Filter Capacitor Bank Protection

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1. Introduction

High voltage filter capacitor bank becomes more and more common in modern power system. They are used to filter out certain higher order harmonics from the network.

In order to protect such filter banks properly protection engineers need to understand how different harmonics flows through different filter branches. It is of utmost importance that correct filtering is used within the selected protection functions in order to appropriately protect the filter bank.

2. Basic understanding of HV Filter Banks

The short summary information about HV filter banks is given in this section.

2.1. Rated Data

HV filters typically have the following main data specified for them:

1. Rated Voltage Ur (e.g. Ur=225kV for Example given in Figure 5).
2. Rated frequency \( f_r \) (e.g. 50Hz or 60Hz depending on country where it is installed).
3. Rated MVAR rating \( Q_r \) (e.g. \( Q_r=80\text{MVAR} \) for Example given in Figure 5 at rated frequency).
4. Tuning harmonic order (e.g. 5\text{th} harmonic) and corresponding tuning frequency \( f_t \) (e.g. 245Hz for a 50Hz system). Pay attention that tuning frequency is very seldom exact multiple of the fundamental frequency (e.g. tuning frequency is 245Hz but the exact 5\text{th} harmonic frequency is 250Hz).
5. Note that due to manufacturing tolerances for capacitor cans, inductors and resistors actual tuning frequency of the filter can vary slightly. Therefore, sometimes even the allowed tolerances for tuning frequency can be specified (e.g. 238 Hz < \( f_t \) < 252 Hz).

From \( Q_r \) and \( Ur \) values the rated filter current and the rated filter capacitive reactance at rated frequency can be calculated as shown below for above given values:

\[
I_r=\frac{Q_r}{\sqrt{3}}/U_r=205\text{A} \quad \text{and} \quad X_r=\frac{U_r\cdot U_r}{Q_r}=-632,8\Omega \quad (\text{i.e. capacitive})
\]

2.2. Type of filter and associated primary components

Often a star connected, C-type filter is used for HV installations. A simplified connection diagram for C-type filter is given in Figure 1. It has the following basic building components:

- \( C_1 \) = Main capacitor bank
- \( C_2 \) = Tuning capacitor bank
- \( L \) = Filter reactor
- \( R \) = Filter resistor

Sometimes a surge arrester (i.e. overvoltage protection) might be required across resistor \( R \).

The filter neutral point can be either grounded or non-grounded depending on the end user preference.

The primary currents flowing through individual filter branches are also shown in Figure 1, where:

- \( I_{C1} \) = Primary current through capacitor \( C_1 \)
- \( I_L \) = Primary current through inductor \( L \) and capacitor \( C_2 \)
- \( I_R \) = Primary current through resistor \( R \)
Note that any CT and VT locations are intentionally not shown in Figure 1.

2.3. **Practical construction details of main components**

The capacitance C1 is by far physically the largest component. It is built as serial/parallel connections of many individual Capacitor Units (i.e. Cans). These units can utilize different fusing technique as preferred by the end user or by filter supplier. It is typically built as an H-connection (i.e. bridge), because then quite effective unbalance protection can be applied. However, for lower voltage levels other connection types may be used (e.g. double star) as shown in Figure 6.

The capacitance C2 is physically much smaller. It is typically built by using just several Capacitor Units. Therefore, it is often quite difficult to provide dedicated unbalance protection for it.

The inductor L is almost always built as a single air-core reactor. Depending on the reactor current level one shall be careful with possible strong magnetic fields in its surroundings. Strong magnetic fields might have influence on CTs or VTs installed in close vicinity of the reactor.

The resistor R is typically physically built either as two parallel resistors or even as four H-connected resistors (i.e. bridge). That is done in order to provide unbalance protection for the resistor.
2.4. Filter response for different frequencies

If values for C1, C2, L and R are known, then the filter overall equivalent impedance for different frequencies can be determined by using the following equation:

\[ Z_{eq} = Z_{C1} + \frac{1}{\frac{1}{Z_{C2} + Z_L} + \frac{1}{R}} \]

How equivalent impedance changes, for filter given in Figure 5, is shown in Figure 2.

![Equivalent Impedance](image)

**Figure 2: Overall impedance for filter shown in Figure 5**

As shown in Figure 2 such C-type filters are typically capacitive (i.e. \( X < 0 \)) for frequencies below the tuning frequency and slightly inductive (i.e. \( X > 0 \)) for frequencies above the tuning frequency.

Another important property of this filter is that typically reactor L and capacitor C2 have a resonance at rated frequency. In mathematical terms that means:

\[ 2 \times \pi \times f_r \times L = \frac{1}{2 \times \pi \times f_r \times C_2} \]

When such special selection of L and C2 values is done this causes the following effects which are important to understand for the protection engineer:

1. Voltage drop across resistor R and serial connection of L and C2 is zero volts at rated frequency.
2. The whole busbar voltage at rated frequency is just applied across C1 capacitor.
3. At rated frequency filter bank behaves as pure shunt capacitor without any resistance (i.e. no losses) and its equivalent capacitance per phase is equal to C1.
4. Current component having rated frequency do not flow through the resistor R.
5. Only harmonic current components flow through the resistor R.

Due to this it might also be beneficial to determine how the fundamental frequency current and different harmonic currents will split between the two parallel branches. With relatively simple mathematics it is possible to calculate the current split between these two parallel branches. This can be mathematically expressed as current magnitude ratio \( |I_L| / |I_R| \). How this current ratio looks like, for filter given in Figure 5, is shown in Figure 3.
In conclusion, the following current and voltages will be applied to the individual filter components:

- Complete fundamental frequency current and all higher harmonic frequency current components will flow through capacitor C1. Full fundamental frequency voltage will be posed across capacitor C1 as well as some part of harmonic voltages.
- Complete fundamental frequency current and some parts of higher harmonic frequency current components will flow through capacitor C2 and reactor L. Some harmonic voltages and relatively small fundamental frequency voltage will be posed across capacitor C2 and across reactor L.
- Only some parts of higher harmonic frequency current components will flow through resistor R. The higher the harmonic order the bigger the part of its current will flow through the resistor. No fundamental frequency current will flow through the resistor R. Consequently, only harmonic voltages will be posed across resistor R.

The above statements are very important to understand in order to properly protect the filter bank.

### 2.5. Location of Instrument Transformers

In order to have a proper protection scheme several instrument transformers (mainly CTs) shall be properly allocated within the filter bank branches. Appropriate ratings and ratios shall be selected in order to have optimal sensitivity of various protection functions. Some typical setups are given in the following three figures.

Some specific issues are:

Due to high short-circuit current level at the HV bus, the main HV CT (i.e. CT1 in Figure 4) might have a primary rated current which is much higher than the filter bank rated current. Such arrangement might cause loss of measurement accuracy for some protection functions (e.g. harmonic overload protection for capacitor C1). In installations where the star point CT is also available (i.e. CTE in Figure 4) the rated primary current of that CT shall be as close as possible to the Filter Bank rated current. This will enable sensitive functions to use that star point CT instead of CT1. Note that a difference in CT ratio will not cause any problem for the stability of the filter bank differential protection, because the through fault current for external faults is quite limited (i.e. often less than the rated current). In general, it is advisable to have current of at least 50% of the CT rating during normal operating conditions of the filter bank when harmonic overload protection function is used.
Due to sensitivity issues, unbalance CTs (i.e. CTA and CTB in Figure 4) might have very low rated primary current. However, during a series fault within the protected capacitor this unbalance current can be tens or even hundred times of its rating. Consequently, such CTs might require varistors or spark gaps on their secondary side. That this will also effectively disable the operation of the unbalance protection under such heavy current conditions. Note also that the filter bank differential protection will not respond for such series faults either. Accordingly, it is recommended to include Cascading Failure Protection function for large filter banks.

Ratings of CT associated with the resistor R (i.e CTC1 and CTC2 in Figure 4) shall be selected based on expected harmonic currents levels and the used resistor ratings.
3. Examples of Protection Schemes

In this section several example of Filter Bank protection schemes will be given.

3.1. 400kV Filter Bank

Proposed protection scheme using RET670 is given in Figure 4.

Figure 4: Example of a protection scheme for 100MVar, 400kV, 145Hz Filter Bank

For list of used protection functions in the above figure, refer to section 3.1.1.
3.1.1. List of functions used for the protection scheme of Filter Banks

- #01, OC4 PTOC: Filter bank Overcurrent protection (set DFT measurement; 4 stages).
- #02, EF4 PTOC: Filter bank Earth-fault protection (uses DFT measurement; 4 stages).
- #03, NS4 PTOC: Filter bank Negative-sequence over-current protection (uses DFT measurement; 4 stages). It can be redundant with function #02 depending on system grounding and filter bank star point grounding. Coordinate their settings.
- #04, T2W PDIF: Filter bank differential protection (uses DFT measurement; 2 stages).
- #05, SCCF PVOC: Cascading failure protection for C1 capacitor (uses DFT measurement; 2 stages). Set “NegSeq” (i.e. negative sequence) for measured quantity.
- #06, CBP GAPC: Harmonic overload protection for C1 capacitor (integrates measured currents and then uses Peak Voltage measurement for its operation). It also has available Reconnection inhibit feature which is typically required and also an over-current protection stage based on peak current measurement.
- #07, CBP GAPC: Harmonic overload protection for C2 capacitor (integrates measured currents and then uses Peak Voltage measurement for its operation).
- #08, SCUC PTOC: Unbalance protection for C1 capacitor (uses DFT measurement; 3 stages i.e. trip, alarm and warning). Feature for compensation of natural unbalances is included.
- #09, SCUC PTOC: Unbalance protection for C2 capacitor (uses DFT measurement; 3 stages i.e. trip, alarm and warning). Feature for compensation of natural unbalances is included. Note that in practice it may be difficult to set this protection because C2 capacitor is typically relatively small.
- #10, OC4 PTOC: Unbalance protection for reactor L and/or capacitor C2 (set DFT measurement; 4 stages). It is based on fact that fundamental frequency component shall not flow through the resistor R. If that happens either C2 or L has deviated from its original designed values.
- #11, OC4 PTOC: Unbalance protection for resistor R (set RMS measurement mode; 4 stages). Note that true RMS measurement mode must be used because the fundamental frequency component does not flow through the resistor R.
- #12, LC PTTR: Thermal overload protection for resistor R (uses RMS measurement mode). Has possibility for outdoor temperature measurement and compensation.
- #13, LC PTTR: Thermal overload protection for reactor L (uses RMS measurement mode). Has possibility for outdoor temperature measurement and compensation.
- #14, CHMMHAI: Current harmonics monitoring (from fundamental up to and including the 5th harmonic) for capacitor C1. It uses approximately one second long data window to filter out all measurands. It shall be used to report these values to SCADA. It also calculates THD value per phase which may be used for Filter Bank monitoring/protection.
- #15, CHMMHAI: Current harmonics monitoring (from fundamental up to and including the 5th harmonic) for resistor R. It uses approximately one second long data window to filter out all measurands. It also calculates THD value per phase but they are not really relevant for resistor branch.
- #16, CHMMHAI: Current harmonics monitoring (from fundamental up to and including the 5th harmonic) for capacitor C2 and reactor L. It uses approximately one second long data window to filter out all measurands. It also calculates THD value per phase. It can be even
used as simple overload protection for reactor L because it is possible to set warning limit and alarm time delay for each harmonic component separately.

- #17, OV2 PTOV: Overvoltage protection (2 stages). Optional function. Can be used for filter bank automatic On/Off control logic if VT1 is located at the busbars.

- #18, UV2 PTUV: Undervoltage protection (2 stages). Optional function. Can be used for filter bank automatic On/Off control logic if VT1 is located at the busbars.

- #19, CV MMXU: Measurement function for the filter bank (Q, U, I, f based on fundamental frequency voltage and current components).

In addition to these protection and monitoring functions the 670 IED can also include the following:

As basic features (i.e. always available):

1. Disturbance recording for all connected CT and VT inputs (up to 10s long one record).
2. Disturbance recording for up to 10 internally calculated analogue quantities (e.g. differential currents, compensated unbalance currents, etc.).
3. Disturbance recording for up to 356 binary signals (configurable).
4. Even List. It logs status changes of the above binary signals (FIFO, 5000 events long).
5. Reporting of measured values to substation control system and/or SCADA system.
6. Running hour-meter function TEILGAPC which for example can be used to accumulate the elapsed time during which the filter bank was energized since last maintenance.
7. Circuit breaker condition monitoring function SSCBR, which among other things also includes number of operation counter.
8. Configurable LHMI. Measured quantities like branch currents, harmonics, THD etc. can be displayed in order to make testing, commissioning and operation of the Filter Bank easier.
9. Built-in multicolor LEDs (up to 45) for protection function start/operation indications.

As optional features (i.e. shall be specifically ordered):

1. Circuit breaker failure protection function CCRBRF (i.e. 50BF).
2. Primary apparatus control for breakers and disconnectors.
3. Transient EF protection function APPTEF. It shall be used when filter bank is installed in a high-impedance grounded system, compensated system or isolated power system.
4. Voltage harmonic monitoring function VHMMHAI.
5. Phase-vise, voltage-based differential protection function for capacitor banks, SCPDPTOV. It might be required depending on available instrument transformers within the filter bank.
6. Voltage unbalance protection function for shunt capacitor banks, SCUVPTOV. It might be required depending on available instrument transformers within the filter bank.
7. Depending on required functionality and number of analogue inputs available from each filter a single REC670 IED can be used for protection and control of several Filter banks (e.g. up to 3 within the same IED). This can be an interesting approach for Filter banks at lower voltage levels (e.g. 10kV, 20kV or 30kV).
3.2. 225kV Filter Bank

Proposed protection scheme using RET670 is given in Figure 5.

Figure 5: Example of a protection scheme for 80MVar, 225kV, 245Hz Filter Bank

For the list of used protection functions in the above figure, please refer to section 3.1.1. Note that functions from that list which are not explicitly shown in the above figure are not used for this protection scheme.
3.3. 63kV Filter Bank

Proposed protection scheme using REC670 is given in Figure 6.

Figure 6: Example of a protection scheme for 30MVAr, 63kV, 175Hz Filter Bank

For the list of used protection functions in the above figure, please refer to section 3.1.1. Note that functions from that list which are not explicitly shown in the above figure are not used for this protection scheme.
4. Protection Scheme Settings and Field Recordings

Settings for used protection function shall be derived based on ratings of filter bank individual components and available instrument transformers. Special attention shall be given for settings of various unbalance protections which, for example, shall not mal-operate during filter bank energizing.

4.1. Energizing of 225kV Filter Bank

Figure 7 shows how individual branch currents may look like during energizing of 225kV filter bank given in Figure 5. Presented current waveforms are given in primary amperes. The CT designation and location are also given in Figure 5.

![Figure 7: Energizing of 225kV Filter Bank](image)

Note relatively large initial transients for currents measured by CT2, CT3 and especially by CT4 (e.g. at the moment when CB is closed). However, these large transient currents typically do not contain much of the fundamental frequency current component.

It takes approximately two power system cycles for all currents to come to more or less steady state levels.
4.2. Steady-State Currents for 225kV Filter Bank

Figure 8 shows how individual steady-state currents may look like for 225kV filter bank presented in Figure 5. Presented current waveforms are given in primary amperes. The CT designation and location are also given in Figure 5.

Figure 8: Steady-state currents for 225kV Filter Bank

Note that currents through resistor, measured by CT4, are relatively small now and do not contain any fundamental frequency component, just harmonic components. Unbalance currents, measured by CT2 and CT3, are extremely small but may contain both fundamental and harmonic components.

The total filter bank currents, measured by CT1 and CT5, have dominant fundamental frequency current component, but also clearly visible superimposed higher harmonic current components.
5. Listing of related documents

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6. Conclusion

This document shall provide basic guidance how to arrange protection of HV Filter Banks by using 670 Series IEDs.

7. Revisions

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