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Automatic capacitor bank identification in power distribution systems

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ABSTRACT

Tracking the performance and health of capacitor banks in distribution systems is a challenging task due to their high number and the widespread geographical distribution of feeder circuits. In this work we propose a signal processing technique capable of identifying and characterizing the number of capacitor banks connected to a standard North-American feeder circuit. The way the technique is applied allows a real-time remote monitoring of their operation, automatically identifying the switching activity for each capacitor bank connected. The technique is based on an unsupervised clustering of the three phase reactance step magnitudes. We demonstrate that using only passive monitoring of conventional substation bus PTs and feeder CTs, without any communication, nor visual inspection, to individual banks, it is possible to predict the number of capacitor banks on the distribution feeder and track their performance and activity over time.

1. Introduction

Capacitor banks are common devices in power distribution systems. They provide reactive power, thereby improving power factor, reduced line loses, improved feeder voltage profile, and lower power line loadings. In order to obtain optimal power factor correction and voltage profile, banks of various sizes are selectively placed along each feeder. Once in operation, unmonitored capacitor banks are difficult to evaluate and their real performance is often unknown. While sophisticated systems provide communication to each and every bank for remote monitoring and control, this practice is expensive and not widespread in the electric utility industry.

Farag et al. performed an extensive statistical study of capacitor banks and other components. The authors investigated failure modes, reliability levels and failure causes for a population of more than 2900 capacitor banks during a period of 10 years (1980–1990) [1]. The authors published statistics of the location of the failures, capacitor banks being the component more prone to present a failure (70.0%), followed by oil switches (12.3%), clocks (3.5%), controllers (3.5%) and jumpers (1.7%). The sources of these failures were identified to be main insulation breakdown (92.4%), oil leaking, which also leads to a main insulation breakdown (5.2%) and broken bushings (2.4%). The study also provided statistics related to the device quality, in form of the average failure rates (*Fr*), which ranged from *Fr* = 0.715% to 2.150% depending on the manufacturer. Given the high number of banks that can be found in power distribution networks and the economical impact of a bank failure, which most of times remains unnoticed, these statistics provide a justification for further research on novel cost-effective methods for locating and monitoring sets capacitor banks in a distribution line.

A number of publications addressing different aspects related to capacitor banks are found in literature. These range from the optimization of capacitor allocation in the distribution lines [7,9], switching control techniques [11], the impact of the switched capacitors on customer systems [4,8]. Comparatively, there are a limited number of publications on warning systems for capacitor banks aimed at the identification, monitoring and detection faults related to capacitor banks in power distribution systems, and most of the existing methods rely on a sensing device placed near -or inside- the capacitor bank. Lee et al. [5] used a modified impedance relay to provide early warning based on a safety operation zone for capacitor bank protection. Sochuliakova et al. [12] developed methods for locating the placing of capacitor banks in radial systems from the analysis of the transient frequencies. The method allowed the use of a single monitoring device at substation level although the results of the analysis required the measurement of the line inductance from the customer to the capacitor, which may

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depend on the distribution line and geometry. Santoso et al. contributed with a different method for bank identification based on the installation of multiple power quality monitors among the line connected to a feeder [13]. Authors demonstrated that, given a capacitor switch event, each power quality monitor could determine whether the bank was placed upstream or downstream from the distribution line. Given that all monitors were placed strategically along the distribution line, it was possible to approximate which bank was activated/deactivated by using the simultaneous information provided by the monitors.

The technique proposed in this paper enables the remote identification and monitoring of capacitor banks using measurements performed only in the substation, with no communication to the banks deployed in the branch and with no prior knowledge of the number and size of the banks deployed. We propose the use of a single monitor device per feeder, as opposed to individual monitoring devices per capacitor banks, combined with pattern recognition techniques for monitoring, detecting and locating grounded capacitor bank failures. To that task we employ a clustering-based technique capable of: (1) grouping capacitor switch events based on the similarity of their transient signals, (2) determining the number of clusters observed at a particular feeder circuit, and (3) characterizing the capacitor size at each phase. The technique can thereby be employed to enumerate and characterize all capacitor banks in a feeder circuit without prior knowledge of their existence devices. The automatic identification and monitoring allows for future localization of abnormalities and failure prevention in capacitor banks at distribution lines.

2. Materials and methods

This work is part of a large-scale project sponsored by EPRI (Electric Power Research Institute, Palo Alto, CA, USA), which is aimed at providing tools for distributed fault anticipation (DFA) in power distribution lines. Within the framework of this project, a number of custom-designed signal acquisition modules have been installed in different feeders from multiple utilities. Each of these modules captures a variety of electrical signals that can be divided into two main groups:

- *Triggered by an event*. Each time that a disturbance is seen by the module, a signal is triggered and a number of waveforms are stored in a capture file. These waveforms include current, voltage, RMS current and voltage, real (P), apparent (S) and reactive (Q) power, and high frequency band energy ($f_s > 2$ kHz) data in the time window of the trigger. Typical capture lengths are 6 s including one second prior to trigger.
- *Statistics*. The system also captures multiple statistics (maximum, minimum, averages and standard deviations) of several variables every 15 min. These variables include power related signals (RMS voltage, RMS current, P, S, Q) plus frequency related information for the current signals, as well as weather conditions (temperature, humidity, rainfall, wind speed and wind direction).

All variables for both groups, *Triggered by an event* and *statistical*, are acquired for the three phases plus neutral where applicable. Data acquisition modules are installed on each feeder in selected substations, and are controlled from a master station at Texas A&M University (TAMU) by means of a TCP/IP connection over digital subscriber lines (DSL). The collection of all captured files is stored locally, and periodically transmitted to TAMU for further processing and archival purposes. Fig. 1 shows an example of a captured waveform. In this case, the acquisition was triggered by a grounded capacitor switch-off event, as evidenced by the clear step in reactive power (dQ_x) in all three phases. Following capture and event signal

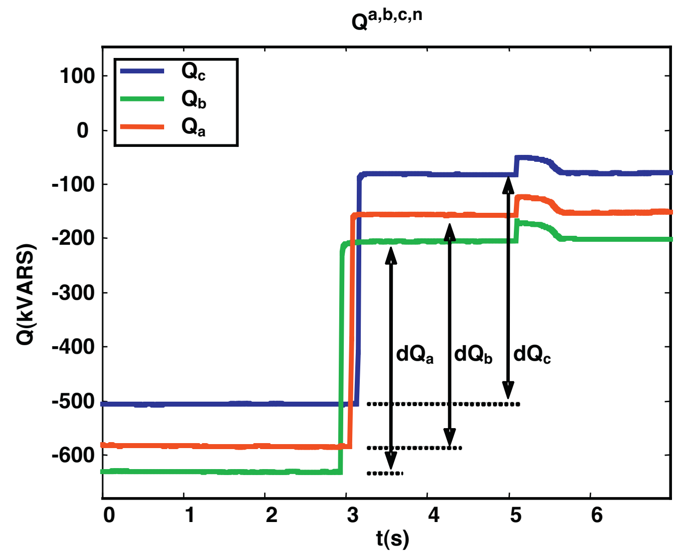

Fig. 1. Reactive power (Q) waveform for a capacitor switch off.

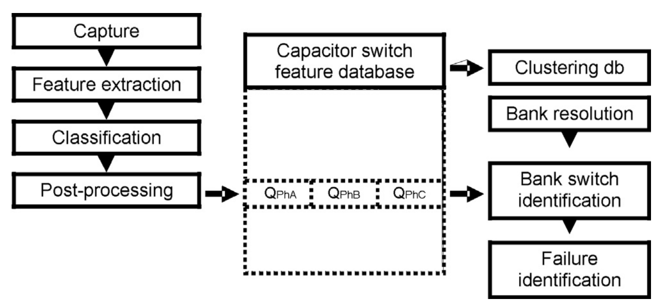

Fig. 2. General overview of the data processing path.

data, undergoes a series of processing steps, summarized in Fig. 2. From this feature set, a classifier algorithm will label each capture as belonging to "capacitor switch" category or "others". Captures labeled as capacitor switches are passed to a post-processing stage that computes a series of features that feeds a database, which is *database-mined* with the tools proposed in this work. The number and characteristics of the banks in a given circuit are then extracted by means of a clustering algorithm and a bank resolution post-processing step, as described in Section 2.2. Once this information is available, it is then possible to monitor the evolution of the banks in a feeder line. The different stages of the processing architecture are described with more detail in the following sections.

2.1. Recognition of capacitor bank events

Four features are extracted from the power (P), reactive power (Q), current *RMS* (I_{RMS}) and voltage *RMS* (V_{RMS}) waveforms:

- The step change between the beginning and the end of the waveform, S^{dif}
- The maximum and minimum value relative to the start of the waveform, S^{max}, S^{min}
- The maximum value of the signal relative to the minimum value, S^{mdif}

This feature extraction is done for each phase. In order to prevent the feature extraction step and further processing to be phase dependant, only the maximum value for the three phases is