TRANSIENTS BY SWITCHING OF FILTER BANKS AT HIGH-VOLTAGE GRID

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Abstract: In this paper, the current and voltage transients by all possible switching operations for a harmonic filter bank (i.e. energizing, reclosing, de-energizing, and circuit breaker restriking) are not only analytically investigated but also by software ATP/EMTP simulated. Then, some measures (e.g. apply a circuit breaker with ability of control switching) to abate these transient are suggested. Consequently, the effectiveness of the suggested solutions is proved through the further simulations. Finally, the proper overvoltage protections are proposed against the unavoidable overvoltages.

1 INTRODUCTION

The insulation co-ordination studies are fundamental studies for design of power systems. Overvoltage calculations are required as input data for insulation co-ordination. In industrial networks in megawatt power range, it is necessary to connect at High Voltage (HV) level. Therefore, considerable power and voltage oscillations as well as harmonics should be directly compensated at the same voltage level. A typical case would be steel industry. Figure 1 shows the simplified layout of a steelwork network with its filter equipments at 110 kV-busbar.

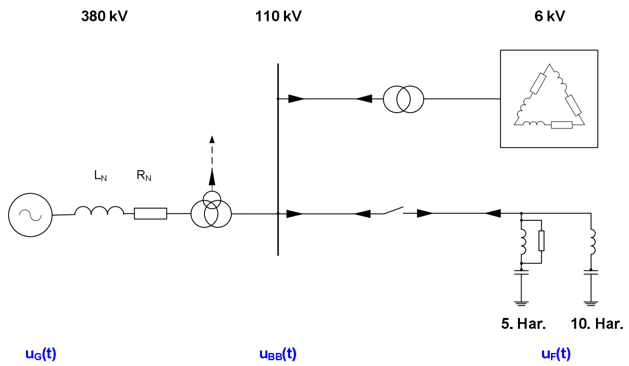


Figure 1: Principle of investigated network

In order to investigate a specific network configuration, e.g. that shown in Figure 1, the maximal overvoltage for filter equipments during all possible operation scenarios must be determined.

2 MODEL

In the above mentioned case study, the steelwork network is connected through a 50 km long double circuit Over Head Line (OHL) with 380 kV-grid. For modeling OHL, the JMARTI line segments are applied. A saturable transformer model is used for the transformer at Point of Common Coupling (PCC). The 110 kV-switchgear is a Gas Insulated Switchgear (GIS). The filters are connected to 110 kV-busbar through a 200 m long single core cable. This cable is modeled using the constant parameter cable model. It should be noted that the cable parameters are adjusted for characteristic frequency of each investigated transient. The electrical parameters of the 5th harmonic filter are given in Table 1.

Table 1: Electrical parameters of the 5th harmonic filter

Element		Value
Inductance L_F	*mH*	*300*
Resistance R_F	*Ω*	*2500*
Capacitors C_F	*µF*	1.33
Reactive power Q_F	*Mvar*	20 (capacitive)

The filter circuit used in simulations is shown in Figure 2.

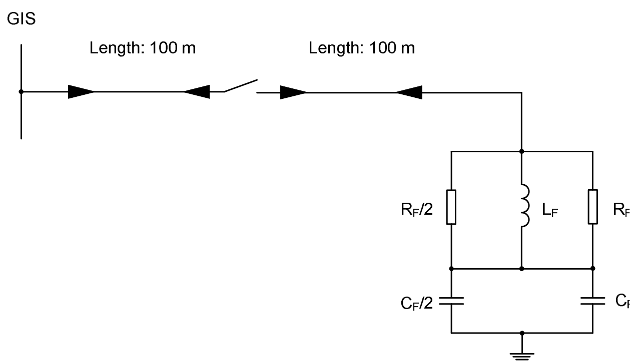


Figure 2: Electrical circuit of the 5th harmonic filter

3 ENERGIZING OF FILTERS

3.1 Inrush Current

Energizing filters can lead to an inrush current, which is considerably higher than rated current of the filter equipments. Figure 3 shows the 110 kV-equivalent circuit used to analyze transient current and voltage during energizing filters in the case study which shown in Figure 3.

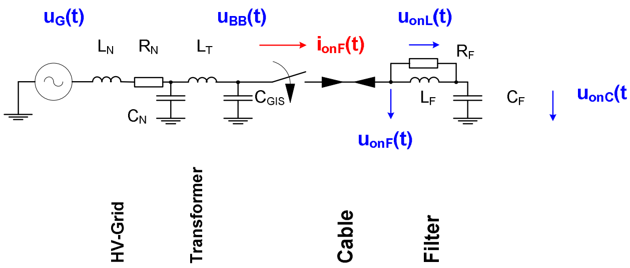


Figure 3: Equivalent circuit used to analyze energizing filters

The electrical parameters of 380 kV-grid are described by L_N, R_N, and C_N. The characteristic filter parameters are also referred as L_F, R_F, and C_F. In addition, the C_{GIS} models the GIS capacitance and all feeder cables connected to it. The transformer is simply represented by L_T.

The complete transient after energizing filter equipments can be described by two separate phenomena. The first and also high frequency one (referred by index *W*) is related to travelling waves which are dependent of the cable length. The second phenomenon (referred by index *I*) is resulted by charging the filter capacitor.

The frequency $f_{(W)}$ of transients related to traveling waves can be calculated according to the cable length and the propagation velocity of waves v_0 as follows :

$$f_{(W)} = \frac{v_0}{4 \times l} \qquad (1)$$

The maximum inrush current $\hat{\imath}_{onF(W)}$ is considerablly dependent on the capacitance of cables connected to GIS, i.e. C_{GIS}, and can be approximately determined using (2).

$$\hat{\imath}_{onF(W)} = \frac{\hat{u}_{BB}}{Z_{WC}} = \frac{110\ kV \times \sqrt{2}}{\sqrt{3} \times 40\ \Omega} \approx 2{,}2\ kA \qquad (2)$$

where $\hat{u}_{BB}$ is the maximum phase-to-ground busbar voltage and Z_{WC} is the cable wave impedance. The current transients due to traveling waves are depicted in Figure 4.

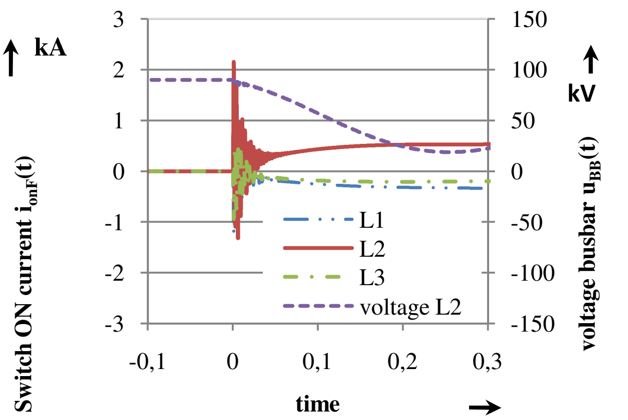


Figure 4: Current transient $i_{onF}(t)$ during energizing the filter bank

Simultaneously to traveling wave transients, the filter capacitor is charging (the second phenomenon). The amount of the second part of inrush current $\hat{\imath}_{onF(I)}$ depends significantly on the parameters of the high voltage grid as well as the configuration of filter circuit (filter eigenfrequency ω_e). Without having damping resistance R_F, $\hat{\imath}_{onF(I)}$ can achieve its maximum possible value by connecting the filter bank at moment of the busbar voltage amplitude $\hat{u}_{BB}$.

The second part of inrush current $i_{onF(I)}(t)$ can be roughly calculated using (3) as sum of the steady state capacitor current and transient current (at eigenfrequency ω_e):

$$i_{onF(I)}(t) = \hat{\imath}_F\left(-sin(\omega t)\right) + \frac{\omega_e}{\omega} e^{-\frac{t}{2T}} \times sin(\omega_e t) \qquad (3)$$

here

$$T = \frac{L_N + L_T + L_F}{R_N} \qquad (4)$$

and ω is the power frequency and $\hat{\imath}_F$ is the maximum of the steady state capacitor current.

Figure 5 shows the inrush current of the filter, without and by having the filter damping resistance R_F (*2500 Ω*).

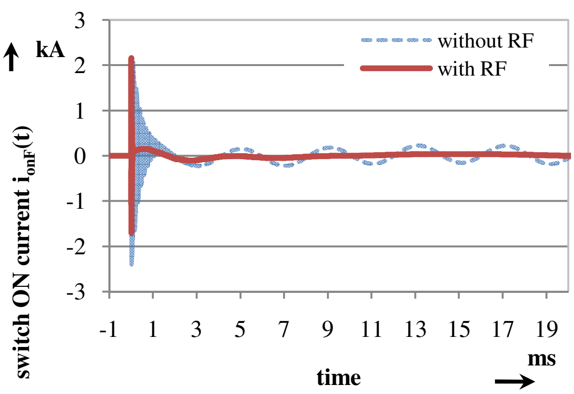


Figure 5: Current transient $i_{onF}(t)$ after connecting the filter bank

3.2 Energizing Overvoltages

Beside the current transients, the corresponding voltage transients are happened. Like the current transients, the voltage transients consist of two phenomena: the traveling waves (referred again by index *W*) and eigenfrequency transients (referred by index *I*).

The overvoltage due to traveling waves can achieve at the worst case the double value of the phase-to-ground busbar voltage amplitude $\hat{u}_{BB}$.

$$\hat{u}_{onF(W)} = 2 \times \hat{u}_{BB} = 2 \times \frac{110\ kV \times \sqrt{2}}{\sqrt{3}} \approx 180\ kV \qquad (5)$$

In Figure 6, the filter transient voltage $u_{onF}(t)$ after energizing the filter bank is shown.

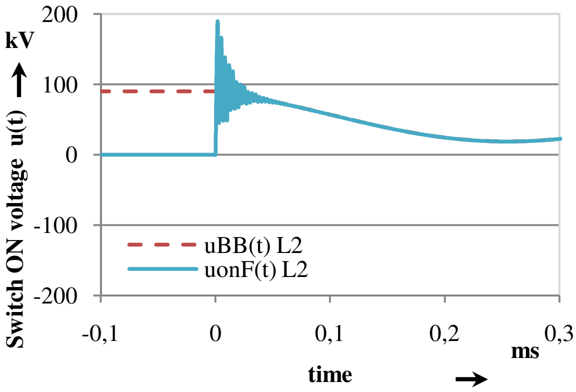


Figure 6: Voltage transient $u_{onF}(t)$ after connecting the filter bank (with R_F)

At the normal energizing operation, the filter capacitor C_F is not charged. Therefore, the complete voltage $u_{onF(W)}(t)$ appears across the filter inductor L_F after connecting the filter bank.

In the case of having charged capacitor before connecting the filter bank, e.g. by reclosing of circuit breaker, the filter can be connected at moment of the busbar voltage amplitude $\hat{u}_{BB}$ with the opposite polarity. In this case, the inductor voltage $u_{onL(w)}(t)$ can achieve its maximum value to 4 p.u..

The second part of filter capacitor voltage $u_{onC(I)}(t)$ can simply determined as the sum of the steady state voltage $u_{BB}(t)$ and the transient voltage (at the filter eigenfrequency ω_e).

$$u_{onC(I)}(t) = \hat{u}_{BB} \times \left(cos(\omega t) - e^{-\frac{t}{2T}} \times cos(\omega_e t) \right) \qquad (6)$$

The transient capacitor voltage $u_{onC(I)}(t)$ can achieve in the worst case the double value of the steady state busbar phase-to-ground voltage amplitude.

As above explained, the overvoltage during energizing the filter bank, especially in the case of already charged capacitor (i.e. reclosing), can lead to a high stress of the filter bank elements, and it must be considered before selecting the insulation level of the elements. In order to achieve a longer lifetime for the filter elements, it is important to reduce their stress and to take measures, for example using a controlled switching, for reducing the overvoltage as well.

3.3 Controlled Switching

A simple but effective solution for reducing overvoltage can be applying a controlled circuit breaker to connect the filter bank. By such a circuit breaker, a synchronizing unit switch each phase of the circuit breaker at its voltage zero crossing $u_{BB}(t)$.

Figure 7 shows the simulation results by connecting the filter bank without and by having the filter damping resistance R_F (*2500 Ω*) through a controlled circuit breaker. In practice, the exact determination of closing time of circuit breakers is not possible and they close usually with a delay time, which may be different for each phase of circuit breaker. In order to have realistic results by simulations, this delay time should be considered.

In Figure 7, the delay time is considered to be *0.5* ms and *1 ms* for the phase L3 and L2, respectively, and for the phase L1, the switching happens approximately at zero crossing of the filter voltage.

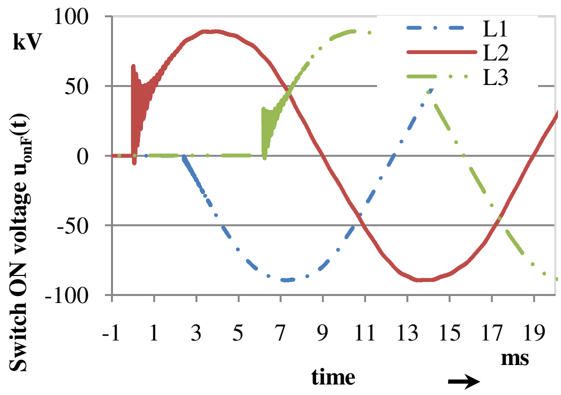


Figure 7: Voltage transient $u_{onF}(t)$ by connecting the filter bank (without damping resistance R_F

By using the damping resistance R_F, the filter current I_F reaches its steady state condition after one period by abating the wave transients.

But the maximum value of inrush current due to traveling wave is not affected by the damping resistance R_F. It depends significantly on phase angle φ_u and its corresponding amount of travelling waves.

4 DE-ENERGIZING FILTER BANK

De-energizing the filter bank can lead to high stress above all for the circuit breaker, which is comparable with switching of large capacitors. The equivalent circuit used by simulations to analyze de-energizing the filter bank is shown in Figure 8.

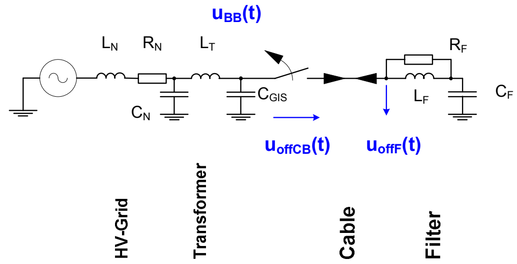
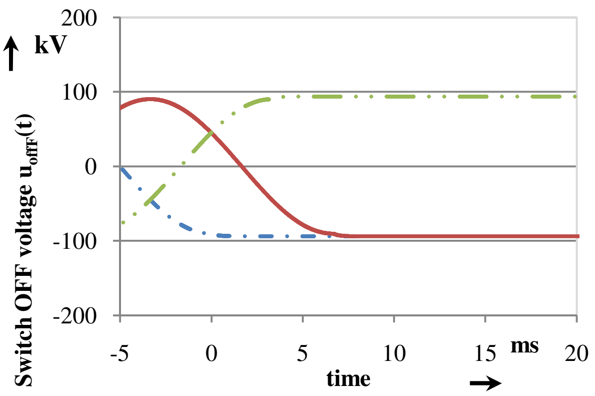


Figure 8: Equivalent circuit to analyze de-energizing the filter bank

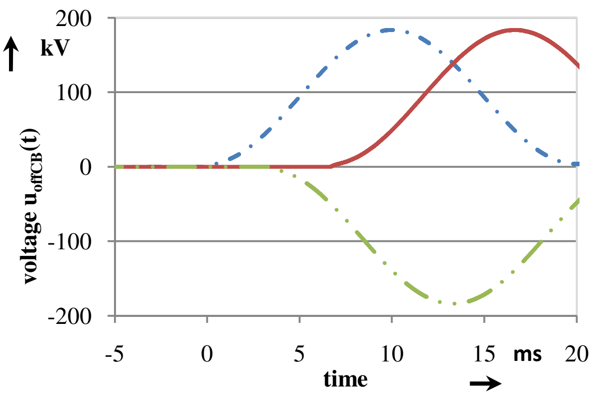
By grounded filter bank, the voltage across circuit breaker contacts achieves in *10 ms* after current zero crossing its maximum value which can be determined by (7):

$$\hat{u}_{offCB} = \frac{2\times\hat{u}_{BB}}{\sqrt{3}} = \frac{2\times 110\ kV\times\sqrt{2}}{\sqrt{3}} \approx 180\ kV\ \ (2\ p.u.) \quad (7)$$

Figure 9 depicts the simulation results by de-energizing the grounded filter bank.



(a) Filter voltage $u_{offF}(t)$



(b) Voltage across circuit breaker contacts $u_{offCB}(t)$

Figure 9: Voltages after disconnecting the grounded filter bank:

In the case of ungrounded filter bank, which is not usual for the high voltage networks, the voltage across circuit breaker contacts can achieve in *10 ms* after switching its maximum value given by (8).

$$\hat{u}_{offCB} = \frac{3\times\hat{u}_{BB}}{\sqrt{3}} \approx 3\ p.u. \quad (8)$$

By de-energizing the filter bank, if the circuit breaker contacts open near to current zero crossing, the switching arc is quenched at really slight distance between the circuit breaker contacts. But after *10 ms*, the voltage across the contacts raises to the double value of the busbar voltage, and it may lead to restrike of circuit breaker. Nowadays, there are some circuit breakers, e.g. class C2, which are able to prevent restriking of circuit breaker with a high probability.

In the case of restriking near to the busbar voltage amplitude, it is possible to appear a high steep overvoltage. The resulted wave transients with amount of 2 p.u. lead to an overvoltage for the filter inductor L_F with a maximum value of 4 p.u.. The high frequency transient may overlap together. The eigenfrequency of these transients can be derived from the parameters of GIS.

5 CONCLUSION

In order to prevent insulation faults, knowing the maximum possible overvoltage by switching operations is required. For this purpose, only analyzing the filter bank is not enough. It is more important to consider all other network parameters and elements.

Through an equivalent model for the filter bank, the overvoltage for each switching operation has been calculated. The derived overvoltages can be used as input information by choosing electrical equipment as well as overvoltage protection devices.

In Table 2, the maximum value of transient overvoltages for various switching operations is given in p.u. (the base voltage is the rated busbar phase-to-ground voltage amplitude $\hat{u}_{BB}$).

Table 2: Calculated maximum value of transient voltages (by grounded filter)

	maximum value û (phase-to-ground) p.u.					
	analytical value			*simulated value*		
	L_F	C_F	R_F	L_F	C_F	R_F
Energizing	*2.0*	*2.0*	*2.0*	*2.1*	*1.9*	*2.1*
Reclosing	*4.0*	*3.0*	*4.0*	*4.8*	*2.9*	*4.8*
CB Restrike	*4.0*	*-*	*4.0*	*3.7*	*-*	*3.7*

As seen in Table 2, the simulated values are considerably greater than analytically calculated ones. It can be a result of overlapping different transients which are related to GIS as well as the cables connected to it.

The maximum value of overvoltage can happen by the filter inductor L_F and damping resistance R_F. By energizing the cable, some overvoltages can appear which are greater than the double value of busbar voltage amplitude $\hat{u}_{BB}$.

If the calculated overvoltages exceed the rated voltage of filter elements (impulse withstand level, SIL), it is necessary to take overvoltage protection measures.

A phase-to-ground overvoltage protection at filter bank limits the filter voltage under its residual value u_{res}. But the voltage across inductor $u_{onL}(t)$ cannot be only slightly affected.

In order to protect the filter elements L_F and R_F, surge arresters should be installed across the filters elements. In this way, the inductor and also damping resistance voltage can be effectively limited.

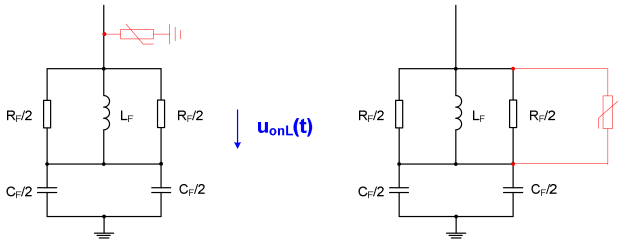


Figure 9: Installation of surge arrester as overvoltage protection:
(a) Surge arrester across the filter
(b) Surge arrester across the filter inductor L_F

Applying a circuit breaker with ability of controlled switching can reduce stress of the filter bank. Switching near to zero crossing of the busbar voltage decreases the overvoltages under 1 p.u..

De-energizing the filter bank can lead to a high stress for the filter circuit breaker. By selecting the filter bank circuit breaker, switching under capacitive current must be taken into account. In this case, it may be also possible to apply controlled switching. With the aid of controlled switching, opening of circuit breaker contacts can be done during the first third of the half period of capacitor current $i_F(t)$ in order to make having enough time to recovery possible.

Re-closing of filter circuit breaker (as long as the capacitor is still charged) should be avoided. It can be carried out either by interlocking the filter circuit breaker in dependence of the capacitor voltage or by applying controlled switching.

6 REFERENCES

[1] KÖTTNITZ, WINKLER, WEßNIGK; Grundlagen elektrischer Betriebsvorgänge in Elektroenergiesystemen; Deutscher Verlag für Grundstoffindustrie, Leipzig 1986

[2] IEC 62271:100 :2001; High-voltage switchgear and controlgear Part 100; High-voltage alternating-current circuit breakers