A Data-Driven Analysis of Lightning-Initiated Contingencies at a Distribution Grid with a PV Farm Using Micro-PMU Data

Alireza Shahsavari†, Mohammad Farajollahi†, Emma Stewart‡, Ciaran Roberts§, and Hamed Mohsenian-Rad†
†Department of Electrical and Computer Engineering, University of California, Riverside, CA, USA
‡Global Security Group, Lawrence Livermore National Laboratory, Livermore, CA, USA
§Grid Integration Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
e-mails: {ashah023, mfara006}@ucr.edu, stewart78@llnl.gov, cmroberts@lbl.gov, and hamed@ece.ucr.edu

***Abstract*—In this paper, we conduct a data-driven experimental analysis of lightening-induced contingencies at a distribution grid in Riverside, CA, using data from three distribution level phasor measurement units, a.k.a, Micro-PMUs. The data was collected during four hours of a rainy day with several lightening strikes on October 24, 2016. Of particular interest was to analyze the impact and the response of a 7.5 MW PV farm. Due to the use of three Micro-PMUs, including one in an outlying area, we are able to distinguish system-wide events across the sub-transmission network against local events at the PV farm and its associated substation. Multiple interesting observations are made and the related causes are discussed. For example, based on the analysis of phase angle difference data, we observe that during at least one of the lightening events, there was a reverse power flow from the PV site to the substation due to a transient short-circuit caused by the surge arresters. This paper takes a first step in using Micro-PMU data to conduct a detailed analysis of how distributed energy resources (DERs) could be affected and and/or respond to the lightening-induced contingencies in distribution systems.**

***Keywords*: Lightning, PV farm, data-driven analysis, active distribution network, reverse power flow, micro-PMU.**

I. Introduction

Lightning strikes may affect quality of power supply as well as service continuity. From power quality point of view, the momentary interruptions made by lightning strikes may cause damages to customers' equipment and revenue loss to power utilities. Lightning strikes may also damage critical elements of the power system such as transformers.

The effect of lightning on power electricity lines can be traced by monitoring the transient impulse voltages, either produced by lightning directly striking a phase conductor or induced by lightning flash striking nearby the power line (indirect lightning). This short tail impulse voltage, with a *micro-second* duration, is large enough to damage the equipment in the system.

In order to protect equipment from lightning impulse voltages, surge arresters are used [1]. In case the overvoltage exceeds the minimum strength voltage of a surge arrester, the flashover will be initiated. This lightning-initiated flashover is a phenomenon which causes an electricity arc due to breaking the minimum threshold of voltage insulator [2]. Such arcing would result in a temporary short-circuit, accompanying with a dip in voltage and increase in current, which might take a few *millisecond*. At distribution level, this kind of temporary short-circuit events can have considerable effects on power quality sensitive loads.

In the context of *active* distribution systems, i.e., distribution systems that are connected to distributed energy resources (DERs) and distributed generators (DGs), the effects of lightning-initiated flashover and temporary short-circuit are becoming major challenges for utilities. In the US alone, the solar energy deployment increased from 2014 to 2015 by 28% [3]. In addition to harvesting power from photovoltaic (PV) farms, there has been a significant increase in penetration of customer-owned behind-the-meter PV panels in recent years [4]–[6].

Many studies have previously examined the effect of lightning-initiated flashover on *passive* distribution systems. In [7], the performance of a distribution line struck by direct lightning was analyzed, which was done based on the flashover and back-flashover calculation due to lightning. In [8], the authors proposed a statistical evaluation of lightning overvoltage on overhead distribution lines based on neural network method. In [9], the authors studied the cause-and-effect relationships between lightning flashes and the corresponding events on the nearby distribution system, such as permanent and transient system outages. In [10], the authors studied the performance of overvoltage protection via surge arresters against lightning overvoltage, in the presence of distributed generators and other smart grid resources.

With respect to DERs, several efforts, such as [11], [12], reported on experimental and field study regarding the effect of direct or indirect lightning striking in a nearby PV modules. However, they did not examine the effect of lightning-initiated flashover propagated on power grid network on the PV inverters connected to the distribution network. Any such analysis inevitably requires using *synchronized* measurements across the power grid at the moment when the lightning strike occurs.

Because of the random nature of lightning, it is highly insightful to conduct data driven studies of lightening and initiated flashover. In [13], the authors discussed on the use of large data sets obtained from different measurements such as phasor measurement units (PMUs) to observe and trace the effect of lightning events. In [14], the author reported on data obtained from PMUs during a lightning strike, which captured some transient changes on voltage and current phasors

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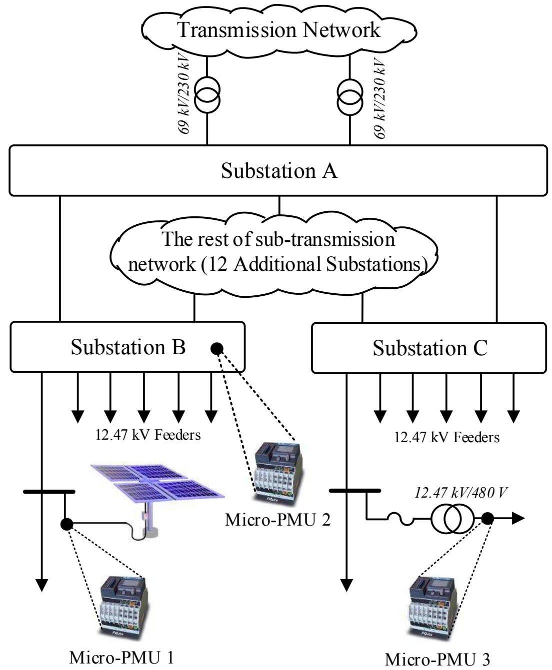

Fig. 1. The real-world test system that is studied in this paper is part of a sub-transmission system in Riverside, CA, which includes a PV farm under Substation B. Data from three Micro-PMUs are used for this analysis.

caused by lightning. In [15], the authors described a PMU data management system that supports input from multiple PMU data streams for detection of events such as lightning strikes.

The studies in [13]–[15] are all based on PMU data at *transmission level*. In contrast, in this paper, we seek to study lightening events using data from distribution-level PMUs, a.k.a, Micro-PMUs. This allows us to focus our analysis on DERs and active distribution networks.

Micro-PMUs have a sampling rate that is higher than that of typical commercial transmission PMUs. They also have higher precision compared to their transmission-level counterparts. Some of the benefits of Micro-PMUs are described in [16], [17], e.g., with respect to event and fault detection and diagnostics at distribution feeders. Micro-PMUs are gradually becoming commercially available, and several innovative applications of Micro-PMU data have recently been proposed in [18]–[25].

This paper aims to propose a novel data-driven approach to use experimental distribution-level synchrophasor data, i.e., voltage and current measurements, on three phases, to analyze transient behaviors of flashovers caused by lightning strikes and the corresponding responses of the system to this phenomenon. In this regard, the synchrophasor data during three actual lightning strikes in a real-world distribution system in Riverside, CA are considered. Based on the obtained data, the transient behavior of short-circuit accompanied lightning-initiated flashover as well as the response of DERs to this phenomenon is investigated. Of particular interest is to analyze the impact and the response of a 7.5 MW PV farm. To the best of our knowledge, this is the first paper that studies lightening-induced events at distribution level using Micro-PMUs.

II. Under-Study Real-Life Test System

In order to study the effect of lightning and lightning-initiated contingencies, a real-life power network is considered in Riverside, CA. The single line diagram of the under-study network is shown in Fig. 1. This network is operated by Riverside Public Utilities (RPU), see *http://www.riversideca.gov*. The point of common coupling between the transmission system and RPU's sub-transmission network is marked as *Substation A*. In total, the under-study sub-transmission network includes 15 substations, 69 kV and 33 kV. Of interest in this paper is *Substation B* and to a lesser extend *Substation C*. *Substation B* is interconnected with a 7.5 MW investor-owned behind-the-meter solar farm comprising 25,000 solar panels. The solar-generated power is fed into the local distribution grid and is enough to power about 1,600 homes.

The network is equipped with several Micro-PMUs, while only the data from three Micro-PMUs is available on the day of interest in this paper. Micro-PMU 1 is at grid-connected side of PV farm, which is a local generation node at distribution feeder. Micro-PMU 2, is deployed at low voltage side of a 69 kV substation marked as *Substation B*. Finally, Micro-PMU 3 is deployed at the secondary side of a 12.47 kV to 480 V transformer at a commercial building located at downstream of *Substation C*. This third Micro-PMU is in an outlying area from *Substation B*. It is intended to allow us distinguish system wide events from events that specific to Substation C and the PV farm.

The installed Micro-PMUs report four fundamental measurements on three phases, i.e., 13 channels total: voltage magnitude, voltage phase angle, current magnitude, and current phase angle, with the sampling rate of 120 Hz, i.e., one sample every 8.333 msec. The 13th channel is GPS Lock, utilized to determine if the sensor has established a satellite lock to ensure precise time synchronization. This high sampling rate, together with the fact that we have direct access to voltage and current data of different locations, allow us capture the effect of lightning-initiated contingencies within a data-driven framework, and also the response of the PV farm and the overall system to such contingencies. Given the fact that since the Micro-PMU 3 is installed at outlying area from Micro-PMU 1 and 2, the system-wide and local contingencies can be distinguished.

The focus in this paper is on the Micro-PMU data that is collected during lightening strikes in Riverside, CA on October 24, 2016 between 11:00:00 AM and 03:00:00 PM local time, which included multiple lightening strikes [26]. The recorded single phase voltage magnitude and current magnitude of Micro-PMU 1 is shown in Fig. 2. The same data at the same location and during the same time frame, but for a sunny day on October 25, 2016 [26], is shown in Fig. 3. Generally speaking, the frequency and magnitude of current (as opposed to voltage) fluctuations are similar on both days with no significant observation on the effect of lightning. However, the two figures differ significantly with respect to the voltage measurements. Specifically, during the sunny day, voltage fluctuated between 282.58 to 290.14 volts, i.e., at almost $\pm 2\%$. In contrast, there are at least four

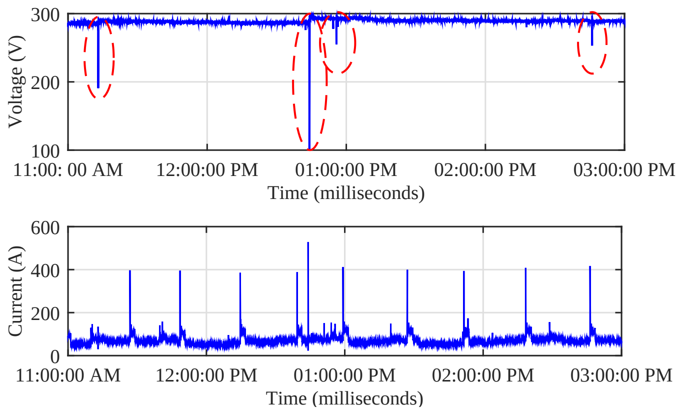

Fig. 2. Single phase voltage and current of Micro-PMU 3 for a four-hours period during a *rainy day*, October 24 2016.

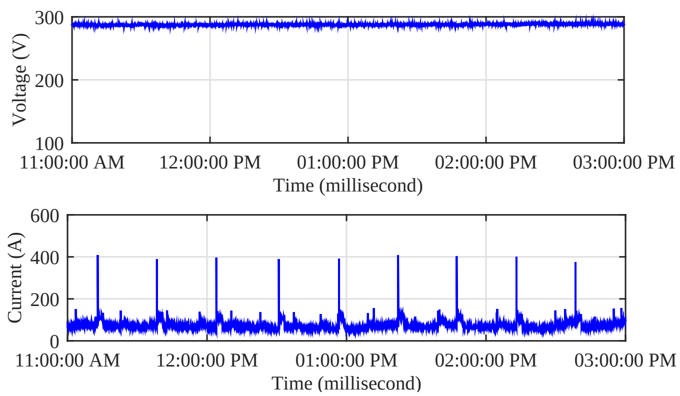

Fig. 3. Single phase voltage and current of Micro-PMU 3 for a four-hours period during a *sunny day*, October 25 2016, one day before the rainy day.

voltage dips during the rainy day with 25%-65% voltage drop, marked by dashed-ellipses in Fig. 2.

The voltage drops could be initiated by a major disturbance like upstream breaker operation or caused by short-circuit event due to surge arrester operation. To an extent of our knowledge, there is no protection system operation reported by crew. Accordingly, and based on the weather data from [26], we can conclude that the captured transient fluctuations in voltage could have been initiated by lightening strikes.

Generally speaking, the induced voltage of a lightning strike will initiate flashover, arcing, and consequently a transient short-circuit, when the surge arresters damp the spike down. The short-circuit current will then flow in the form of an arc, thus, posing a fault in the power system. Next, we provide data driven explanations for the three major voltage dips in Fig. 2, at 11:13:01 AM, 12:44:05 PM, and 12:55:46 PM.

III. Data-Driven Analysis of Lightning-Initiated Contingencies

In this section, the three lightning-induced transient contingencies that we identified at the end of the previous section are analyzed. Our data-driven approach is conducted for all three installed Micro-PMUs so that we can distinguish the local and system-wide events, i.e., in the sense of transmission or sub-transmission levels, followed by per-phase analysis.

A. First Lightning Event

The first event is occurred at 11:13:01 and lasted for about 200 milliseconds. Fig. 4 shows the recorded per-phase voltage and current from the Micro-PMUs. The immediate observation is that the under-study transient event is system-wide, i.e., it is not confined to Substation B and its interconnected PV farm, because Micro-PMU 3 is also seeing the same event.

According to the captured voltage signatures, the voltage drop at Micro-PMUs 1, 2, and 3 are 51%, 56%, and 60%, respectively. As mentioned before, there is no recorded fault in the utility's database during the under-study period of time. Another important observation is that the voltage dip signatures are homologous with lightning-initiated flashover and arcing voltage sags. Consequently, we can conclude that the transient event is indeed system-wide and caused as a result of lightning followed by flashover and arcing on surge arresters, somewhere on the in transmission level or sub-transmission level.

Based on the voltage signatures in Fig. 4, there are two voltage stress periods caused by lightning, from :01.1 to :01.17 and from :01.17 to :01.3. The voltage stresses are high enough to exceed the withstand voltage of insulator and consequently cause flashover. Also, it seems that the magnitude of voltage stress is higher on *phase C* is higher than the other two phases.

Since there exists a transient behaviour in the voltage of the entire RPU's network, i.e., the system-wide voltage dip, there must be current responses to the disturbance. However, the current response of each device highly depends on its own dynamic. For instance, the current signature of Micro-PMU 1, see Fig. 4 (a), shows that there is a three phase surge current in the PV farm, which may or may not cause a reverse power flow in transient period, because we know that in normal operation, power flows from *Substation B* towards the *PV Farm*.

Thus, if there is any possible reserve power flow, it should be detected in relative phase angle difference (RPAD) between Micro-PMU 1 and 2 or the current angle of Micro-PMU 1 should be change 180°. Fig. 5 shows pre-event and post-event current of phase C measured by Micro-PMU 1. Note that, in the rainy day, the downstream loads of PV farm are greater than the generated power. As it can be seen from this figure, current angle changes about 180° which means there could be a reverse power flow from PV farm toward the short-circuited point. Also, the magnitude of current increases as mentioned in Fig. 4. Also, the active power supported by phase C of Micro-PMU 1 is shown in Fig. 6. As expected, there exists a reverse power flow in post-event compared to pre-event.

The above observation on momentary reverse power flow is important because most distribution networks are designed to operate on a unidirectional power flow, i.e., power flows from substation to the end of radial feeder. Accordingly, feeder protection system, e.g., overcurrent protection relay, is designed to trigger based on unidirectional power flow and current. While in the case of possible reverse power flow, feeder protection system may not work properly. Accordingly, the protection

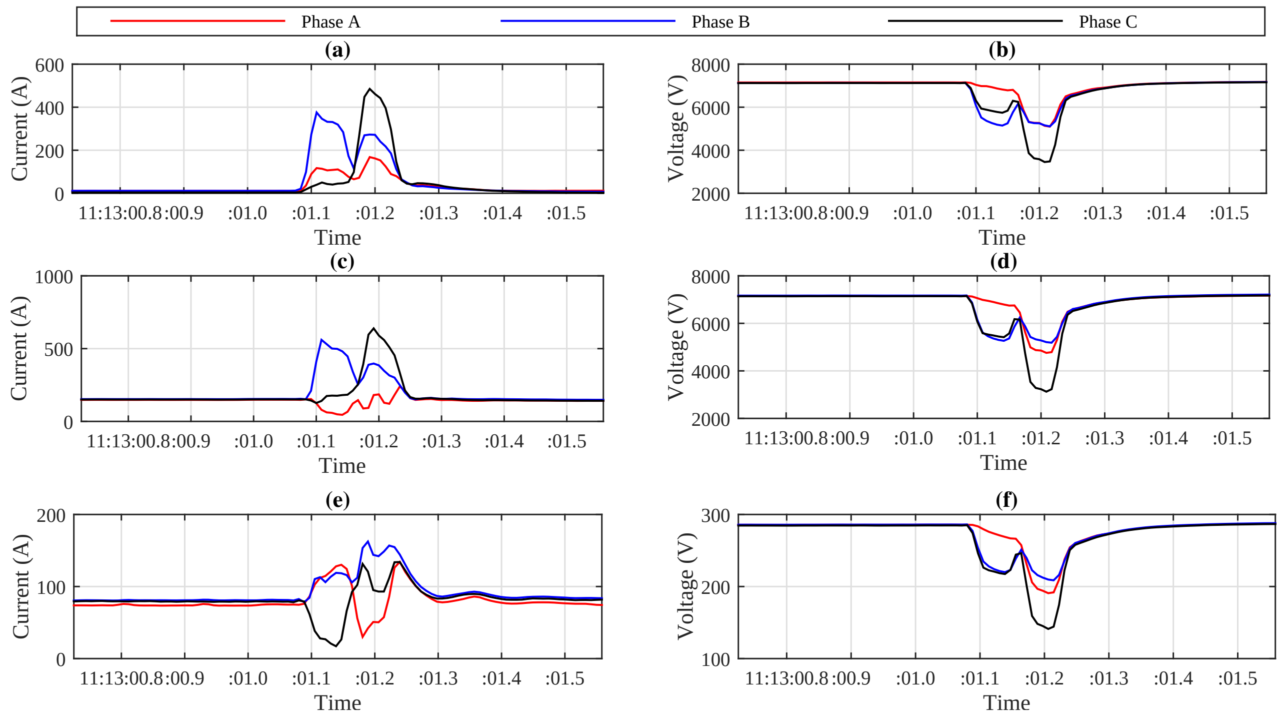

Fig. 4. Three phase voltage and current transients at the first lightening event: (a) and (b) Micro-PMU 1; (c) and (d) Micro-PMU 2; (e) and (f) Micro-PMU 3.

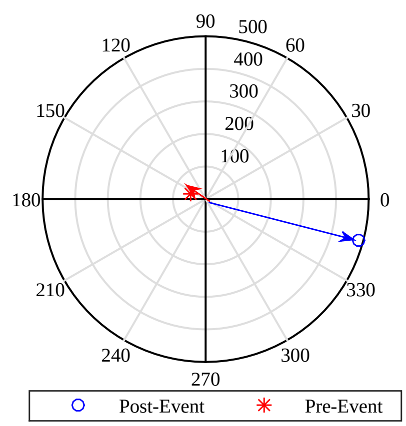

Fig. 5. Post-event and pre-event current phasors at Micro-PMU 1.

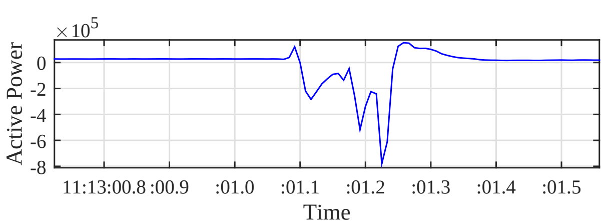

Fig. 6. Active power of phase C measured by Micro-PMU 1.

system should be re-designed based on the possible reverse power flow to ensure the network security and reliability.

B. Second Lightning Event

The second event occurred at 12:44:05 and lasted for about 250 milliseconds. Fig. 7 shows the recorded per-phase voltage and current from Micro-PMUs 2 and 3. Note that, no data was provided for Micro-PMU 1 in this figure. The reason is that Micro-PMU 1 stopped recording right before this second lightning event. Our understanding is that this happened because the PV farm was temporarily disconnected from the grid due to the drop in solar irradiance beyond a threshold. Although, as we will see later in Section III.C, Micro-PMU 1 automatically reset and resumed operation a few minutes later.

Same as in the first event, the under-study transient event is system-wide, because both Micro-PMU 2 and 3 detected it. The amount of drop in voltage magnitudes at these two locations is 65% and 71%, respectively. Again, there is no recorded fault in the utility's database for during the under-study period of time. In addition, the voltage dip signatures are homologous with lightning-initiated flashover and arcing voltage sags. Consequently, we can conclude that the transient event is system-wide and caused as a result of lightning followed by flashover and arcing on surge arresters in transmission level.

Unlike in the first event in Section III.A, the magnitude of voltage stress on all phases are roughly the same, see Fig. 7. Since there exists a transient response in voltage across RPU's network, i.e., the system-wide voltage dip, there would be current response to the disturbance. However, again, the current responses of various devices highly depend on their own dynamic. For instance, the current fluctuations in customer level, Micro-PMU 3, depends on the load type, i.e., capacitive, inductive, or resistive.

Of great interest in the second lightning event is the fact that

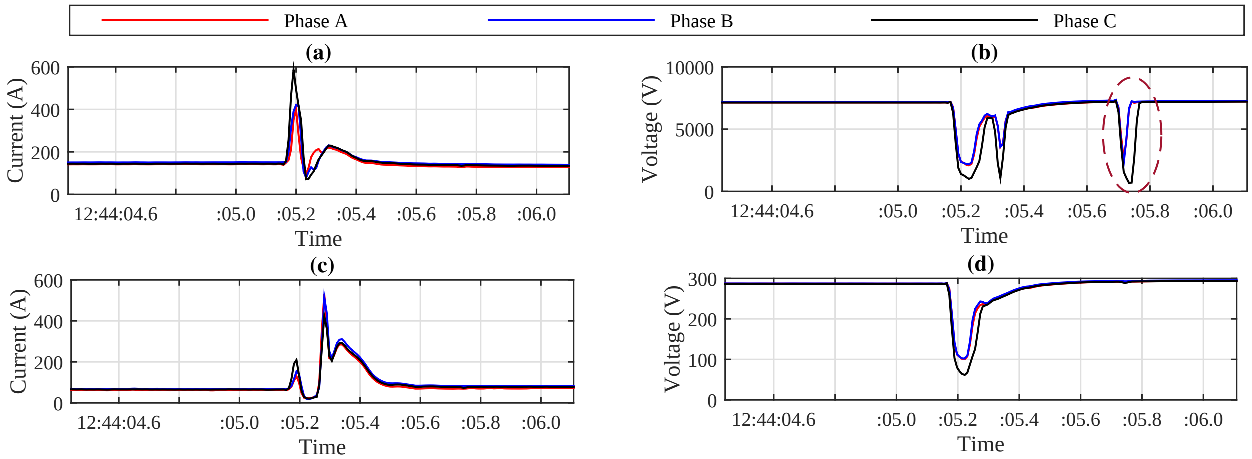

Fig. 7. Three phase voltage and current transients at the second lightening event: (a) and (b) Micro-PMU 2; (c) and (d) Micro-PMU 3.

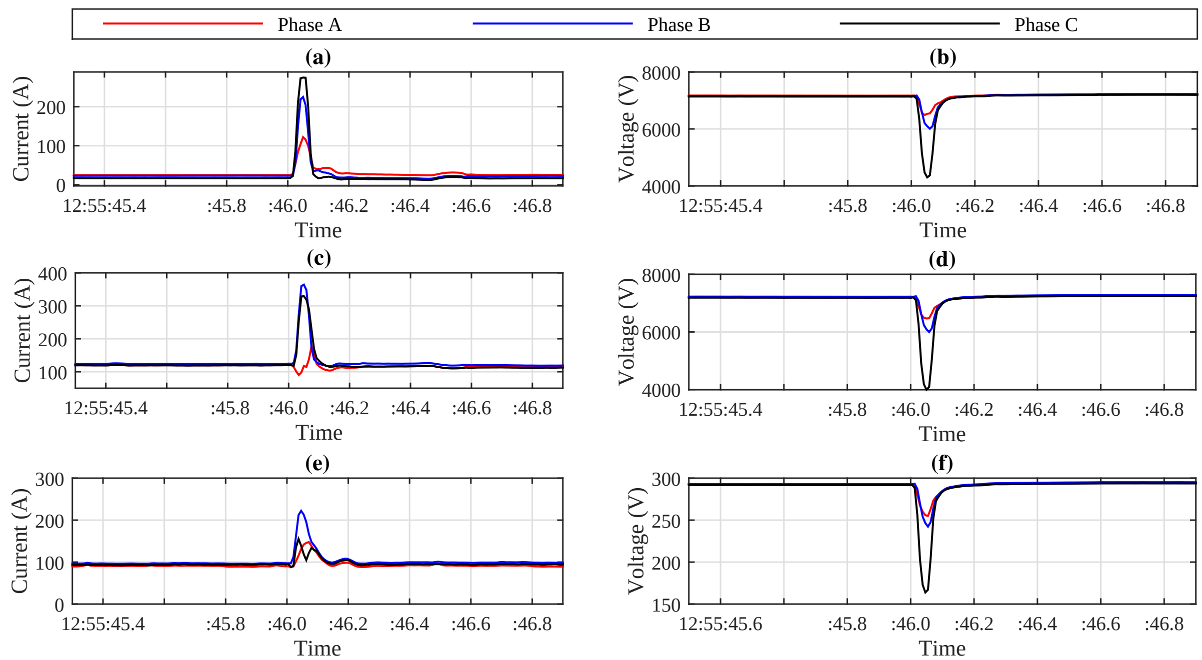

Fig. 8. Three phase voltage and current transients at the third lightening event: (a) and (b) Micro-PMU 1; (c) and (d) Micro-PMU 2; (e) and (f) Micro-PMU 3.

the Micro-PMU 2 shows *another voltage dip* which was *post-event*, marked by a dashed-ellipse in Fig. 7 (b). This event was in fact local to Substation B, *because it had no effect on voltage or current at the outlying meter point*, i.e., on the measurements of Micro-PMU 3. Our conjecture is that there was an issue at the PV farm, possibly losing some of the inverters at the moment of reconnection, which caused the disturbance.

C. Third Lightning Event

The last lightning event occurred at 12:55:46 and lasted for about 150 milliseconds. Fig. 8 shows the recorded per-phase voltage and current from all three Micro-PMUs. Note that, the PV farm has already reconnected and Micro-PMU 1 has already started recording by the time that we reach the third lightning event. Again, the event is system-wide because all three Micro-PMUs have detected it. There exists voltage drop at all three phases; however, the magnitude of voltage drops are different for each phase, e.g., the voltage stress in phase C is more than phase A and B. Therefore, phase C experienced a significant voltage dip. Similar to the first two events, we can conclude that the transient event is caused as a result of lightning, followed by flashover and arcing on surge arresters in transmission level.

In this case, the current response to the disturbance is resembles the surge current in switching on a load. However, the signatures are not the same for different phases.

Interestingly, similar to the first lightning event, the current of phase A at Substation B decreases at the beginning of the event while the PV farm feeds Phase A, see Fig. 4 (c) and Fig. 8 (c). The amount of drop in current depends on the level of PV farm generation and the load of the feeder in phase A.

IV. Conclusions and Future Work

A data-driven experimental analysis is provided to investigate lightening-induced contingencies at a real-life distribution system based on synchronized measurement data from three Micro-PMUs. The core of the analysis is to separately explain the system-wide and local contingencies during three specific lightening events. Of particular interest was to analyze the impact and the response of a 7.5 MW PV farm. Several observations are made and the related causes are discussed. For example, it was shown that during a lightening strike, there can be a reverse power flow from the PV site to the substation due to a transient short-circuit caused by the surge arresters operation. This is despite the fact that during normal operation of the PV farm, i.e., at any time other than during a lightening strike, there is no reverse power flow due to the larger load at the feeder compared to the generation output of the PV. This is important, because most distribution networks have been designed to operate on a unidirectional power flow, and feeder protection system is designed and triggered based on unidirectional power flow. While in the case of reverse power flow caused by lightning event, the protection system should be re-designed to ensure the network security and reliability. These and other similar observations can lead the way to investigate how different distributed energy resources (DERs) could be affected and and/or respond to the lightening-induced contingencies in distribution systems. The results in this paper can also ultimately help with improving *resilience* in active distribution systems with PVs and other DERs.

The analysis in this paper can be extended in several directions. For example, if a large data set is available for a large number of lightning events, then one can conduct a statistical analysis, for example on whether the observed reverse power flow at the PV farm is rare occurrence or rather a trend; and thus a potential reliability risk. Accordingly, one can also look into finding proper remedy options to the observed potential issues, such as re-calibration of the distribution system protection device in presence of major PV and other DER installations.

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