td>
</tr>
</tbody>
</table>

Another 25-MW PV system testbed is adopted to observe the subcycle overvoltage dynamics. This model was developed and posted by PSCAD [17]. The system topology is shown in Fig. 3. The solar farm consists of 100 PV arrays. Each unit generates a maximum power of 0.25 MW at the nominal irradiation of 1000W/m² and nominal temperature of 28 degrees celcius. The MPPT, detailed DC/DC boost converter, and detailed three-phase switches are included, shown as Fig. 4. The system parameters are given in Table II.

The base voltage on dc side is 1 kV. The dc voltage is converted to 0.55 kV ac voltage through GSC. Fig. 4 shows the detailed IGBT switches are adopted in the GSC. In the GSC outer control, $V_{dc}$ and $V_{pvcc}$ are regulated on $d$-axis and $q$-axis.
respective. There is no voltage feedforward filter added in the GSC inner current control. A damper along with a LCL filter are used to minimize the impact of harmonics generated by the switches. Note that the $C_{\text{damp}}$ has very small compensation effect on system, i.e., 0.85% pu. A transformer with 0.05 pu inductive reactance is to boost the voltage level from 0.55 kV (PCC) to 33 kV (POC). A 20% shunt capacitor is connected on POC bus.

C. Analytical Model

The analytical model considers VSC grid integration. VSC dc-link capacitor $C_{\text{dc}}$ is explicitly modeled with input power $P_{\text{PV}}$ treated as a known parameter. Dc/dc boost converter, MPPT and PV electrochemical characteristics have been ignored. The simplified system is shown in Fig. 2a. $R_g$ and $L_g$ represent the aggregated resistance and inductance of transformers and distribution line.

Analytical models of the VSC grid integration system have been built in the authors’ prior work [8] and employed for analysis of wind in weak grids [9]–[11]. This model is based on two $dq$-reference frames. All state variables assume constant values at steady-state. Thus, it is possible to use numerical perturbation to extract linear models.

The block diagram of analytical model is shown in Fig. 2b. The model is based on two $dq$-frames: the grid frame and the $dq$-converter frame, notated by superscript $\gamma$. The grid voltage is assumed to have a constant nominal frequency and a phase

![Fig. 1: EMT testbed 1: 400-kW PV farm in Matlab/SimPowersystms.](image1)

![Fig. 2: (2a) Simplification by treating left of the dc-link as a controlled current source to provide constant power. (2b) Block diagram of the $dq$-frame based analytical model.](image2)

![Fig. 3: EMT testbed 2: 25-MW PV solar farm in PSCAD.](image3)
angle $0$. Therefore, the angle between its space vector and the static frame is $\omega_0 t$, where $\omega_0$ is the nominal frequency (377 rad/s). $d$-axis of the grid-frame is aligned with the grid voltage space vector. The converter frame is aligned with the sensed PCC voltage space vector. The angle of the PCC voltage space vector (notated as $\theta_{\text{PCC}}$) is sensed by PLL as shown in Fig. 5(a). Output of the PLL is $\theta$ and this angle tracks the PCC voltage angle $\theta_{\text{PCC}}$. The $d$-axis of the converter frame is ahead of the static frame by an angle. This angle is the PLL output angle $\theta$. Fig. 5(a) is the three-phase PLL adopted in the EMT testbeds.

Fig. 5 (b) presents the linearized model of the PLL with the assumption that the PCC voltage magnitude is at 1 pu and the PLL tracks the PCC voltage angle closely. $\Delta \theta_{\text{PCC}} = \theta_{\text{PCC}} - \omega_0 t$ and $\Delta \theta = \theta - \omega_0 t$.

Since the converter frame is based on the PLL output angle, it is also named as the PLL frame. The angle between the PLL frame and the grid frame is notated as $\Delta \theta$, where $\Delta \theta = \theta - \omega_0 t$. Fig. 6 presents four frames: the static frame, the grid frame used in the analytical model (notated as Grid frame 1), the PLL frame, and another grid frame notated as Grid frame 2. Grid frame 2 will be used in Section IV.

The converter’s vector control is based on the PLL frame or the converter frame, which consists of outer control to regulate dc-link voltage and ac voltage at PCC, and inner current control. The dc-link voltage control generates $d$-axis current order while the ac voltage control generates $q$-axis current order. The inner current control tracks the current orders and generates VSC voltage order $v_{\text{c},d}$ and $v_{\text{c},q}$. The voltage feedforward (VFF) units are employed in both axes. In Fig. 2b, the $q$-axis VFF includes a low-pass filter with time constant $T_{\text{VF}}$.

While the converter control is based on the converter frame, the grid dynamics are modeled in the grid frame. The $d$-axis of the grid frame is aligned with the grid voltage. The system parameters are given in Table I.

### III. Subcycle Dynamics: Demonstration and Eigenvalue Analysis

The NERC report [2] indicates that when PV inverters sense voltage drop, PV inverters immediately reduce its current injection to 0. This stage is termed as “momentary cessation”: PV inverters are connected to the grid while injecting zero currents to the grid.

#### A. Demonstration in the EMT testbeds

1) **MATLAB/SimPowerSystems testbed**: Simulation is carried out using the EMT testbed 1. At $t = 1$ second, the grid voltage experiences 0.1 pu drop. Immediately, the current orders of the VSC reduce to 0. After 0.04 seconds, the grid voltage recovers. The converter voltage, PCC voltage, point of interconnection (POI) voltage and the grid voltage are plotted together. The POI voltage is assumed to be measured at the 25 kV side of the transformer and the transformer is assumed
to have a reactance at 0.15 pu. The total reactance from the PCC bus to the grid $X_g$ is selected to be 0.5 pu.

Fig. 7 presents the simulation results of ac side voltage magnitudes, current magnitudes, power, three-phase voltage and current waveforms, and dc-side control variables and measurements (DC/DC converter duty cycle ratio $D_1$, 260 V dc-side voltage, 500 V dc-side voltage, dc current and power measured between the dc-link capacitor and the VSC). It can be observed that 0.1 pu voltage dip in the grid voltage results in 1.34 pu overvoltage in the converter voltage. In addition, reverse dc current has been observed during the subcycle dynamics.

2) **PSCAD testbed:** At $t = 5$ seconds, the momentary cessation is applied in PSCAD PV testbed. The simulation results are shown in Fig. 8. The PCC bus and POC bus voltage magnitudes, converter current in dq-frame, and power on POC bus are plotted in Fig. 8(a). The three-phase converter voltage, PCC bus voltage and converter current are plotted in Fig. 8(b). The dc side voltage and current are plotted in Fig. 8(c).

Fig. 8(a) shows that 1.71 pu overvoltage can be observed on the PCC bus. The three-phase converter voltage plot indicates the detailed inverter switches result in significant harmonics.
The filter and damper can filter out the high-frequency harmonics.

Remarks: Both EMT testbeds, based on average model or full switching details, can demonstrate the occurrence of subcycle overvoltage due to momentary cessation. The two testbeds have very different converter control parameters, which indicates that converter control parameters play an insignificant role in the occurrence of subcycle dynamics.

B. Eigenvalue analysis and demonstration based on the analytical model

EMT Testbed 1: Relying on the analytical model, linear models can be extracted using numerical perturbation at certain operating condition. For EMT Testbed 1 at the operation condition of 1 pu PCC voltage, 1 pu grid voltage, and 0.937 real power dispatch, linear models are extracted for different $X_g$ to examine the effect of grid strength on dynamics. In addition, the analytical model is assumed to operate at the beginning of momentary cessation stage, i.e., the outer control loops are no longer functioning. Instead, the converter control is under current control only.

Fig. 9 present eigenvalue loci for a varying $X_g$. It can be found that there are two modes in the range of 60 ∼ 200 Hz. These modes are sensitive to the current control parameters, grid reactance $X_g$, and the shunt compensation level. With $X_g$ increasing, the two modes move to the right half plane, which indicates that weaker grid strength may cause more severe dynamics. The participation factor table of the two modes is presented in Table III. It can be seen that the 200 Hz mode (mode 1) is heavily influenced by the PCC voltage and converter current. The 60 Hz mode (mode 2) is influenced by the line and converter currents as well as the feedforward filter.

The same event is applied on the analytical model to carry out time-domain simulation. Fig. 10 presents voltages at different locations. It can be seen that the oscillation frequency is about 200 Hz. When the grid is weaker, overvoltage is more severe. For this system, when $X_g$ is at 0.50 pu, the voltage at inverter can reach 1.4 pu.

EMT Testbed 2: Analytical model-based simulation and eigenvalue analysis are also carried out using EMT Testbed 2’s parameters. Fig. 11 presents the time-domain simulation results for momentary cessation. Subcycle overvoltage is observed. Eigenvalue analysis results are presented in Fig. 12(a). It can be seen that the system has two modes: one at 133 Hz and the other at 266 Hz.

The high-order harmonics in $V_{PCC}$, abc voltages in Fig. 8(a) are indeed caused by the 133 Hz mode and the 266 Hz mode. The FFT analysis results of $V_{PCC}$ are shown in Fig. 12 (b). The FFT analysis is conducted from 5.0 s to 5.06 s for the PSCAD simulation data. The FFT analysis is conducted on the analytical model based simulation data from 1.0 s to 1.06 s. The FFT analysis confirms that 133 Hz and 266 Hz modes are major components for subcycle dynamics. Participation factor analysis (results are not presented in the paper) confirms that the 266 Hz mode is related to LC dynamics while the 133 Hz mode is related to the converter current as well as converter control.

Remarks: The analysis and simulation results show that the

<table>
<thead>
<tr>
<th>TABLE III: Participation factors (PF) of modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Grid Dynamic</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>PLL</td>
</tr>
<tr>
<td>Feedforward filter</td>
</tr>
<tr>
<td>Current controller</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Fig. 10: Simulation results of voltages at different locations via the analytical model. PV enters momentary cessation after 1 second.
subcycle overvoltage dynamics are related to grid dynamics which is influence by the PV farm shunt compensation and grid inductance. The inter-relationship between shunt compensation, subcycle overvoltage and momentary cessation has been identified as Finding 8 in [2]. The eigenvalue analysis confirms the finding.

IV. CIRCUIT MODEL BASED ON ADMITTANCES

In this section, a more insightful explanation of subcycle overvoltage dynamics is sought using circuit model. The PV farm is now viewed as a Norton circuit with the converter current order reflected as a current source and converter controls and RL filter as an admittance. Fig. 13 presents the circuit model that is desired. Using the circuit model, momentary cessation can be represented as step changes in the current source. Thus, PCC voltage dynamic response can be found using circuit analysis. Derivation of VSC admittance has been carried out in the literature since 2007 in [14]. For this research, accurate representation of converter under momentary cessation is desired. During momentary cessation, the converter works under current control only. Thus, PLL and current control details should be modeled. Furthermore, to achieve concise expressions, selection of grid-frame is very important. In this research, the approach used in [18] is adopted for grid-frame selection. Grid frame 2 shown in Fig. 6 is used as the grid frame.

A. Admittance Model of the PV Viewed at the PCC Bus

Based on the current control loop relationship show in Fig. 2b, the following relationship of the converter voltage, PCC voltage, and converter current in the PLL frame can be found.

![Figure 11: Dynamic simulation results of the analytical model using EMT Testbed 2 parameters. (a) AC side PCC voltage, POC voltage, converter current, and PCC power. (b) DC side voltage, current, and the input dc power.](image)

![Figure 12: Eigenvalue analysis results and FFT analysis results. (a) Eigenvalue: $X_g$ varies from 0.2 to 0.5 pu, with each step 0.02 pu. (b) FFT analysis on PSCAD and analytical PCC bus voltage.](image)
Combining (4) and (5) leads to the expressions of the \( q \)-axis PCC voltage in the PLL frame and the PLL output angle in terms of the \( q \)-axis PCC voltage in the grid frame \( \Delta v_{\text{PCC},q} \).

\[
\Delta v_{\text{PCC},q} = \frac{1}{1 + \overline{v}_{\text{PCC}} H(s)} \Delta v_{\text{PCC},q} \quad (6)
\]

\[
\Delta \delta = \frac{H(s)}{1 + \overline{v}_{\text{PCC}} H(s)} \Delta v_{\text{PCC},q} \quad (7)
\]

\[
\begin{bmatrix}
\Delta v_{\text{PCC},d} \\
\Delta v_{\text{PCC},q}
\end{bmatrix}
= M_1 \begin{bmatrix}
1 \\
0
\end{bmatrix}
\begin{bmatrix}
\Delta v_{\text{PCC},d} \\
\Delta v_{\text{PCC},q}
\end{bmatrix} \quad (8)
\]

The current phasor viewed in the PLL frame and that viewed in the grid frame have the following relationship:

\[
i_{1d} + j i_{1q} = (i_{1d} + j i_{1q}) e^{-j \delta} \quad (9)
\]

Linearizing (9) leads to the following small-signal model.

\[
\Delta i_{1d} + j \Delta i_{1q} = (\Delta i_{1d} + j \Delta i_{1q}) + (i_{1d} + j i_{1q}) (-j \Delta \delta) \quad (10)
\]

Substituting \( \Delta \delta \) by (7) leads to the following:

\[
\begin{bmatrix}
\Delta v_{\text{PCC},d} \\
\Delta v_{\text{PCC},q}
\end{bmatrix}
= M_2 \begin{bmatrix}
i_{1d} \\
i_{1q}
\end{bmatrix} \cdot \begin{bmatrix}
0 \\
H(s)
\end{bmatrix} \Delta v_{\text{PCC},q} \quad (11)
\]

Note that the assumption of \( \delta \) at steady-state is 0 leads to the above concise expression. Should \( \delta \) is not 0 at steady-state, a coefficient matrix will be multiplied with the grid-frame current in (11).

Similarly, the converter voltage in the PLL frame can be expressed as the converter voltage in the grid frame and the PCC voltage in the grid frame.

\[
\begin{bmatrix}
\Delta v_{d} \\
\Delta v_{q}
\end{bmatrix}
= M_3 \begin{bmatrix}
\Delta v_{d} \\
\Delta v_{q}
\end{bmatrix} \cdot \begin{bmatrix}
0 \\
H(s)
\end{bmatrix} \Delta v_{\text{PCC},q} \quad (12)
\]

For (1), replace the variables (converter voltage, PCC voltage and converter current) in the PLL frame by those in the grid frame using (8), (12), and (11).

\[
\begin{bmatrix}
\Delta v_{d} \\
\Delta v_{q}
\end{bmatrix} = M_3 \begin{bmatrix}
\Delta v_{d} \\
\Delta v_{q}
\end{bmatrix} \cdot \begin{bmatrix}
0 \\
H(s)
\end{bmatrix} \Delta v_{\text{PCC},q} + F_F \cdot M_1 \begin{bmatrix}
\Delta v_{\text{PCC},d} \\
\Delta v_{\text{PCC},q}
\end{bmatrix} \quad (13)
\]

Note that the PCC voltage and the converter voltage are connected through an RL filter. Hence,

\[
\begin{bmatrix}
\Delta v_{d} \\
\Delta v_{q}
\end{bmatrix} = \begin{bmatrix}
R_L + L_I s \\
\omega_0 L_I
\end{bmatrix} \Delta i_{1d} + \begin{bmatrix}
R_L + L_I s \\
\omega_0 L_I
\end{bmatrix} \Delta i_{1q} \quad (14)
\]

Finally, we can have the VSC admittance in (15).
\[
\begin{align*}
\frac{\Delta i_{1d}}{\Delta V_{1d}} & = (Z_c + Z_{RL})^{-1} K_c \left[ \frac{\Delta V_{1d}}{\Delta i_{1d}} \right] v_{VSC} \\
& \quad + (Z_c + Z_{RL})^{-1} (F_F M_1 - I - M_3 - Z_c M_2) \frac{\Delta V_{PCC,d}}{\Delta v_{PCC,d}} \\
& \quad - Y_{VSC} \frac{\Delta v_{PCC,q}}{\Delta V_{1q}} v_{VSC}
\end{align*}
\]

(15)

It has to be noted that the admittance matrix has a zero column. The \(dd\) and \(dq\) components are all 0. Fig. 14 presents the Bode plots of the admittance components. It can be seen that the \(dd\), \(dq\) components are zero and \(qq\) component is dominant. In addition, at the frequency close to 100 Hz to 200 Hz, the \(qq\) component has a phase angle at 0 degree, which indicates that the \(qq\) component is resistive.

![Bode Diagram](Fig. 14: PV viewed from the PCC bus as an admittance. Only current control and PLL are included. Two sets of PLL parameters are examined.)

If the PLL dynamics are ignored and the two frames (the PLL frame and the grid frame) are exactly same, then \(M_1\) is an identity matrix, \(M_2\) and \(M_3\) are \(0\) matrices. If the feedforward filter is ignored, \(F_F\) will be an identity matrix. Eq. (15) will be reduced into the following model:

\[
I = I_{VSC}.
\]

(16)

That is, the PV viewed from the PCC bus is a current source only (see Fig. 13). Thus, it can be found that the admittance is due to the effects of PLL and feedforward filter.

### B. Validation

The derived admittance matrix of the PV system viewed from the PCC bus assumes only current control. This derived admittance matrix will be compared with the admittance obtained by numerical perturbation of the analytical model shown in Fig. 2b. The measurement testbed is set to have the PCC voltage connected to a grid voltage through a small impedance. The outer controls are all ignored. With the grid voltage as input, the grid current as the output, the input/output transfer function matrix is indeed an admittance matrix viewed at the grid.

\[
Y = \left( Y_{VSC} + Y_c + Y_g \right)^{-1} + \left[ \frac{R_g + L_g s}{\omega_0 L_g} \right]^{-1}
\]

(17)

Fig. 15 presents the Bode plots of the two admittance models. One is obtained based on (15) and (17) and the other is obtained based on numerical perturbation of the analytical model. They show excellent match.

![Bode Diagram](Fig. 15: Comparison of admittance obtained by derivation and numerical perturbation of the analytical model.)

### C. Circuit Model

The total admittance viewed at the PCC bus is as follows.

\[
Y = Y_{VSC} + Y_c + Y_g
\]

(18)

where \(Y_c = \begin{bmatrix} C_1 s & -C_1 \omega_0 \\ C_1 \omega_0 & C_1 s \end{bmatrix}\),

and \(Y_g = \begin{bmatrix} R_g + L_g s & -\omega_0 L_g \\ \omega_0 L_g & R_g + L_g s \end{bmatrix}^{-1}\).

Thus, the PCC voltage can be related to the two current sources using circuit analysis:

\[
Y V_{PCC} = I_{VSC} + Y_g V_g
\]

(19)

where \(V_{PCC} = \begin{bmatrix} \Delta V_{PCC,d} \\ \Delta V_{PCC,q} \end{bmatrix}\), \(V_g = \begin{bmatrix} \Delta v_{gd} \\ \Delta v_{gq} \end{bmatrix}\), and \(I_{VSC}\) is defined in (15).

With total current injection to the PCC bus as the input and the PCC bus voltage as the output, the transfer function is \(Y^{-1}\). Thus, the system’s eigenvalue is the poles of the transfer function matrix \(Y^{-1}\), or the zeros of the total admittance matrix \(Y\). Matlab function \(tzero\) can be used to find zeros of \(s\)-domain \(Y\) matrix.

In addition, momentary cessation effect on the PCC voltage can be simulated using the linear model. Fig. 16 presents the circuit model-based time-domain simulation results. Before \(t = 1\) second, the system is operating at steady-state condition. The PCC voltage \(dq\)-axis components are 1 and 0 respectively. The \(dq\)-axis components of the converter output current are...
0.937 and 0.1176 respectively. At $t = 1$ second, the two converter current orders become 0. In turn, the $dq$-axis current components experience dynamics and the current magnitude reduces to 0 in less than 0.06 seconds. On the other hand, the PCC voltage experiences overvoltage as shown in Fig. 16. 1.534 pu is reached in less than 0.02 seconds.

If the effects of PLL dynamics and the feedforward filter are ignored and the PV is viewed as a current source only, the PCC voltage may reach 1.827 pu as shown in Fig. 17. The Bode plots of the admittance indicate that the $qq$ component is resistive. Since the admittance is due to the effects of PLL and feedforward filter, it can be viewed as PLL and feedforward filter provide damping in the subcycle range. Hence, the overvoltage is less severe.

**D. Sensitivity Analysis**

Impacts of grid strength ($X_g$), PLL parameters, and converter current control parameters are examined using eigenvalue loci generated by `zzero(Y)`.

Fig. 18a presents the system eigenvalue loci when the grid strength reduces for a different PLL. The proportional and integral gains are 300 and 3000. This PLL has a higher bandwidth. It can be seen that the 60 Hz mode is influenced by PLL and this mode moves to the right half plane. The effect of PLL is also tested in time-domain simulation using the analytical model. See Fig. 19. It can be seen that for a PLL with higher bandwidth, the subcycle overvoltage is more severe and the converter voltage may reach 1.565 pu after 0.01 seconds. Note that for the same operation condition, for the PLL with a lower bandwidth, the converter voltage reaches 1.4 pu (See Fig. 10).

Finally, the effects of current control parameters are compared. Fig. 20 presents the Bode plots of the admittance matrices for two types of current controllers. The solid lines correspond to the current control with proportional and integral gains at (0.3, 5) while the dashed lines correspond to that with parameters at (1, 15). The difference in the admittance frequency response is also manifested in time-domain simulation results in Fig. 21. For the current control with a larger gain, subcycle overvoltage appears slightly more severe.

**E. Remarks and Discussion**

In this paper, we have presented three types of models for subcycle dynamics investigation: (i) the EMT testbeds for validation and demonstration, (ii) nonlinear analytical model.
significant in subcycle overvoltage phenomenon.

Occurrence of subcycle overvoltage dynamics is due to two prior conditions: PV farm has shunt compensation installed; the grid strength becomes weak due to transmission line tripping. On top of the existing conditions, PV systems’ momentary cessation excites LC dynamics. Thus, quickly recovering grid strength from contingencies is of great importance for system operation with high penetration of PVs.

V. CONCLUSION

This paper reveals the mechanism of real-world dynamic phenomena observed recently in PV farms: subcycle transient overvoltage when PVs enter into momentary cessation mode. The dynamics are found to be associated with the LC dynamics related to shunt compensation and grid inductance. Converter controls, e.g., PLL dynamics, voltage feedforward, and current control parameters, more or less influence subcycle overvoltage dynamics. However, compared to PV shunt compensation and grid strength, they play a much less significant role.

REFERENCES


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