Fast Locating of a Switched Capacitor in a Power System using Slope-based Method

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***Abstract*—This paper introduces a fast method, using the slope based technique, to locate a switched shunt capacitor with respect to the monitoring points of a power system. The method locates the capacitor based on the slope signs of the voltage/current space vectors at a switching instant. The slope signs at a monitoring point determine that the capacitor is located upside or downside of the monitoring point considering the power flow direction as a reference. The paper compares the advantages of the proposed method based on space vectors with the conventional method which uses the phase quantities and deals with an algebraic algorithm for the realization of the method. The capabilities of the proposed method are evaluated via time-domain simulation of a study system with two utility capacitor banks. The time-domain simulations performed in PSCAD/EMTDC show that the method successfully locates the capacitor in presence of limited measurement noises, harmonics, and under unbalance conditions.**

***Index Terms*—Transients Source Locating, Switched Shunt Capacitor, Power Quality, Capacitor Locating, Slope base Method, Fast Locating Algorithm.**

I. INTRODUCTION

Switching of shunt capacitor banks commonly occur in a power system causing low frequency transients in the system. These transients can adversely impact on the power system normal operation by activating the system's protections. Also, the transients degrade the quality of power due to causing undesirable harmonic resonances [1]-[4]. The adverse impacts of transients will be more significant in small and/or isolated power systems such as micro-grids due to less amount of inertia available in small systems. Therefore, to mitigate the effects of transients and as a first step, it is necessary to identify the transients source and its location as fast as possible. This paper deals with a fast method for locating a switched shunt capacitor in a power system based on the slope sings of voltage/current space vectors at the system monitoring points.

Several techniques for locating a switched shunt capacitor have been proposed and investigated [5]-[7] which mainly work based on processing of the measured voltage/current waveforms at the system monitoring points. Most of these techniques collect data and start processing when the transients are over. The slope based technique [7], however, is the only method that can determine the location of a switched capacitor merely based on the slopes of voltage/current waveforms at a switching instant. Thus, the slope based technique can be inherently a very fast locating method. However, utilization of this method requires a networked communication infrastructure for interconnection of the monitoring point devices. Therefore, the actual locating time and accuracy of the slope based method will be limited by performance of the local interconnection network in a zone. This paper, by using the idea of conventional slope based technique, presents an improved method which uses the magnitude of space vectors of the voltage/current instead of phase voltage/current quantities.

The amplitudes of three phase voltages (currents) transients highly depend on a switching instant. However, as the magnitude of a space vector is less dependent to the switching instant, using the space vector in the slope based method can enhance the accuracy and robustness of the method. The paper presents the statement and a realization method of the slope-based method in terms of voltage/current space vectors. Then, the performance of the method will be verified via time-domain simulations of a study system under different conditions including harmonics, measurement noises, and unbalanced conditions.

II. STATEMENT AND REALIZATION METHOD OF THE SLOPE BASED TECHNIQUE

Considering the schematic of a power system as shown on Fig. 1, a capacitor bank is defined *down-stream* from the monitoring point M_1 if the real power flows toward the capacitor. Similarly, the capacitor bank is defined *up-stream* from M_2 if the flow of real power is outward from the capacitor bank. The slope based method determines the location of a capacitor bank using the slope signs of voltage and current waveforms at a switching instant. These slopes are given by

$$S_v = \frac{v(t_0 + T_s) - v(t_0)}{T_s}, \tag{1}$$

$$S_i = \frac{i(t_0 + T_s) - i(t_0)}{T_s}, \tag{2}$$

where t_0 is the sampling time in which the switching occurs and T_s is the sampling period of a monitoring device. v and i denote the phase voltage and current quantities, respectively. The slope based technique states that the capacitor bank is up-stream (down-stream) from a monitoring point if the sign of S_V/S_i is negative (positive) [7]. An intuitive proof of this

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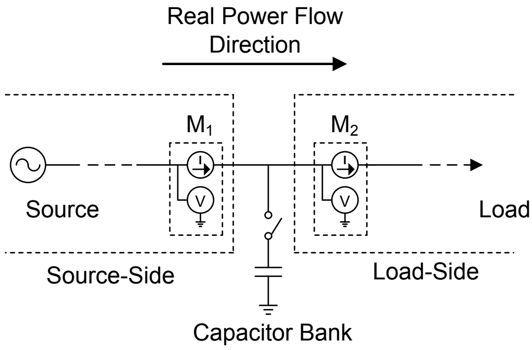

Fig. 1. Switched capacitor bank is down-stream (up-stream) from M_1 (M_2).

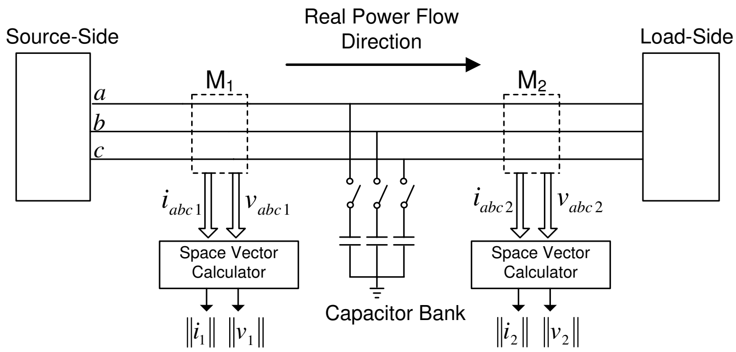

Fig. 2. Schematic of the space vector slope based method for locating a switched capacitor.

statement can be explained based on Fig. 1 in which we assume the initial charge of the capacitor bank is zero. At the switching instant, there is a sudden decrease in the voltage level due to continuity of the capacitor voltage. Thus, both monitoring points M_1 and M_2 record negative slopes for the measured voltages. There is also an inrush current to charge the capacitor bank along the direction of the real power flow. Thus, on Fig. 1, the charging of the capacitor bank increases (decreases) the current at M_1 (M_2) which means a positive (negative) slope of the current at M_1 (M_2). Hence, the voltage and current slopes at M_1 have opposite signs while they have the same signs at M_2 which are consistent with the statement of slope based method. We extend the idea of slope based method by using the magnitude of a voltage (current) space vector instead of phase quantities. Therefore, the slope based method can be re-introduced in terms of the space vector magnitudes by substituting S_v and S_i with the following expressions:

$$S_v = \frac{||\overrightarrow{v}(t_0+T_s)|| - ||\overrightarrow{v}(t_0)||}{T_s}, \tag{3}$$

$$S_i = \frac{||\overrightarrow{i}(t_0+T_s)|| - ||\overrightarrow{i}(t_0)||}{T_s}, \tag{4}$$

where $||\overrightarrow{\cdot}||$ represents the magnitude of a space vector. The space vector of a three phase quantity, f_{abc}, can be obtained from $||f|| = \sqrt{f_q^2 + f_d^2 + f_0^2}$ where f_{qd0} are components of f_{abc} in a $qd0$ reference frame with an arbitrary frequency [8]. The advantage of using $||v||$ and $||i||$ instead of phase quantities is that the space vector quantities encounter the information of all three phases at the switching instant. If the method is established based on phase quantities, at the switching instants close to the zero crossing of the phase waveforms, the magnitude of the phase quantities are small. Therefore, harmonics and measurement noises can be comparable with the phase quantities which can cause erroneous results. The magnitude of a voltage (current) space vector represents variations of the three phase voltages (currents) with a single quantity and is less dependent of a switching instant. Therefore, using space vectors increase the accuracy and robustness of the algorithm against the measurement noises and harmonics. Figure 2 shows a realization scheme for the slope based method using space vectors. The measured abc voltages and currents are introduced to a space vector calculator which provides the magnitude of the voltages and currents vectors. The reference for calculation of $qd0$ components of the vectors can be arbitrary selected the same as system frequency (synchronous frame) or zero ($\alpha\beta$ frame).

III. Verification of the Method

The performance of the slope based method using space vector method was verified through time-domain simulation of the radial study system shown in Fig. 3. The system consists of a source, loads, two capacitor banks, and distribution lines and its parameters are given in [9]. The locating algorithm was test for capacitor switching scenarios under balanced and unbalance conditions. Also, the effect of measurement noises and harmonics on the the performance of the algorithm was investigated.

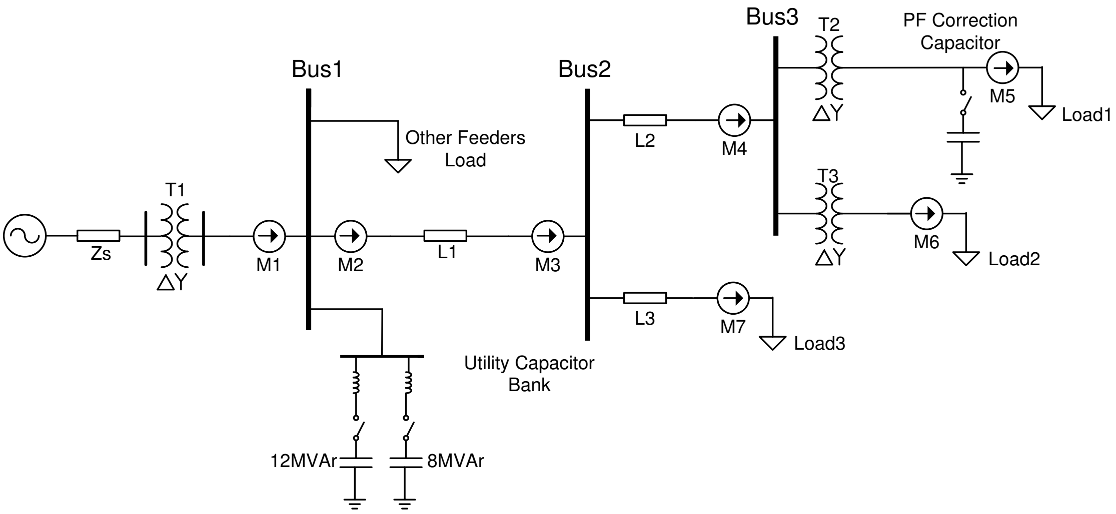

Fig. 3. Schematic diagrams of the study system

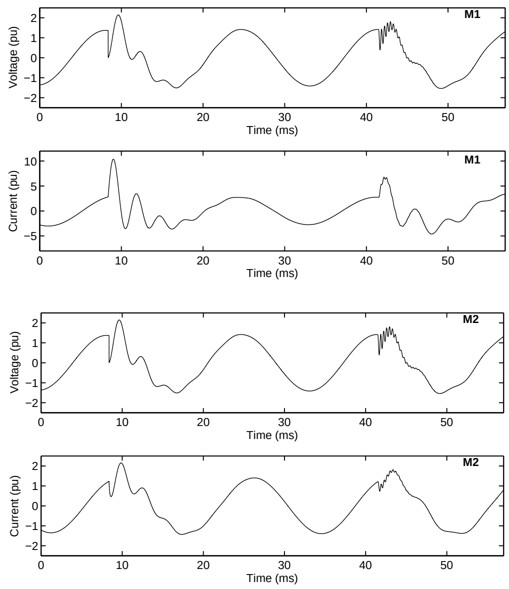

Fig. 4. Voltage and current waveforms of the study system at monitoring points M_1 and M_2 for phase a for single and back-to-back switching.

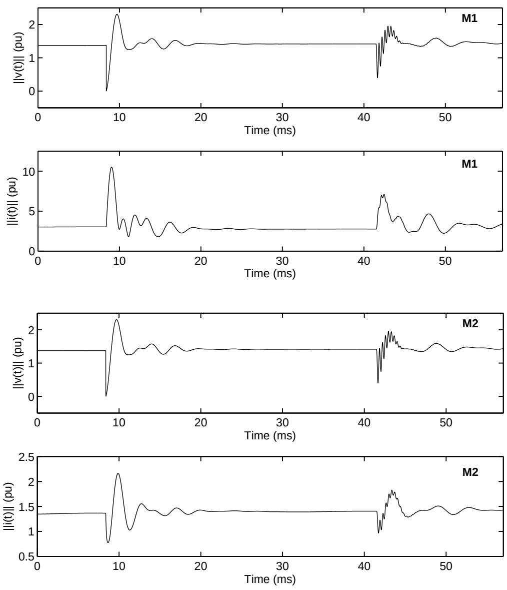

Fig. 5. Voltage and current space vector of the study system at monitoring points M_1 and M_2.

A. Capacitor Switching

Figure 4 shows the monitored voltages and currents at M_1 and M_2 based on time-domain simulation of the study system in PSCAD/EMTDC environment. The first switching of capacitors occurred at $t = 8\ ms$ to model the single capacitor switching scenario via energizing the $12\ MVAr$ capacitor bank. The capacitor had no initial charge and the switching time was selected at the voltage peak value to consider the maximum transient. The second switching occurred at $t = 42\ ms$ corresponding to the energization of the $8\ MVAr$ capacitor while the $12\ MVAr$ capacitor was in service. This scenario represents the behavior of the system subsequent to a back-to-back switching event. The initial inrush currents of the capacitors which were successively connected in a back-to-back scenario were limited by using series inductors with impedances typically less than 1% of the capacitors reactances [10]. As Fig. 4 shows the back-to-back switching transients include high frequency transients due to resonance between the limiter inductor and the capacitors. Such a high frequency transient does not occur in the single capacitor switching since the first capacitor only interacts with the system with a large inductance. The magnitudes of the space vector voltages and currents at the monitoring points, M_1 and M_2, are shown in Fig. 5. Slopes at the transient instants on Fig. 5 are consistent with those obtained for phase a on Fig. 4. Thus, the space vector locating method correctly detects the location of the capacitor bank with respect to the monitoring points. The high frequency oscilla-

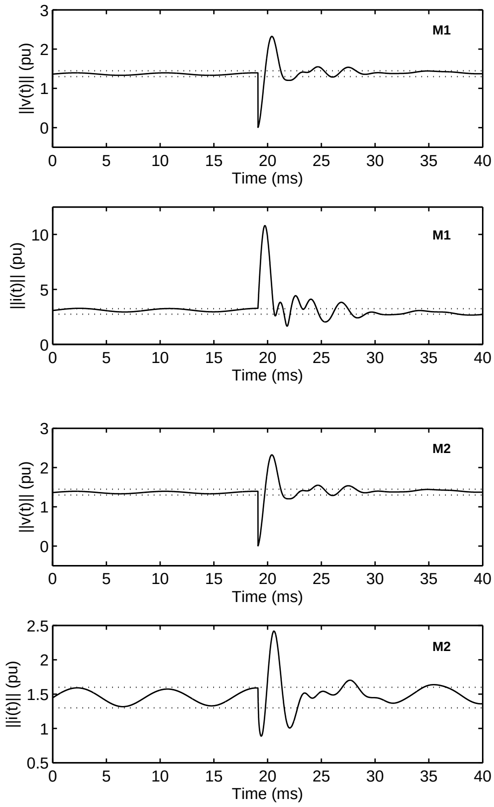

Fig. 6. The magnitude of space vectors under unbalanced source and load condition.

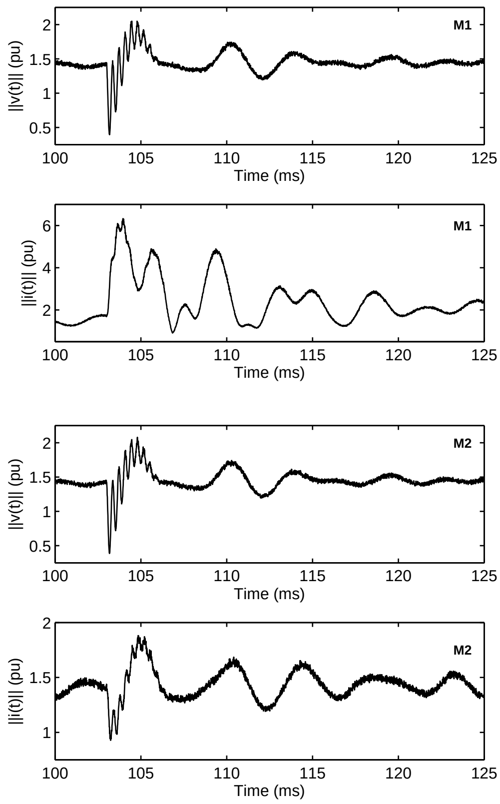

Fig. 7. Effects of harmonic and noise on the magnitude of space vectors ($THD = 10\%$ and $S/N = 15\ dB$).

tions observed in the back-to-back switching quantities, dictate a limit for the minimum sampling frequency in the slope based locating methods (for both phase and space vector methods). That is, the sampling frequency must be well-above the highest transient frequency (here the resonance frequency at the back-to-back capacitor switching that can be in kilohertz [1]) to avoid erroneous calculation of the slope at a switching instant.

B. Unbalanced Conditions

To investigate the effects of unbalanced grid voltage on the space vector locating method, the amplitude of phase a in the voltage source was kept constant at $69/\sqrt{3}\ kV$ (rms, line-to-ground) as a reference. Then, the amplitudes of phases b and c were changed by $+3\%$ and -5% with respect to that of phase a amplitude, respectively. The effect of an unbalanced load on the locating method was simulated by adding a $1\ MW$ resistive load to phase b in parallel with the balanced $Load1$ in Fig. 3. The unbalance source and load cause an unbalance condition in the system with the overall voltage imbalance degree of about 2.5% at the monitoring points M_1 and M_2 (The degree of voltage imbalance is defined as $(|V_n|/|V_p|) \times 100$ where V_n and V_p represent the negative and positive voltage sequence amplitudes, respectively).

Figure 6 shows the magnitudes of the voltage and current space vectors under the unbalanced load and source conditions. As Fig. 6 shows, the magnitude of current vector before the transient instant is not constant and is affected more than the voltage vector magnitude under an unbalanced load condition. However, the slopes of space vector quantities have the same signs as those obtained for the balanced condition in Figs. 5. Thus, the space vector locating method correctly works under load and source unbalanced conditions.

C. Harmonic and Measurement Noise

The effects of harmonics and measurement noise on the locating method were investigated by adding noise to the measured signals and by injecting harmonics to one of the loads. To consider the noise, we used $x_n = x + k_n \alpha x$ where x represents the recorded voltage or current quantities (without noise) at the monitoring points M_1 or M_2, α is a randomly generated number between -1 to 1, and k_n signifies Signal-to-Noise ratio S/N, ($k_n = 0.031$ corresponding to $S/N = 15\ dB$). In simulations, the noisy signal x_n, instead of x, was used to calculate voltage and current space vectors.

To consider the effect of harmonics, two current sources (3-phase) were connected in parallel with $Load3$ in the study system, Fig. 3. The frequencies of the current sources were selected at 300 and 420 Hz, corresponding to the 5th and the 7th harmonics. The amplitude of the 5th and 7th harmonic current sources were arbitrarily selected as $I_5 = 2I_7 = 14.3\ A$ to simulate a load with the total harmonic distortion (THD) of 10%. Figure 7 shows the magnitudes of voltage and current space vectors corresponding to the back to back capacitor switching in presence of harmonics and measurement noises with $S/N = 15\ dB$ (*i.e.* noise amplitude is about 3% signal).

As Fig. 7 shows, the slopes of voltages and currents at monitoring points M_1 and M_2 are consistent with those obtained from the back to back capacitor switching of Fig. 5. Thus the space vector method can correctly determine the location of a switched capacitor in a noisy and harmonically polluted environments as well. However, Fig. 7 reveals that an upper limit for sampling frequency at the monitoring points should be considered, since a noise signal includes high and low frequency components in a broad frequency range. If the sampling frequency at the monitoring point is sufficiently increased, the effect of noise in variations of a measured amplitude can be dominant at the beginning of a capacitor switching instant. The reason is that when the sampling frequency is high, the timing interval between two successive samples is very small such that the variations of the main signal amplitude can be less or comparable with the total variation in the signal due to the effect of noises. To avoid such a case, the sampling frequency should be limited. Such a limit is basically determined by the highest frequency of the main signal during the switching transients. The transient signal frequency is typically in the range of 300 to 1000 Hz [1], therefore, a limit of about 10 kHz is suggested as the maximum sampling rate for the space vector locating method.

IV. Conclusion

A fast method is presented for locating the source of the transients, originated from a shunt switched capacitor bank, in a power system. The method uses online measured voltages and currents signals at the monitoring points of the system to determine the location of a switched capacitor with respect to the monitoring points. Determining the location of the switched capacitor is based on the slope signs of the voltages and the currents at the switching instant. The main conclusions of the paper are: (i) The slope-based method can locate a switched capacitor bank using a few samples of the system monitoring points which makes the method a fast and simple approach when compared with the other possible methods; and (ii) The proposed space vector method improves the performance of the slope-based method since the space vectors simultaneously use the information of all the three phases.

Validity of the slope-based method and the proposed space vector method are investigated based on the time-domain simulation of a study system. The investigations show that: (i) the space vector method correctly locates the switched capacitor under various capacitor switching scenarios and system conditions such as harmonics and noises; and (ii) the implementation of the method requires the voltage and current signals recorded with a minimum sampling rate to be above the fastest transients frequency.

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