A Data-Driven Analysis of Capacitor Bank Operation at a Distribution Feeder Using Micro-PMU Data

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***Abstract*—In this paper, we conduct a data-driven experimental analysis on capacitor bank switching event at a distribution grid in Riverside, CA using data from two distribution level phasor measurement units, a.k.a, μPMUs. Of particular interest was to detect the capacitor bank switching events based on feeder-level and load-level μPMUs and thus eliminating the need to install separate sensors for the switched capacitor banks. In addition, the operational parameters of capacitor bank is investigated. Moreover, the dynamic effects of capacitor bank switching events is also considered through voltage and current synchrophasor data. This paper takes a first step in using μPMU data to conducting a detailed analysis of how different voltage-levels are affected by capacitor bank switching events in distribution systems.**

I. INTRODUCTION

In the context of distribution system and the load it serves, utilities seek to keep the overall power factor close to 1, or within its 5%, for optimal network efficiency and manageable voltage profiles with respect to the operational constraints. Reactive power regulation methods are employed by utilities to compensate demanded reactive power, and bring the power factor close to optimal values, by using equipment which provides local reactive power (VAR) generation at distribution level. Capacitor bank installation is an efficient approach to achieve Volt-VAR control. Hence, there is an ongoing growth in capacitor bank deployment at distribution level to improve voltage profile, decrease losses and improve power factors.

Fixed capacitor banks are typically used to improve the power factor of individual inductive loads, such as motors, or a group of loads that have a relatively constant demand for reactive power (VAR). In contrast, switched capacitor banks are connected to the grid based on some predetermined operational objectives. Accordingly, switched capacitor banks are often equipped by a controller which sends the closing and tripping commands to a circuit breaker when the predetermined criterion is meet. Even though the automatic capacitor banks typically operate their switched on and off events properly through the Volt-VAR controller, the system operator often does not have any insight regarding the exact status of the capacitor banks due to lack of useful state measurement.

The identification of capacitor banks switching is useful. From operation point of view, some power-factor based identification applications, including network reconfiguration, service restoration, Volt-VAR control, fault detection and location, peak and loss reduction, in distribution level highly depend on the capacitor banks status. Also, switching of capacitor banks leads to high magnitude and high frequency transient disturbances. These disturbances in power systems may damage key equipment and potentially have impact on system reliability, by causing anomalies and unplanned Distributed Energy Resource (DER) trips. Thus, operators desire useful monitoring of capacitor banks for optimal network operation.

Generally speaking, the capacitor bank switching could be identified by employing specific sensors which monitor the units in a real-time manner, which is not economically justifiable due to increasing growth in small-scale switched capacitor banks. On the other hand, there has been significant research and development progress in distribution system monitoring and event detection, for example distribution-level phasor measurement units, i.e., μPMUs [1], and advanced line current sensors. However, these potential options should be investigated in practice to see whether the data collected by these sensors, whose primary application is not capacitor bank monitoring, are capable to identify the operational parameters of capacitor banks as a by product; thus eliminating the need to deploy individual capacitor banks sensors.

Several efforts in the literature investigate the capacitor bank switching events. The effect of switching transmission capacitor banks on phase-to-phase voltages and consumer-end distribution capacitors is studied in [2], [3]. Also in [4], the authors investigate interaction of capacitor bank in the utility system with the failure of a drive system. Real evaluation of impact of capacitor bank switching events, requires a voltage and current view prior to the transient and subsequent switching action. In [5], the transient treatment of capacitor bank voltage and current is during switching action only. Also, the authors in [6], [7] consider key parameters that can determine the transient of inrush current caused by switching of capacitor banks.

Apart from considering the effect of capacitor bank switching on the system, there is lack of investigation regarding useful capacitor bank monitoring in tandem with other analytics. In [8], [9], the authors discuss control schemes using coordinated measurements and communications between field devices. In

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this regard coordination of the control actions of the voltage regulator and capacitor results in more effective Volt/VAR control. More specifically, [10] reported the usage of μPMU to solely detect the capacitor events via considering the instantaneous changes in the reactive power demand. In this regard, reactive power average is calculated every second, so the capacitor bank changes can detected in a short time. In this regard, the analysis in [10] did not move on to use the key synchronization and high sampling rate properties of μPMUs to possibly go beyond only detecting a capacitor event.

This paper aims to propose a novel data-driven approach to use experimental distribution-level voltage and current synchrophasor data, on three phases, to identify the operational parameters of the switched capacitor bank with no need to install separate asset sensors. We analyze the voltage and current synchrophasor data that is collected from a real distribution system in Riverside, CA during a 24 hours period. The steady-state analysis is conducted to answer the following question: would the data collected by μPMUs allow identifying the operational parameters of the switched capacitor bank, such as the per-phase reactive power support and its comparison with the switched capacitor banks nameplate parameters? Also, the transient and dynamic analysis aims to answer the following question: what are the dynamic effects of capacitor bank switching events on feeder-level and load-level voltage and current synchrophasor data, on three phases? This is a novel contribution because it studies fast-scale analysis of capacitor bank switching events, for both impact, performance verification and parameterization at distribution level using μPMUs.

II. UNDER-STUDY REAL-LIFE TEST SYSTEM

In order to identify the operational parameters of the capacitor bank, a real-life distribution feeder is considered in Riverside, CA. The single line diagram of the under-study feeder is shown in Fig. 1. This feeder is operated by Riverside Public Utilities (RPU), see *http://www.riversideca.gov*. The point of common coupling between the sub-transmission system and the under-study feeder is marked as *Substation*. The under-study feeder includes one three-phase fixed capacitor bank rated at 600 kVAR, which is always connected, as well as a three-phase switched capacitor bank rated at 900 kVAR. The switched capacitor bank is switched by a vacuum circuit breaker and controlled by a *Volt-VAR controller*, i.e., the capacitor bank is *switched-on*, when any phase of the bus voltage is below the low-voltage override threshold. Conversely, the controller *trips* any energized capacitor banks when any phase of the bus voltage is above the high-voltage override threshold. The rated Volt-VAR controller time delay is set to be 300 seconds. As it can be seen from Fig. 1, transient limiting inductors (TLIs) are installed in series with each phase of the switched capacitor bank. The TLIs limit transient currents during switching events or faults.

Neither the fixed nor the switched capacitor bank are monitored, i.e., they are not equipped with any sensors. Accordingly, in principle, RPU is not aware of the following: 1) how these capacitor banks operate on a daily basis; 2) how the operational parameters might be different from their rated values, possibly due to wear and tear over time. However, the under-study feeder where these two capacitor banks are located is equipped by two distribution-level PMUs, a.k.a, μPMUs. One μPMU is located at the substation and another μPMU is located at a secondary side of a three-phase load transformer that is located about 400 yards from the switched capacitor bank. The μPMUs were not installed with the intention of monitoring the operation of the capacitor banks, but more in general for monitoring the feeder performance overall, and as such are not optimally placed. The key question we seek to answer with this paper is: Would the data collected by μPMUs allow identifying the operational parameters of the switched capacitor bank, and thus eliminating the need to install separate sensors for the switched capacitor bank?

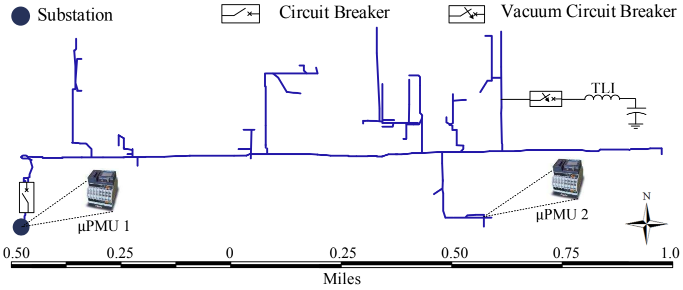

Fig. 1. Test system is a real-life feeder in Riverside, CA, which includes a switched capacitor bank and is equipped with two μPMUs.

The installed μPMUs report four fundamental measurements on three phases, i.e., in total there are 12 measurement channels: 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. We hypothesize that this high sampling rate, together with direct access to voltage and current data at different yet time synchronized locations, could allow us identify the operation of the switched capacitor bank within a data-driven framework. Our study involves both stead-state, i.e., slow time-scale, and dynamic, i.e., fast time-scale, analysis.

III. STEADY-STATE ANALYSIS

The focus in this paper is on the μPMUs data on one day. Note that, the two μPMUs generate 248,832,000 data points every day. The recorded single-phase voltage magnitudes and current magnitudes are shown in Fig. 2. Generally speaking, the fluctuations in this figure are statistically similar during period of a day, with no significant observation on the potential effect of capacitor switching events. A similar conclusion can be made by plotting voltage phase angles and current phase angles as well as by plotting voltage phase differences. Note that, the latter two cases are not shown here due to space limit.

A. Analysis of Data from μPMU 1

Fig. 3 shows the recorded three-phase power factor and reactive power at *Substation*, measured by μPMU 1. The immediate observation from this figure is that there exist drastic instantaneous changes in power factor and reactive power.

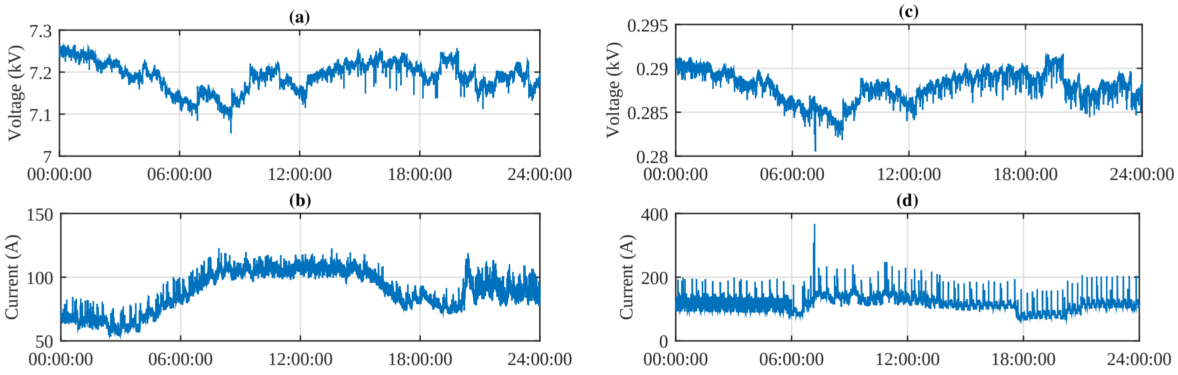

Fig. 2. Single phase voltage magnitude and current magnitude on one day measured by: (a) and (b) μPMU 1, (c) and (d) μPMU 2.

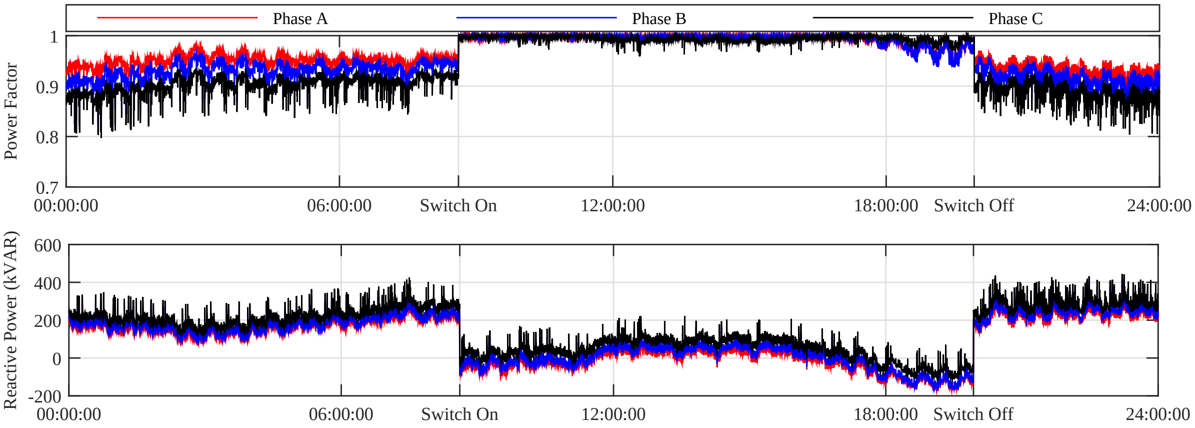

Fig. 3. Power factor and reactive power at *substation*: (a) Power factor, (b) Reactive power.

Based on Fig. 3(a), at 08:36:45 the power factor increases by 10% in all phases and lasts for almost 11 hours, till 19:55:54. Possible scenarios for power factor fluctuation at 08:36:45 are: 1) switching off a large inductive load, or 2) switching on a large capacitor bank. Likewise, the fluctuation at 19:55:54 could be the effect of: 1) switching on a large inductive load, or 2) switching off a large capacitor bank. To the extent of our knowledge, there is such large inductive load in the under-study network. Therefore, both events should be due to the operation of the switchable capacitor bank.

We can confirm the above conclusion by examining the results on reactive power in Fig. 3(b). From this figure, the *per-phase* reactive power change at both events is about 300 kVAR, which is equal to the installed 900 / 3 = 300 kVAR per-phase switched capacitor bank. From now on, we refer to 08:36:45 as *switched-on time* and 19:55:54 as *switched-off* time.

According to the steady-state analysis on per-phase reactive power, the exact injected reactive power by capacitors at phase A, B, and C are 291, 294, and 288, respectively. Therefore, the operational parameters of the capacitor banks are slightly different from their rated values, possibly due to error in voltage and current measurements, 0.3% and 1.2% respectively, or due to wear and tear over time. Importantly, the impact of degradation appears to be somewhat imbalanced across the three phases.

Another observation in Fig. 3(b) is that quite often there exist *reverse* reactive power flows from the under-study feeder toward the sub-transmission network. This may not be desirable and may suggest the need to possibly update the operational parameters of the switched capacitor bank, possibly in coordination with adjusting the tap changers inside the substation.

B. Analysis of Data from μPMU 2

As for the measurements at μPMU 2, the operation of the capacitor bank did not demonstrate any visible impact on the power factor and reactive power measurements as far as steady-state analysis is concerned. This is not surprising because μPMU 2 is dedicated to make voltage and current phasor measurements at a particular load point, even though such load is in a close-by location to the capacitor bank. Note that, the related figures are not shown here due to the space limitation.

C. Possible Applications of Results

The above analysis may find applications in operating the distribution system, e.g., with respect to the following aspects:

- Network reconfiguration;
- Service restoration;
- Volt/VAR control;
- Fault detection and location;
- Peak and loss reduction;
- Load balancing;
- Energy management.

For instance, consider the first item, i.e., suppose *service restoration through reconfiguration* is called upon due to fault occurrence at a feeder that is coupled with the under-study feeder. In this scenario, the under-study network should energize transferred loads from the faulted feeder. The decision maker requires the status of the unmeasured capacitor bank to check the feasibility of the post-reconfiguration operating point, i.e., feeder constraints such as voltage threshold. In addition, if force-switching of capacitor bank is not possible, the power factor estimation based on previous data provides information on feasibility or infeasibility of reconfiguration in next hours.

IV. TRANSIENT AND DYNAMIC ANALYSIS

In this section, the effect of capacitor bank switching events on the under-study feeder are studied in fast time-scale.

A. Analysis based on an RLC Model

To facilitate the analysis in this section, we consider an illustrative RLC circuit, shown in Fig. 4. Suppose the capacitor bank has initial voltage $v_c(0^-)$ and then it is connected to the circuit at time $t = 0$, which is the switch on time in our context. The differential equation of the RLC circuit is obtained as:

$$\frac{d^2i(t)}{dt^2} + \frac{R}{L}\frac{di(t)}{dt} + \frac{1}{LC}i(t) = \frac{\omega}{L}cos(\omega t + \phi), \tag{1}$$

The solution of above differential equation with respect to the initial condition is obtained as:

$$i(t) = \gamma_1 e^{-t/\tau_1} + \gamma_2 e^{-t/\tau_2} + \gamma_3 cos(\omega t + \varphi). \tag{2}$$

The first two terms indicate the transient current due to the capacitor switching event and the last term is the steady-state current, where the coefficients depend on the initial condition, source phase angle at switching event, and circuit parameters, i.e., $\gamma_i := \Gamma_i\left(v_c(0^-), \phi, \omega, R, L, C\right)$, where Γ_i is a function.

We can conclude that the transient current of the under-study feeder in response to a *switch on* event of the switched capacitor bank depends on both the *initial condition* and the *phase angle* at the moment of switching. Typically, in capacitor bank switch on event, the circuit breaker is closed when the source voltage is nearly equal to zero. However, the zero crossing of phases A, B, and C occur at 0°, 60°, and 120°, relative to the three-phase voltage with no phase shifting. Therefore, when the circuit breaker is *not* equipped with pre-insertion resistors, there will be current transients in at least two phases.

Similarly, we can also conclude that the transient current of the under-study feeder in response to a *switched off* event of the switched capacitor bank depends only on *phase angle* at the moment of switching. Unlike in switch on switching, in switch off event, the circuit breaker is closed in zero-current. Accordingly, due to 120° phase shift between phases, there will be current transients in at least two phases, when the circuit breaker is *not* equipped with pre-insertion resistors.

B. Analysis of Data from μPMU 1

Fig. 5 shows the transient response of the under-study feeder during the capacitor bank's *switch on* event. As mentioned in Section III and shown Fig. 5(a), the feeder power factor at *switch on* event increases by 10%. Also, Fig. 5(b) represents pre-switching and post-switching reactive power flow on the under-study feeder. Voltage transient of the under-study feeder is shown in Fig. 5(c). As expected, the voltage magnitude is increased due to reactive power compensation by the switched capacitor bank. However, there is no significant changes in voltage transient, possibly due to available TLIs or insufficient sampling rate. The three-phase transient current is shown in Fig. 5(d). While there is no significant transient change in phase A, the current of phases B and C include an *overshoot* and an *undershoot*, respectively. Therefore, we can conclude that the capacitor bank is switched on at zero crossing of phase A.

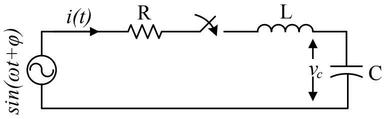

Fig. 4. Illustrative simple RLC circuit to study capacitor switching events.

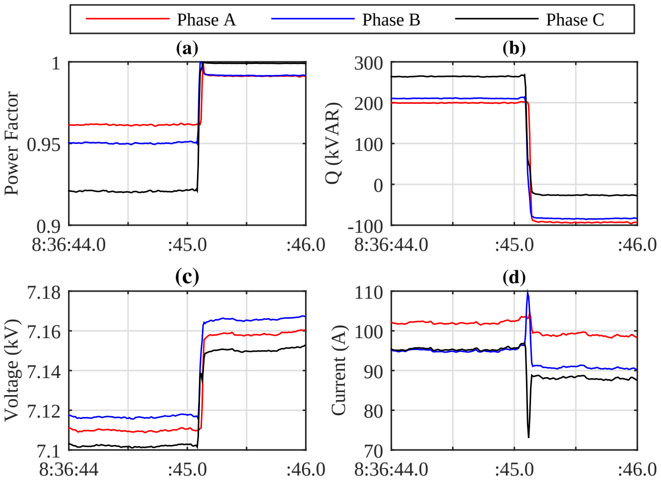

Fig. 5. Under-study feeder dynamic response to capacitor *switch on* event: (a) Power factor, (b) Reactive power, (c) Voltage magnitude, (d) Current magnitude.

Fig. 6 shows the transient response of the under-study feeder during the capacitor bank's *switch off* event. The changes in power factor, reactive power, and voltage magnitude are as expected, see Fig. 6(a), (b), and (c). However, in this event, there exists a transient current in phase A and B, there is no significant transient change in phase C. Accordingly, the capacitor bank is switched off at zero crossing of phase C.

C. Analysis of Data from μPMU 2

Fig. 6 shows the transient response of the load where μPMU 2 is located during the capacitor bank's switching events, both on and off. As it can be seen from Fig. 7(a) and (c), voltage magnitude of the load follows the changes in voltage magnitude in substation. Current magnitude depends on changes in voltage when there is no changes in the overall active and reactive power at downstream customers, see Fig. 7 (b) and (d).

Fig. 8 shows the relative phase angle difference (RPAD), which is calculated based on the voltage phasors, between the two μPMUs. In the switch on event, see Fig. 8(a), the RPAD *increases* due to the reverse reactive power flow and also the fact that in distribution network, we have $R \gg X$. In contrast, in the switch off event, the RPAD *decreases* as shown in Fig.

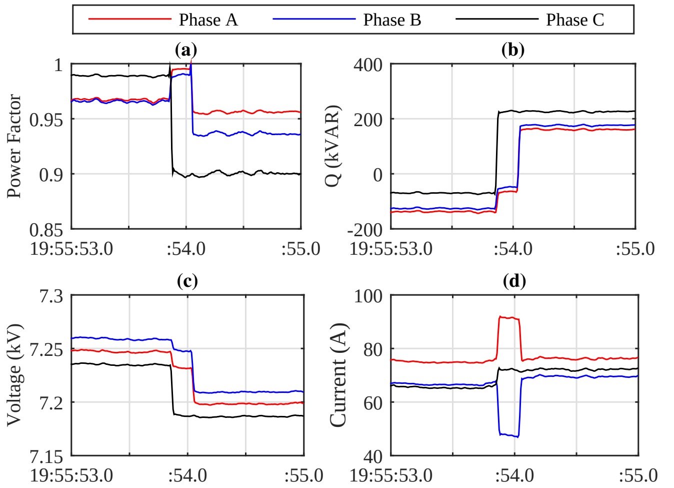

Fig. 6. Under-study feeder dynamic response to capacitor *switch off* event: (a) Power factor, (b) Reactive power, (c) Voltage magnitude, (d) Current magnitude.

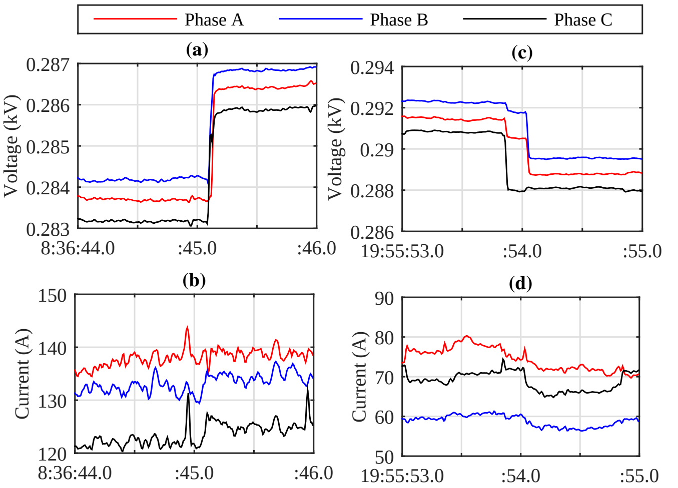

Fig. 7. Load level dynamic response to capacitor switching event: (a) Voltage transient at *switch on* event, (b) Current transient at *switch on* event, (c) Voltage magnitude at *switch off* event, (d) Current magnitude at *switch off* event.

8(b). The exact explanation for these contrasting observations is not clear to the authors yet. Addressing this issue is difficult at this point due to at least two reasons: First, in general, we still lack a clear understanding of how RPAD should be interpreted at distribution level. This is different from the interpretation of RPAD in relationship with inter-area oscillations at transmission level. Second, due to the small RPAD values at distribution level, maintaining high measurement accuracy is still a major instrumentation challenge. Therefore, it is hard to say whether the above contrasting observations have engineering explanations, or they are just due to measurement noise and possible significant aliasing effects caused by the presence of higher swing frequencies at distribution level.

V. CONCLUSIONS

A data-driven experimental analysis is provided to investigate the operational parameters of capacitor banks switching events at a real-life distribution system based on data from two μPMUs. According to feeder level μPMU, *capacitor bank switching events*, *operational parameters of capacitor banks*, as well as *direction of reactive power flow* are observed. In the

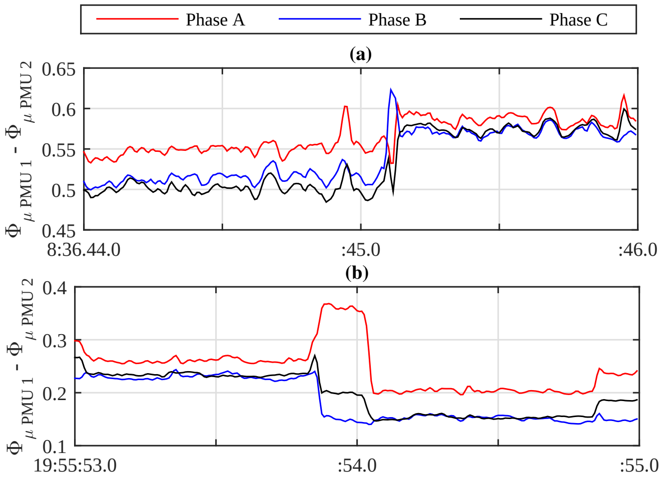

Fig. 8. Relative phase angle difference between μPMU 2 and μPMU 1: (a) *switch on* event and (b) *switch off* event.

fast-time scale analysis, the effects of capacitor bank switching events on the under-study real-life feeder are studied. The results show that the transient current of under-study feeder in response to *switch on* event of the switched capacitor bank depends on both *initial condition* and *phase angle* at the moment of switching. Accordingly, in three-phase capacitor bank *switch on* event both *overshoot* and *undershoot* in phase currents are possible and observed in actual real-life data. While, in three-phase capacitor bank *switch off* event both *overshoot* and *undershoot* in phase currents are possible and observed in actual real-life data.

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