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Improved Control Strategy for AC-Filters Switching in UHVDC Converter Station

LI Hui, WANG Xiaofei, YU Bin, LIU Haifeng, XU Hao, GUO Siyuan
State Grid Hunan Electric Power Corporation Limited Research Institute, Changsha 410007, China
E-mail: lihui4219@sina.com.cn

Abstract. The AC-filter configuration, reactive power consumption, reactive power control function, switching and replacement strategy in SHANSHAN UHVDC converter station are introduced in detail. The various types of AC filters in the converter station are evenly configured in the large groups of filters based on their quantity. And the related types of filters within a large group are usually switched preferentially. The problem of this switching strategy that may cause large impact on the AC system and long reactive power recovery time during the large group of AC filter bus lines fault are analyzed. Then an improved strategy that the needed filters with same type are equally switched on the large AC-filter group is proposed. The proposed strategy can effectively reduce the influences of AC-filter bus fault to the AC system which will give some references for the design and operation of subsequent UHVDC projects.

1. Introduction

The AC-filter is an important part of the DC system in the converter station. It is mainly used to filter out the harmonics generated by the converter in the inverter process and provide reactive power compensation for the DC system, which directly affects the size of the transmission power and the power quality of the DC transmission system [1]-[9]. Take the example of the QISHAO (JIUHU) ±800 kV UHVDC transmission project. This UHVDC transmission project starts from Jiuquan in Gansu Province to Xiangtan in Hunan Province, with a total length of 2361.5 kilometers. It carries the strategic mission of national clean energy delivery and air pollution prevention and control [1]-[2]. SHANSHAN Converter Station, as the receiving end converter station of the project, shoulders the heavy responsibility of converting DC to AC and feeding it into Hunan Power Grid. Due to the large transmission capacity, the reliability of the equipment in the station will directly affect the safe and stable operation of the entire DC system and even the Hunan power grid.

Compared with the UHVDC projects that have been put into operation, the receiving end of the QISHAO UHVDC transmission project——Hunan Power Grid, due to its unreasonable power supply layout, results in the AC system exhibiting weak reactive power support capabilities and low voltage stability margins. The system features make the significance of reactive power control strategies more prominent in this project.

In this paper, the AC-filter configuration, reactive power consumption and reactive power control functions in SHANSHAN converter station are introduced in detail, and the switching and replacement control strategies of the AC-filter in the station are emphatically analyzed. It is pointed out that the existing switching strategy may cause problems such as large impact on the AC system and long reactive power recovery time when the large group of AC filter bus lines in the station fails, which may further affect the safe and stable operation of the connected AC weak systems. On this basis, an improved input strategy is proposed that when the same type filter is put into operation, the

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average input of the filters in each group is prioritized, which effectively reduces the impact and influence of AC bus fault on the AC system in the station. The research results can provide reference for optimization of UHVDC reactive control strategies.

2. SHANSHAN converter station AC-filter configuration

According to the Q/GDW 146-2006《Technical guide for reactive power compensation and allocation of HVDC converter stations》, DL/T 5426-2009《System design standard for ±800kv HVDC system》 and other standard specifications. The SHANSHAN converter station is equipped with a total of 4 groups and 19 sub-groups of AC filters, which can provide up to about 4940 MVar reactive power support: Among them, the HP-12/24 filter has 8 sub-groups, mostly used to filter 12th and 24th order harmonic; HP-3 filter has 2 sub-groups, mainly used to filter 3rd order harmonics; SC capacitor has 9 sub-groups, mainly used for reaction compensation. In addition, two low-voltage reactors are also deployed on the low-voltage side of the transformer used in the station to participate in reactive power control and adjustment. The specific configuration parameters, main circuit diagrams and grouping situations of various types of AC filters and reactors in the station are shown in Table 1, Figure 1 and Figure 2.

Table 1. Configuration of AC-filters and reactors at SHANSHAN converter station

Equipment type	Number of configuration groups	Single group capacity（MVar）
HP12/24	8	260
HP3	2	260
SC	9	260
Low resistance	2	60(Inductive Reactive Power)

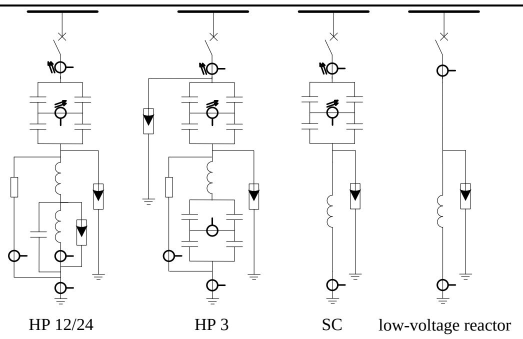

Figure 1. Circuit diagrams of AC-filters and reactors

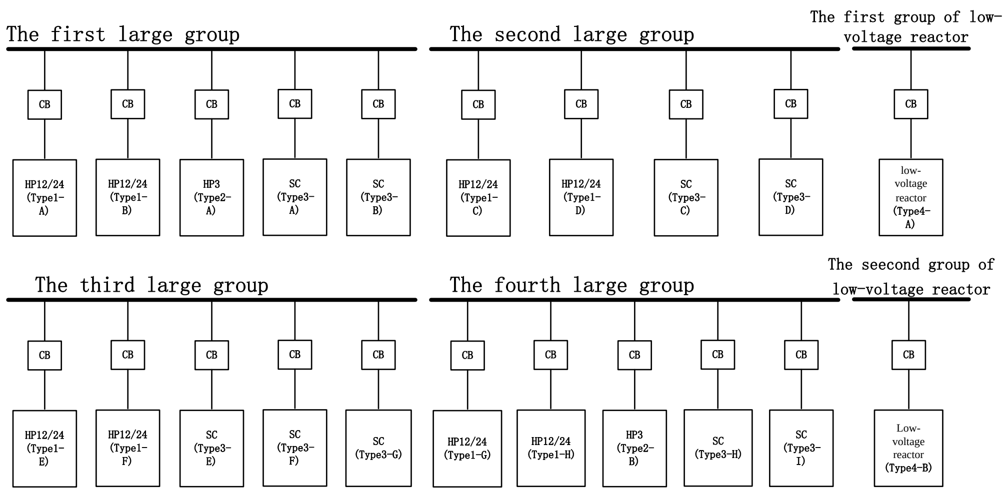

Figure 2. Grouping situations of AC-filters and reactors at SHANSHAN converter station

3. Reactive power control strategy at SHANSHAN station

The main control object of reactive power control is the AC filter (including low-voltage reactor) in the converter station. The main purpose of reactive power control is to guarantee the reactive power exchange between the converter station and the AC system within the allowable range or the AC bus voltage within the safe operation range, which is achieved by controlling the switching of the AC filter and the calculation of the reactive power consumption in the converter station according to the operating mode and working condition of the current DC system. In addition, the safety of AC filter equipment and the influence of harmonic on AC system should also be considered and realized in the reactive power control functions [10]-[15].

3.1. Calculation of reactive power consumption

The reactive power consumed by a 12 pulse converter can be expressed as:

$$Q_{\mathrm{d}} = 2\chi I_{\mathrm{d}} U_{\mathrm{di0}} \tag{1}$$

Where χ is a function of the commutation overlap angle μ, for the inverting side:

$$\chi = \frac{1}{4}\frac{2\frac{\pi}{180}\mu + \sin 2\gamma - \sin 2(\gamma+\mu)}{\cos\gamma - \cos(\gamma+\mu)} \tag{2}$$

The commutation overlap angle on the inverter side can be calculated according to formula (3):

$$\mu = \arccos(\cos\gamma - 2d_{\mathrm{xN}}\frac{I_{\mathrm{d}}}{I_{\mathrm{dN}}}\frac{U_{\mathrm{di0N}}}{U_{\mathrm{di0}}}) - \gamma \tag{3}$$

Where: Q_{d} is reactive power, the unit is MVar; I_{d} is direct current, the unit is kA; U_{di0} is an ideal no-load DC voltage with a unit of kV; γ is the trigger angle of the inverter side (turn off angle), the unit is degree; μ is the phase overlap angle, the unit is degree; d_{xN} is the inductive DC voltage drop, per-unit value; the I_{dN} is the rated DC current, the unit is kA; the U_{di0N} is the rated ideal no-load DC voltage, the unit is kV.

According to equations (1)-(3), the relationship between I_{d}, γ and reactive power can be obtained as shown in Figure 3.

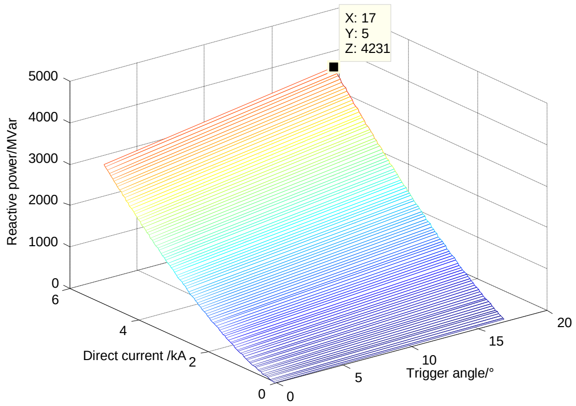

Figure 3. Relationship of reactive power, I_{d} and γ

As shown in Figure 3, reactive power consumption in converter station increases with the increase of DC current or γ. For SHANSHAN Converter Station, the reactive power consumption is 4231MVar under rated conditions (bipolar 4-valve bank, rated current 5kA, γ=17°). Taking into account the certain overload capacity of the DC system, the total reactive power consumption will increase, but the AC filter bank configured in SHANSHAN converter station can still match the reactive power consumption requirements in the station.

3.2. Reactive power control function

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The reactive power control function in the DC pole control host collects the operating parameters of the entire station, and switches the AC filter according to the power transmission level of the DC system and the reactive power consumption. The main control functions and the priority are shown in Table 2.

Through the six reactive power control sub functions described in Table 2, the reactive power exchange between the converter station and the AC system is within the allowable range or the AC bus voltage is within the safe operating range, whether in normal or fault conditions. On the other hand, it also effectively prevents the harmonic overload of the AC filter equipment in the converter station, protects the safe operation of the AC filter equipment and suppresses the influence of the station harmonics on the AC system.

Table 2. Functions and priorities of reactive power control

function name	Functional description	priority
Over voltage control	When the AC voltage reaches the reference value, quickly cut the AC filter to fulfil the absolute minimum filter requirement	1
Absolute minimum filter control (Abs Min Filter)	Filter bank required to prevent overloading of filter equipment (this condition must be satisfied during normal operation)	2
Highest/lowest voltage limit (U_{max}/U_{min})	Used to monitor and limit the steady state AC bus voltage of converter station	3
Maximum reactive switching limit (Q_{max})	Limit the number of input filter banks and limit the steady state overvoltage according to the current operating conditions	4
Minimum filter capacity requirement （Min Filter）	Minimum filter bank required to meet the requirements of filtering out harmonics	5
Reactive power control/voltage control ($Q_{control}$/$U_{control}$)	Control the reactive power exchange (or AC bus voltage) in the station to match the set reference value	6

The priority of each sub-function in reactive power control is mainly used to coordinate the switching filter bank instructions issued by each sub-function. A switching instruction issued by a sub-function is valid only when it does not conflict with a higher-priority constraint. The priority of the above six reactive control sub-functions is from 1 to 6, and the priority levels are reduced in turn.

3.3. Filter bank switching strategy

3.4. Filter bank switching principle

During the rise and fall of DC power, input and excision of AC-filter banks must follow certain principles and sequence. In general, first of all, it is necessary to ensure the safe operation of the AC-filter device, that is, to prevent the AC-filter harmonic overload occurring, which is generally achieved by the absolute minimum filter control; Secondly, the influence of the harmonics in the station on the AC system should be considered. That is, the harmonics in the station should be suppressed within a certain level, which is generally controlled by the minimum filter capacity requirement. In addition, it is also necessary to ensure that the reactive power exchange between the converter station and the AC system is within the allowable range or the AC bus voltage is within the safe operation range, which is generally implemented by AC overvoltage control, maximum/minimum voltage limitation, maximum reactive power exchange limitation, reactive exchange control/voltage control, etc.

The switching points of the absolute minimum filter and the minimum filter are usually determined by the AC filter research report; Reactive power control ($Q_{control}$) is determined by calculating the reactive power exchange quantity ΔQ on both sides of AC and DC in real time. ΔQ can be calculated from equation (4):

$$\Delta Q = Q_{d} - \sum Q_{filter} \tag{4}$$

Where: Q_d is the total reactive power consumed by the converter in the station and can be calculated by formula (1)-formula (3). ΣQ_{filter} is the reactive power provided by the filter/shunt capacitor bank and can be calculated by equation (5):

$$\sum Q_{filter} = \sum_{n=1}^{N} \left(\frac{U_{ac}}{U_{acN}} \right)^2 * \frac{f_{ac}}{f_{acN}} * Q_{filterNn} \tag{5}$$

Where: U_{ac} is the actual voltage of the AC system, the unit is kV; U_{acN} is the rated voltage of the AC system, the unit is kV; f_{ac} is the actual frequency of the AC system, the unit is Hz; f_{acN} is the The rated frequency of the AC system, the unit is Hz; $Q_{filterN}$ is the rated working condition of the filter/shunt capacitor bank, that is, reactive power supplied under U_{acN} and f_{acN}. n is the number of filter/capacitor groups actually put into operation.

When the amount of reactive power exchange on both sides of AC and DC exceeds the limit value, the instruction is issued to control the switching of the filter/shunt capacitor bank, that is, when the equation (6) is satisfied, a command to excise AC-filter/shunt capacitor bank is issued. When the equation (7) is satisfied, a command to input the AC-filter/parallel capacitor bank is issued.

$$\Delta Q > Q_{ref} + Q_{dband} \tag{6}$$

$$\Delta Q < Q_{ref} - Q_{dband} \tag{7}$$

Where: Q_{ref} is the reference value set by the operator, the unit is MVar; Q_{dband}(Q_{dband}>$Q_{filterN-max}$/2) is the dead zone of the action set by the operator, the unit is MVar. In addition, considering that when the DC system is running at low power and the absolute minimum filter is guaranteed, there will usually be an excess of reactive power compensation at the converter station. Generally, low-voltage reactors are added to absorb excess reactive power.

Table 3 shows the switching power point of the AC-filter determined by the absolute minimum filter and the minimum filter condition under the operating conditions of the bipolar 4 valve group in SHANSHAN converter station. As shown in Table 3, the power points required by the minimum filter are usually less than the power points required by the absolute minimum filter after the start of the pole. Therefore, the minimum filter is normally required to issue an input filter instruction prior to the absolute minimum filter requirement.

Table 3. Configurations of abs min filter and min filter at SHANSHAN converter station

Input filter bank number	HP 12/24	HP 3	Absolute minimum filter corresponding power point (MW)	Minimum filter corresponding power point (MW)
1	1	0	0	0
2	2	0	1582	1190
3	3	0	3128	2360
4	3	1	4265	3129
5	4	1	6115	4265
6	5	1	7197	5381
7	6	1	-	6478
8	6	2	-	7900

Figure 4 shows the switching sequence of filter/capacitor bank in SHANSHAN converter station from blocking to 1.0 p.u. power, then to blocking. As can be seen from Figure 4, each reactive control sub-function issues a switching command to control the switching of the filter/capacitor group according to its own requirements. When the power rises, the number of AC-filters/capacitors that are put into operation gradually increases, and the AC-filter input order is: HP12/24→HP12/24→HP12/24→HP3→HP12/24→HP12/24→HP12/24→HP3→HP12/24→HP12/24→SC→SC→SC→SC→SC→SC(→SC→SC→SC) (The last three groups of capacitors serve as backup).

During light load (the transmission power is less than 2000MW), the input of the filter is mainly issued by the minimum filter and the absolute minimum filter control function. It shows that the system is mainly restricted by the harmonic characteristics of the converter station access point and the performance of the AC-filter equipment, and a certain amount of AC-filter banks must be put into the system. However, due to the reasonable selection of AC-filter single-group capacity and the cooperation of low-voltage reactors, the reactive power exchange ΔQ on both sides of AC and DC does not exceed the Q_{control} limit. With the continuous rise of the power, more and more reactive power is consumed in the station. Q_{control} gradually seizes the control. When ΔQ exceeds the limit, a set of filters is input in order.

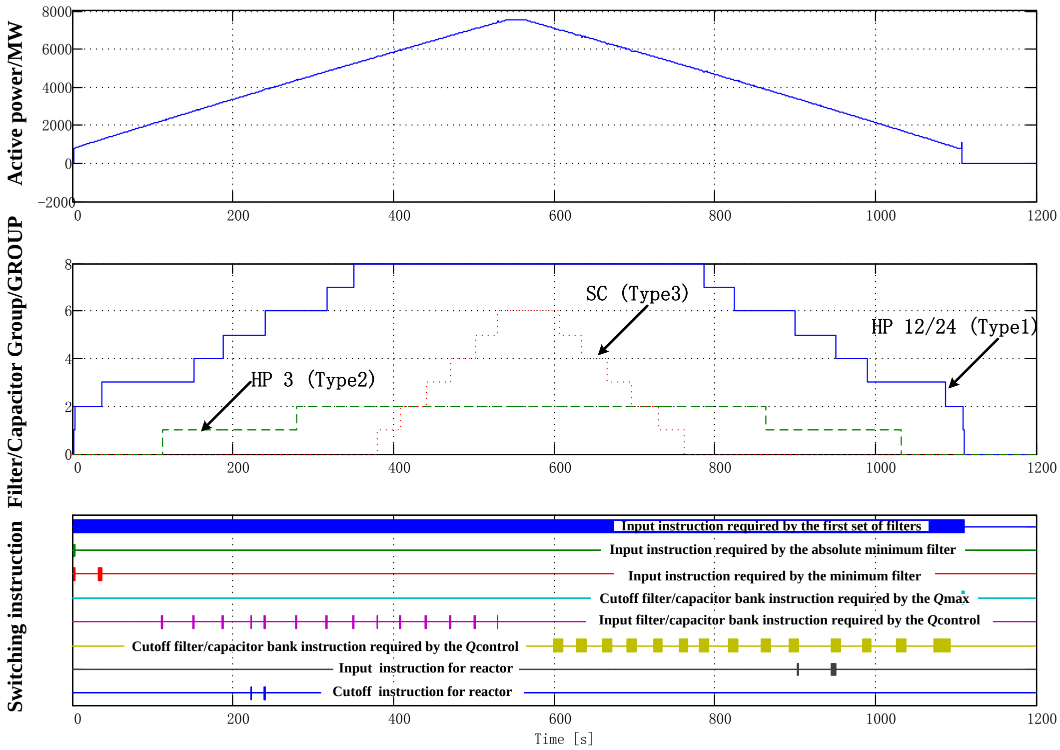

Figure 4. Switching of AC-filter during active power change

When the power of the DC system drops, the AC-filter is gradually removed, and the cut order is opposite to the power rises.

3.5. Filter bank replacement principle

As shown in Figure 5, when the AC filter is removed due to an unusual action such as a protection action or a switch sneak-off, the reactive power control sub-function of the AC filter will issue a filter input command to control the input of the filter, since the original reactive power balance is destroyed. As mentioned earlier, the Abs Min Filter is the least filter bank required to prevent harmonic overload of AC-filter. Therefore, when the Abs Min Filter is not satisfied, the resected filter will be replaced by the same type of filter. If there is no available same type filter at this time, the power return command will be executed to meet the absolute minimum filter bank condition. If the power dropped to the last stage still fails to meet the absolute minimum filter bank requirement, the reactive power control will stop the DC system after the default time delay.

When the requirement of harmonic filtering is not satisfied, the Min Filter module is used to send the input instruction of AC-filter group, and the resected filter is replaced by the same type of filter. If there is no available same type filter at this time, an alarm signal is sent to the operator, and the operator decides whether or not to perform power back-off.

In the same way, when the voltage or reactive power exchange capacity does not meet the requirements, U_{min}, $U_{control}$, $Q_{control}$ and other functions will issue instructions to input the AC-filter for replacement.

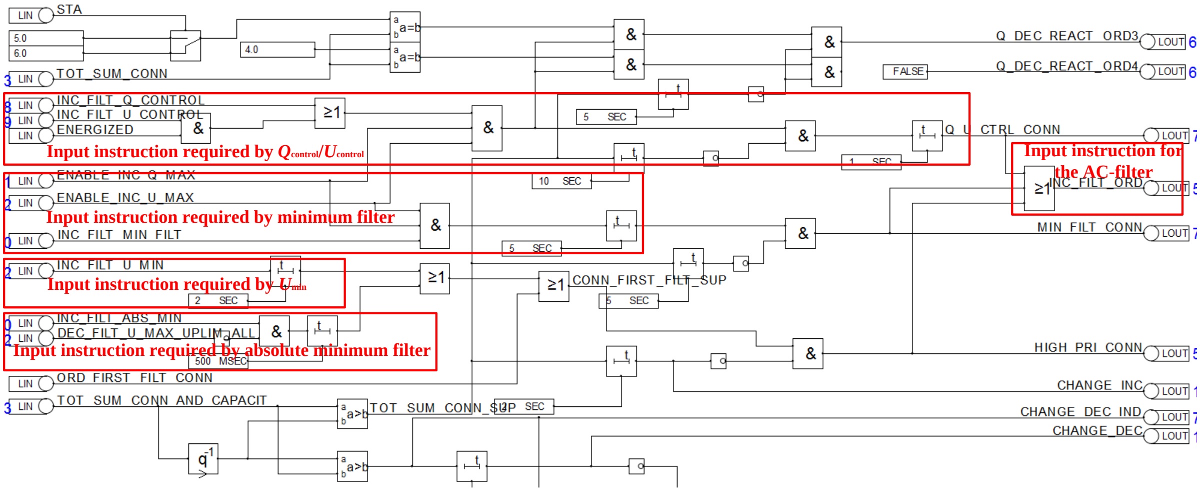

Figure 5. Replacement of AC-filterOptimization of Reactive Power Control Strategy in SHANSHAN Station

3.6. Requirement of transient voltage change rate

According to the Q/GDW 146-2006《Technical guide for reactive power compensation and allocation of HVDC converter stations》, the voltage change rate caused by reactive group switching should generally not exceed 1.5%~2%; The change rate of the transient voltage of the bus bar at the converter station caused by the large group of reactive power removal is generally not more than 5%~6%.

The following relationship exists between the each group of AC filter reactive power capacity in the converter station and the transient voltage change rate of the AC bus:

$$\Delta U = \frac{\Delta Q_{\text{filter}}}{S_{\text{d}} - \sum Q_{\text{filter}}} \tag{8}$$

Where: ΔU is the transient voltage change rate of the AC bus of the converter station; ΔQ_{filter} is the each group of AC filter reactive power capacity in the converter station, and the unit is MVar; S_{d} is the short-circuit capacity of the AC bus of the converter station and the unit is MVA.

Taking SHANSHAN converter station as an example, according to formula (8), the voltage change rate caused by switching a group of filters is about 1.2%; the maximum voltage change rate caused by removing a large group of reactive power is about 5.9%, which meets the standard requirements. However, taking into account the relatively heavy load in the near area of SHANSHAN converter station, poor dynamic reactive power support capability, and the low voltage problem of the power grid, the removal of large groups of filters will result in large transient voltage fluctuations, which is obviously very unfavorable for the operation of the Hunan power grid. Therefore, how to reduce the influence of the removal of large group filters on the AC system and the AC-filter equipment in the station should be considered as much as possible on the basis of the existing filter configuration.

3.7. Problems with existing strategies

The various types of filters of the SHANSHAN converter station are usually evenly configured in the large groups of filters based on the quantity, as shown in Figure 2, and 8 groups of HP12/24 filters are evenly distributed to four large filter groups. 2 groups of HP3 filters are evenly distributed to two filter large groups. 9 groups of SC capacitors are evenly distributed to four filter large groups. During the DC system operate at high power level(in this situation, the AC filters except some capacitor bank are all put into use), this configuration can avoid the power fall back caused by the mismatch of the Abs Min Filter requirements when a large group of filters is cut off. The input of the filter is considered by a large group of filters. That is, according to the input sequence, the related types of filters within a large group are preferentially used. Then the input of the next large group of filters is considered. In actual operation, the two groups of HP12/24 filters in the first large group are preferentially put into operation according to the order, and then a group of HP12/24 filters in the second large group are put into operation. Next, a group of HP3 filters in first large group are put into operation, etc.
Assuming the current transmission power of the SHANSHAN converter station is 2000MW, as mentioned above, the function of reactive power control will put into two groups of HP12/24 filters in the first large group, and then put into a group of HP12/24 filters in the second large group. If the bus of the first group of filters fails at this time, the two sets of filters connected to this group of filters will be cut off. With reference to the replacement logic diagrams shown in figure 5 and figure 6, and the switching power points of Abs Min Filter and Min Filter shown in Table 3, both the Abs Min Filter and the Min Filter conditions are not satisfied. The Abs Min Filter has higher priority than the Min Filter. It will give priority to request input of filter instructions and replace the already-removed filter with the same type of filter. The first HP12/24 filter is put into operation at 0.5s, and the second HP12/24 filter is input after a delay of 2s, for a total of 2.5s to complete the replacement. During the replacement process, although DC system blocking and power back-off will not occur, it can be known from equation (8) that the maximum transient voltage disturbance of the AC bus will reach 2.447%. Meanwhile, the running filters will withstand the harmonic overload of 2.5s. Also, the power quality of the transmission power cannot not meet the requirements (Min Filter is not satisfied). Taking into account the weak power supply characteristics of Hunan power grid, this result is extremely unfavorable for the safety and stability of Hunan power grid and AC filter equipment in the station.

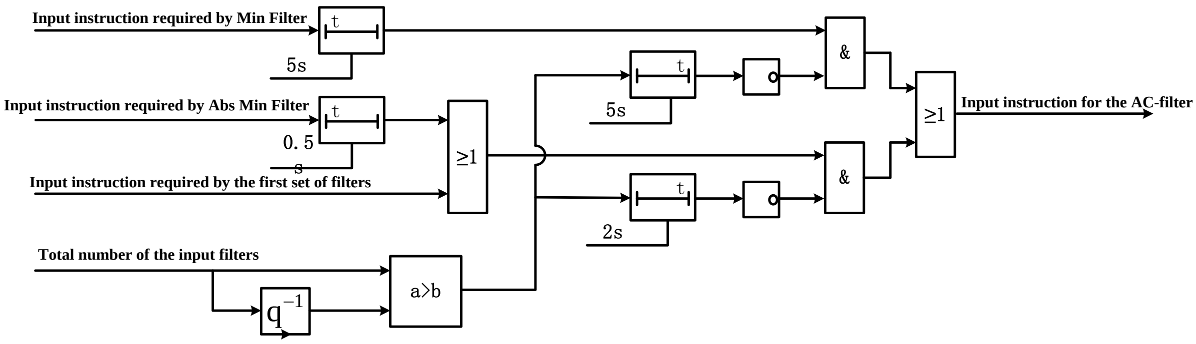

Figure 6. Automatic replacement logic of AC-filter with Abs Min Filter and Min Filter not fulfilled

3.8. Improve control strategy

If the input strategy of the same type filters is changed. The same type filters are evenly input among the large groups of filters preferentially instead of the related types of filters within a large group being preferentially used. It can effectively shorten the recovery time and reduce the harmonic and voltage disturbance. It is still assumed that 3 groups of HP12/24 filters are used in the SHANSHAN station, but unlike the existing strategies, the 3 groups of HP12/24 filters are evenly put into operation from the first large group to the third large group, that is, each large group has one small group. If the first large group of filter bus faults still occurs at this time, only one HP12/24 type filter will be removed. According to the calculation of (8), the maximum transient voltage disturbance of the AC bus will be reduced to 1.223%. Meanwhile, because the replacement time will be shortened to 0.5s, the running filter withstands harmonic failure and transmission power quality failure time will also reduce synchronously to 0.5s, which will greatly reduce the impact on Hunan power grid.

Table 4 shows the comparative results of switching optimization strategy in SHANSHAN Converter Station. It can be seen that the performance with the proposed strategy has improved significantly compared to the existing strategies.

If only two sets of AC filters are put into use in SHANSHAN converter station. When the first large group of bus faults occurs, the recovery time is slightly different from that of the three groups filters used, because the existence of “first set of filters require input commands”, the recovery time is 2s. However, it is still longer than the optimized switching strategy, as shown in Table 4. The replacement time of other filter input groups and the influence on the grid can be analyzed in the same way.

Table 4. Comparative analysis of switching optimization strategy at SHANSHAN converter station

Input filter bank number		Before optimization	After optimization
3	Resection filter number (group)	2	1
	Maximum transient voltage change rate (%)	2.447	1.223
	Recovery time (s)	2.5	0.5
	Whether it will cause DC blocking	no	no
	Whether it will cause DC power back drop	no	no
2	Resection filter number (group)	2	1
	Maximum transient voltage change rate (%)	2.417	1.209
	Recovery time (s)	2	0.5
	Whether it will cause DC blocking or tripping	no	no
	Whether it will cause DC power back drop	no	no
Minimum short circuit capacity[1] (MVA)		21914	

When the system is running at high power level with the AC filter fully input, the replacement is unavailable, so the reactive power shortage and voltage disturbance can only be reduced by the Q_{control} input capacitor bank. When using this method, the capacitor bank is also preferred to put into use evenly among the large groups of filters. When the single bus fault occurs, especially the previous groups of AC-filter bus faults, the number of excised filters will be less than the original strategy. Thus, with the proposed strategy, the recovery time is shorter and the impact on the system is smaller.

Of course, the influence of voltage disturbances on AC system can be further suppressed and better control effects can be obtained through the adjustment of γ-kick (transition angle transient control), SVC, STATCOM and synchronous condenser [16], etc.

4. Conclusion

In this paper, the AC-filter configuration, reactive power consumption, reactive power control function, switching and replacement strategy in SHANSHAN UHVDC converter station are introduced in detail. An improved strategy that the needed filters with same type are equally switched on the large AC-filter group is proposed to reduce the influences of AC-filter bus fault to the AC system. Considering that the power grid in Hunan will not be able to operate under heavy load for a long period of time in the future. In this case, the filter will have a large amount of redundancy, Compared with the existing strategy, the proposed strategy can effectively reduce the impact on the AC system, shorten the recovery time and reduce harmonics and voltage disturbances when the failure of the filter bus in the station, which has positive significance for the safe operation of Hunan power grid. The method proposed in this paper also has certain reference significance for the design and operation of subsequent HVDC transmission projects.

With the application of the synchronous condenser, SVC and STATCOM in UHVDC transmission project, the interrelationship and coordination control strategy of these equipments are the subjects for further investigations.

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