# 21C Cap bank Protection

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***Abstract*— When designing the protection of capacitor banks, protection engineers resort to the well-known voltage differential protection (87V), wherever is feasible. This protection scheme aims to detect faults in the Shunt Capacitor Banks by measuring a ratio of voltages between two measurement points in the capacitor bank. Failed capacitor elements, as well as rack faults, cause a change in measured voltages, resulting in a change of ratio. Impedance-based protection for capacitor banks (21C) is proposed to overcome some drawbacks of voltage differential protection (87V) within different capacitor bank configurations or even high tolerance of the measurement of input voltage in protection relays. More specifically, to be more fault tolerant in fuseless capacitor banks.**

**The impedance protection on capacitor banks measures the operating complex impedance of the capacitor bank. Under healthy conditions this impedance remains stable.**

**A change in the elements of the capacitor bank, from a blown fuse as an example, will change the impedance of the capacitor bank. This change is detected by the 21C impedance protection function.**

***Keywords—Capacitor Bank, Impedance, Protection***

## I. Introduction

Shunt Capacitor Banks (SCB) are typically used to deliver capacitive reactive compensation or power factor correction. The use of shunt capacitor banks has gained popularity because they are affordable, simple to install and commission and can be placed anywhere in the electrical distribution system. Its usage has additional advantages on the electrical distribution system such as: enhancement of the voltage at the load side, increased voltage regulation, decrease of power losses and decrease or postponement of investments in electrical transmission network.

The use of SCBs has increased because they are relatively inexpensive, easy, and quick to install and can be deployed anywhere in the network.

The main disadvantage of SCB is that its reactive power output is proportional to the square of the voltage and consequently when the voltage is low and the system need them most, they are the least efficient.

Shunt capacitor banks are protected against faults that are due to external or internal conditions. Internal faults are caused by failures of capacitor elements that make up the capacitor units, and units that make up the capacitor bank. Also, other faults inside the bank such as a flashover within the rack (short circuit over a single or multiple series groups of units of the same phase) and rack phase-to-phase and phase-to-earth faults belong to this category. Depending on the number of failed elements/units, the employed protection may first initiate an alarm to notify the operator about a potential bank problem.

Tripping in due time must take place if the stress to the healthy capacitor elements/units or their subsequent components exceed a predefined limit of the measured phase current or voltage, to minimize damage and to prevent possible rapid cascading of the fault by other failed elements/units.

## II. Why Impedance-Based Protection (21C)

### A. *Adaptable with different SCB configuration*

Capacitor banks can have many different configurations using a grounded or ungrounded Starpoint. The protection applied depends on the configuration and available measurement. In the simplest configuration (Star connection) which is common in the United States, available measurements are limited, and in most cases not physically possible to add a CT or VT inside the capacitor bank to have a dedicated measurement for any differential (Voltage or Current) protection. By using the 21C method, we can simply measure the operating complex impedance of the capacitor bank. Under healthy conditions the complex impedance remains stable and when elements of the capacitor bank change (e.g., due to a blown fuse on a unit), the impedance of the capacitor bank will change and enabling the operation of the impedance protection function.

### B. *Limits of Voltage Differential (87V)*

Voltage differential protection (87V) is one of the popular protections for Shunt Capacitor Banks, however this protection has limitations. As an example, in fuseless SCBs specially used in high voltage networks, the sensitivity of this method is low, such that a failure in a small portion of the bank makes a voltage variation which is within the tolerance of the measurement of input voltage protection relays and practically undetectable.

Lowering this sensitivity and threshold to faults voltage variation, increases the likelihood of detection of false faults, removing a healthy capacitor bank from the system.

## III. IMPEDANCE-BASED PROTECTION (21C)

Figure 1 shows a description of ungrounded single star capacitor bank (single string per phase) which is used in an exemplary capacitor bank configuration to show how the 21C function is working.

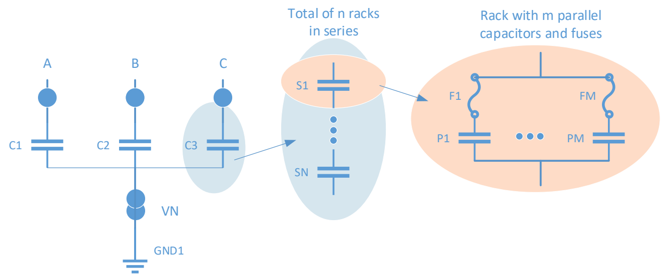


Fig. 1. Ungrounded single star capacitor bank configuration (single string per phase)

This capacitor bank is made up of racks with (m) parallel fused capacitors. There is a total of (n) racks connected in series in each string of each phase. The electrical parameters of the capacitor bank can be calculated with the data of the individual parallel fuse-protected elements in each rack. (Cp is the capacitance of one fuse-protected element in the rack)

$$C_{rack} = m \cdot C_p$$

$$C_{phase} = \frac{1}{n} \cdot C_{rack} = \frac{m}{n} \cdot C_p$$

$$X_{phase} = \frac{1}{2\pi f \cdot C_{phase}}$$

The 21C function will measure the impedance of each phase capacitance, whereby the reactance will correspond to Xphase under healthy conditions.

For the ungrounded capacitor bank, the voltage used in the measurement is derived from the phase voltage minus VN.

The current used in the measurement is the phase current that may be measured at the terminals or at the Starpoint.

This method can be adapted to alternative capacitor bank configurations following similar steps to what is described in this paper for the configuration shown in Figure 1.

### A. *Impact on Impedance when a fuse is blown*

Depending on the configuration of the capacitors and fuses, impedance of the cap bank will change when a fuse blows (open circuits an element of the bank). For the configuration shown in Figure 1 the following applies when 1 fuse is blown in a rack:

$$C_{rack\_1F} = (m-1) \cdot C_p$$

$$C_{phase\_1F} = \frac{m \cdot (m-1)}{n \cdot m - n + 1} \cdot C_p$$

The ratio of phase capacitance with one fuse blown to healthy phase capacitance is as follows:

$$\frac{C_{phase\_1F}}{C_{phase}} = \frac{n \cdot (m-1)}{n \cdot m - n + 1}$$

For example, if there are 12 (m) parallel Cp and 10 (n) series Crack then:

$$\frac{C_{phase\_1F}}{C_{phase}} = \frac{10 \cdot (12-1)}{10 \cdot 12 - 10 + 1} = \frac{110}{111} = 0.991$$

The percentage change in capacitance is less than 1%.

### B. *Impedance Caculation*

The impedance is calculated for each phase as follows:

$$\underline{Z_{phase}} = \frac{\underline{V_{ph}}}{\underline{I_{ph}}}$$

Or:

$$\left|\underline{Z_{phase}}\right| = \frac{\left|\underline{V_{ph}}\right|}{\left|\underline{I_{ph}}\right|}$$

$$\emptyset\left(\underline{Z_{phase}}\right) = \emptyset\left(\underline{V_{ph}}\right) - \emptyset\left(\underline{I_{ph}}\right)$$

Internally the current and voltage values in the calculation are processed in percent relative to the set rated current and voltage. The calculated impedance values are therefore in per unit. A conversion to the actual (primary or secondary) value is possible, but not required. As a result, settings and measured values of the function will be in percent and per unit.

## C. *Operation of 21C Stages*

Having measured the impedance of the capacitance as shown above, threshold for operation of alarm and trip stages can be applied. For this purpose, both static delta and dynamic delta stages can be used. In the example below the application of these stages is explained

*Static Stage*

- The static stage responds with an output when the measured capacitor bank impedance deviates from the nominal value by more than the set threshold. The threshold of this stage is set to be less sensitive to allow for temperature variations of the capacitor bank impedance. The measurement of the static stage is mostly the operational value that shows the value of the presently measured capacitive reactance. It can be used as a serious fault protection with set threshold above maximum “drift”.
- The “Static Delta” stage checks the difference between the measured capacitive reactance and the rated per unit reactance. Since the response is relative to the nominal operating impedance of the cap bank, it can be used to detect large deviations. This measurement is not suitable for very sensitive thresholds, as slow drifts due to temperature changes, which are not eliminated. Typical application is to report an alarm due to impedance offsets near the expected operational boundary.

*Dynamic Delta Stage*

- The dynamic delta stage responds to “jump” changes of the measured impedance. It can be set with a sensitive threshold to detect the operation of a fuse on the capacitor bank. The output may be used to trigger an alarm or trip the circuit breaker
- The dynamic delta stage responds to a jump of the per unit capacitive reactance. As the response is due to change over a short interval, slow drifts of impedance due to temperature change, do not affect this stage and it can be set with a sensitive threshold. Typical application is to detect the operation of internal fuses that switch off elements of the capacitor bank.

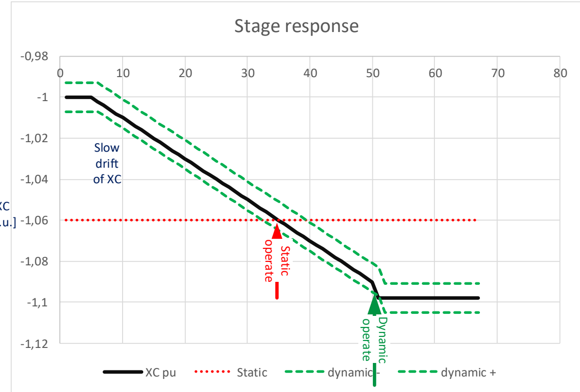


Fig. 2. Measured XC over an interval

## D. *Description of Stages*

*Static Stage (reactance)*

- The static response to reactance uses a per unit reactance method as shown in the diagram below:

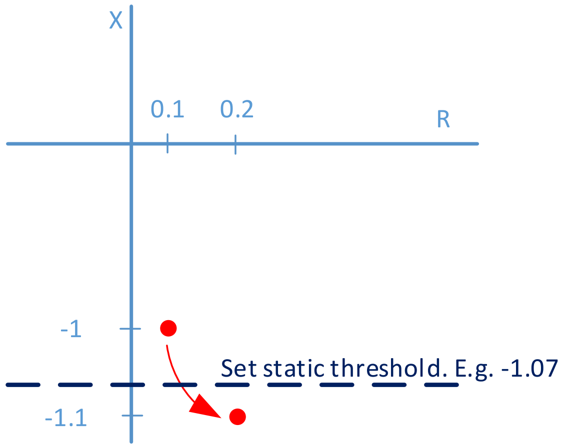


Fig. 3. Change of measured impedance – static stage (reactance) response

- The response to reactance uses an absolute threshold in the impedance plane. When the measured value crosses as shown the stage will pick-up and assert its output.
- For capacitor bank applications this is recommended as a change of the capacitance will result in change of the measured reactance. The reactance will assume a larger negative value as shown in the diagram above when there are internal failures in the cap bank.

*Dynamic Delta Stage (reactance)*

- The dynamic delta stage responds to small changes in a short interval (jumps). Compared to the static stage above it can be represented as follows:

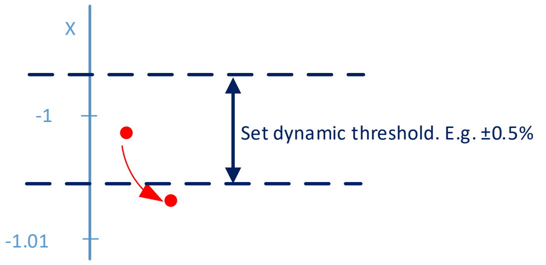


Fig. 4. Dynamic stage

- The threshold of the dynamic stage is always relative to the previous measured impedance. If the magnitude of the reactance change (delta) exceeds the set boundary as shown above the stage will respond with an asserted output.

*Static Stage (impedance)*

- The static stage may also be applied in an alternative manner with response to the measured impedance. In this case also resistive change of the measured impedance can result in an operation. The stage boundary is as shown below:

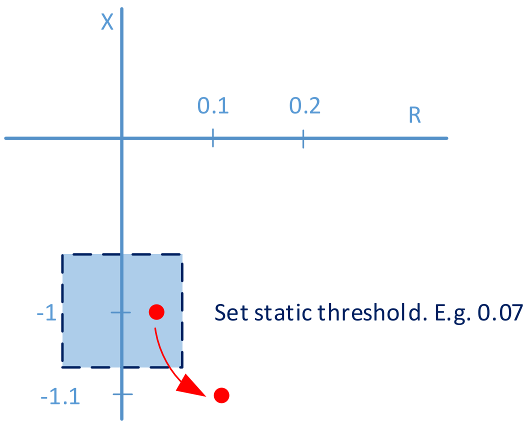


Fig. 5. Change of measured impedance – static stage (impedance) response

- In the "impedance" method the boundary is set as a per unit deviation from -1.0. As soon as either the measured R or X value deviates by more than the set boundary the stage asserts its output

*Dynamic Delta Stage (impedance)*

- In the impedance mode dynamic delta stage responds to small changes, in either R or X, in a short interval (jumps). It is represented as follows:

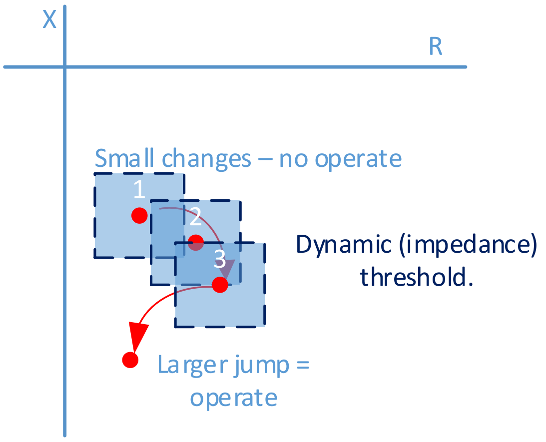


Fig. 6. Change of measured impedance–Dynamic stage(impedance) response

- In the 3 successive stages shown above the delta is not large enough for an operate from 1 to 2 and from 2 to 3. However, the measurement with stage 3 shows that the next value has a jump that exceeds the set threshold and at this point the stage will operate.

## IV. Temperature Effect

One of the most important concerns in Impedance based protection is Temperature Variation. In temperature variation range of 0 ~ 140 F the capacitance variation could be ± 2% of nominal value. This factor is getting worse when Shunt Capacitor Bank is in sun exposure which can be affected as non-uniform temperature variation across the Shunt Capacitor bank.

This temperature variation is more important when the number of Capacitor bank elements are high. Simply when the number of elements per string is more than 30 units, the capacitance variation in range of ± 2% is same as single capacitor bank element failure

To mitigate the temperature-induced impedance variation, the blow temperature compensation algorithm is used:

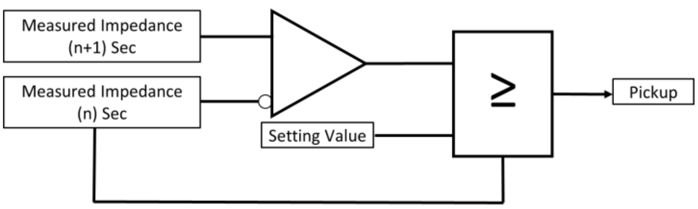


Fig. 7. Temperature effect compensation

## V. Voltage and Current supervision

To prevent transient response of the 21C during energization or external faults, a current and voltage plausibility check is included. The settings for these are applied as follows:

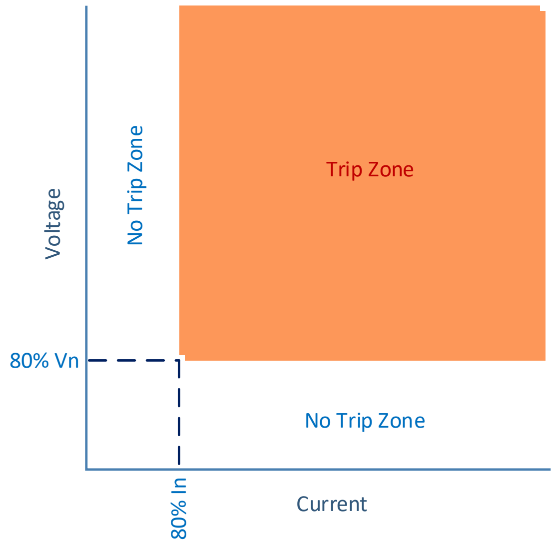


Fig. 8. Current and Voltage supervision

By using the 21C method, we can simply measure the operating complex impedance of the capacitor bank. Under healthy conditions the complex impedance remains stable and when elements of the capacitor bank change (e.g., due to a blown fuse on a unit), the impedance of the capacitor bank will change and enabling the operation of the impedance protection function.

## Conclutions

Capacitor banks can have many different configurations with grounded and ungrounded Starpoint. The protection applied depends on the configuration and available measurement values. In most of the simple configurations (Star connection) which is common in United States, the available measurement values are limited, and it is not easy to add CT or VT inside the capacitor bank to have a dedicated measurand values for any differential (Voltage or Current) protection.

## References


[1] Eric Thibodeau, Benjamin Couil , Dean Sorensen, Song J, Improved Protection and Maintenance for Shunt Capacitor Bank

[2] Satish Samineni, Casper Labuschagne, and Jeff Pope, Principles of Shunt Capacitor Bank, *Presented at the 64th Annual Georgia Tech Protective Relaying Conference Atlanta, Georgia May 5–7, 2010*

[3] Roy Moxley, Jeff Pope, and Jordan Allen, Capacitor Bank Protection for Simple and Complex Configurations , *Presented at the65th Annual Conference for Protective Relay Engineers College Station, Texas April 2–5, 2012*

[4] Gustavo Brunello, M.Eng, P.Eng, Dr. Bogdan Kasztenny, Craig Wester; Shunt Capacitor Bank Fundamentals and Protection, *2003 Conference for Protective Relay Engineers - Texas A&M University April 8-10, 2003, College Station (TX)*


## Biography

**Amir Hossein Soroush,** received his B.Eng. degree in electrical engineering from Iran University of Science and Technology. He started his professional experience with ABB in 2000 as design Engineer for power utility Protection and Control system in Iran and has been involved with the commissioning, control, protection, monitoring and automation of power system apparatus up to 400 kV for 20 years. His research interests include power system protection, IEC61850, Digital Substation and SCADA.

In 2020 he joined SIEMENS USA as an application engineer where he is responsible for the application and design of protective relays and Substation Automation Systems.