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CENTRALIZED COMPENSATION OF HIGH HARMONICS IN ELECTRICAL NETWORKS

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Summary: **The problems of choice of filter-compensating devices in electrical networks with nonlinear loads are considered. The method of centralized compensation of high harmonics is offered. The example of centralized compensation of high harmonics in electrical supply systems with nonlinear loads is given.**

Filtration of high harmonics by means of connecting a filter-compensating device (FCD) to the network points to which non-linear loads are connected is predominant in electrical engineering practice. However, in large distribution networks with a number of high harmonics (HH) sources such a solution turns out to be quite expensive and the degree of reactive power compensation might be higher than required.

Centralized correction of non-sinusoidal modes in some cases is more economical. The idea of high harmonics centralized filtration implies compact placing of one or more FCD in one of the distribution network sub-stations, providing the reduction of non-sinusoidality to the allowable value within all network points.

To select the possible FCD installation sites during the first stage it is necessary to perform calculations of voltage non-sinusoidality by means of installing four ideal filters for 5, 7, 11 and 13 harmonics sequentially at each point. To perform this it should be assumed in the calculation that short circuit occurs at the given point at the frequency of these harmonics. This is realized by adding the following value to the proper conductivity of the point under consideration:

$$Y_F(\nu)=\begin{cases}0, & \nu \neq 5,7,11,13\\ \infty, & \nu = 5,7,11,13\end{cases}$$

After the non-sinusoidality levels for each variant of the centralized installation of FCD have been defined, only those points in which FCD installation provides for reducing non-sinusoidality to the levels specified by the standards, are selected. It should be noted that the non-sinusoidality coefficient values, obtained as the result of the proposed calculation method, can be both: somewhat less or somewhat more than the real values after the FCD have been installed. This may be explained by the following:

- — variance in the number of filters and the number of harmonics in the network;
- — inaccuracy of adjustment and the presence of resistance of filters;
- — neglect of cumulative effect produced by HH current sources, located in different points of electrical network,
- — changes in network configuration which results in changes of its amplitude-frequency characteristics.

As a rule, The most rational installation site is the main busbars of the sub-station (immediately following the supply transformer). However, it is advisable to determine it by way of variant calculation. Experience and engineering intuition will help to decrease its volume.

After the FCD for centralized filtration has been chosen, it is necessary to consider other operating conditions of the network, maintenance condition in particular, because it is under these conditions that resonance occurs which causes, as a rule, a considerable increase on non-sinusoidality in individual network points. Analysis of these conditions may demand for introducing corrections in the already made decision. It is desirable that the difference between maximal and minimal reactance values of the supplying system is taken into consideration. Evidently, the application of active filters does not give rise to such fears.

The problem of selecting the FCD power in distribution networks with a number of HH sources is solved by the method of successive approximations. Initially the FCD power in the network point is taken under the assumption that only those harmonic currents to which the FCD is tuned flow through them (basically, a short circuit mode for each harmonic that is supposed to be supplied with a FCD is considered). With consideration of these currents a preliminary FCD power selection is carried out. Further on the harmonic currents in parallel branches are considered taking into account

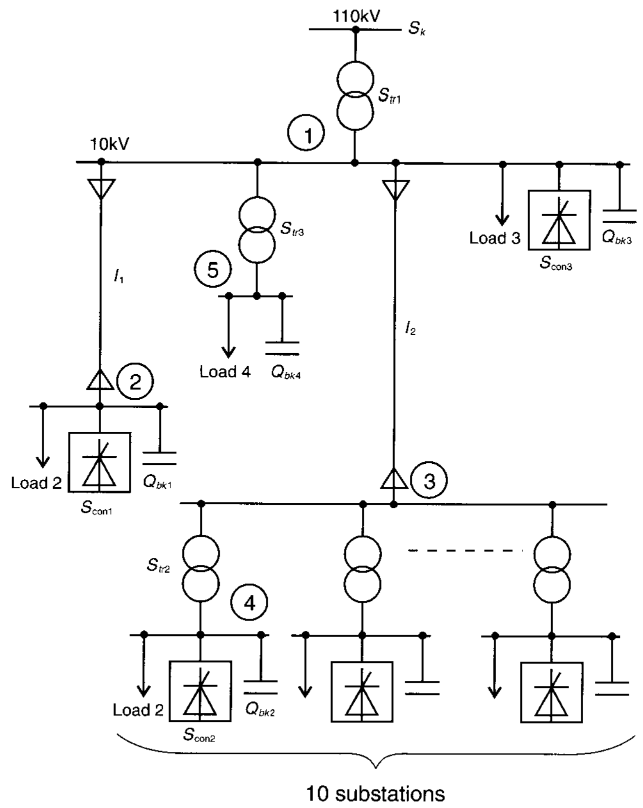

Fig. 1. Electrical power supply system

the pre-selected FCD which is followed by the final selection of FCD by their values (the first approximation). Then the operation is repeated; as a rule it is possible to not to go beyond the second approximation.

Centralized correction of non-sinusoidal modes of distribution networks is most efficient for the system of electrical supply with a stable configuration and loads, i.e. the networks where the parameters can be considered as the determined ones. Centralized installation of FCD in electrical networks of supply systems (110 kV and more) cannot be effective due to the probability nature of their frequency characteristics.

Let us consider the solution of the problem of centralized FCD application on industrial electrical supply system using a concrete example.

Example

Calculations of high harmonics levels in electrical power supply system (Fig.1) are to be performed and the appropriate FCD for centralized compensation of non-sinusoidal voltage is to be selected.

Initial data: short circuit power on busbars 110 kV S_k = 2000MVA; transformer T1 S_{tr1} = 63MVA, U_K = 12%, ΔP_k = 250kW;

point 1: cable line l_1 = 2km, 4 cables with r_0 = 0,028Ω/km, x_0 = 0,075Ω/km; transformer S_{tr3} = 2500kVA, U_K = 10%, ΔP_k = 10kW; cable line l_2 = 4.8km, r_0 = 0.028Ω/km, x_0 = 0.075Ω/km; load S_{n3} = 25 MVA, cos φ = 0.8; 12-phase converter S_{con3} = 5MVA, φ = 30°; capacitor bank Q_{bk3} = 15MVAr;

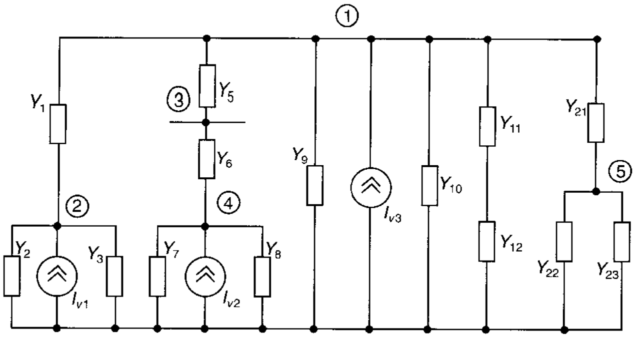

Fig. 2. Equivalent circuit for calculation high harmonic voltage

point 2: load S_{n1} = 15MVA, cos φ = 0.8; 6-phase converter S_{con1} = 15MVA, φ = 10 capacitor bank Q_{bk1} = 8MVAr;

point 3: 10 identical substations, each including transformer S_{tr2} = 2500kVA, U_k = 10%, ΔP_k = 10kW; load S_{n2} = 1.3MVA, cos φ = 0.8; 6-phase converter S_{con2} = 200kVA, φ = 20°; capacitor bank Q_{bk2} = 800kVAr (point 4);

point 5: load S_{n4} = 2MVA, Q_{bk4} = 1MVAr.

For calculating high harmonic voltage equivalent circuit is provided. (Fig.2)

Calculations of high harmonic current are performed applying the method of main potential in the relative values with basic power S_k = 100MVA. Calculation program is based on using mathematical processor Mathcad 7 professional. Below the calculation results are given in the sequence predetermined by the program, except for the input calculation data.

Primarily non-sinusoidal coefficients in the network points have been calculated.

Calculations for the equivalent circuit parameters:
Transformers:

$$Y6(v) = \frac{1}{\sqrt{v\frac{P_{k2}S_b}{S_{tr2}^2}} + jv\frac{u_{k2}\,S_b}{S_{tr2}}}$$

$$Y11(v) = \frac{1}{\sqrt{v\frac{P_{k1}S_b}{S_{tr1}^2}} + jv\frac{u_{k1}\,S_b}{S_{tr1}}}$$

$$Y21(v) = \frac{1}{\sqrt{v\frac{P_{k3}S_b}{S_{tr3}^2}} + jv\frac{u_{k3}\,S_b}{S_{tr3}}}$$

Capacitors bank:

$$Y3(v) := \frac{S_{bk1}}{S_b} \cdot j \cdot v \qquad Y8(v) := \frac{S_{bk2}}{S_b} \cdot j \cdot v$$

$$Y10(v) := \frac{S_{bk3}}{S_b} \cdot j \cdot v \qquad Y23(v) := \frac{S_{bk4}}{S_b} \cdot j \cdot v$$

Kable lines

$$Y1(v) := \frac{1}{\left(r_0\sqrt{v} + x_0 vj\right)\frac{l_1}{4}\frac{S_b}{U^2}}$$

$$Y5(v) := \frac{1}{\left(r_0\sqrt{v} + x_0 vj\right)l_2\frac{S_b}{U^2}}$$

Loads

$$Y2(v) = \frac{1}{\frac{0.8}{S_{n1}}S_b\sqrt{v} + \frac{0.6}{S_{n1}}S_b vj}$$

$$Y7(v) = \frac{1}{\frac{0.8}{S_{n2}}S_b\sqrt{v} + \frac{0.6}{S_{n2}}S_b vj}$$

$$Y9(v) = \frac{1}{\frac{0.8}{S_{n3}}S_b\sqrt{v} + \frac{0.6}{S_{n3}}S_b vj}$$

$$Y22(v) = \frac{1}{\frac{0.8}{S_{n4}}S_b\sqrt{v} + \frac{0.6}{S_{n4}}S_b vj}$$

Electrical supply system

$$Y4(v) = \frac{S_k}{j \cdot v \cdot S_b}$$

Calculation for the elements of conductivity matrix:

v = 1, 2 ... 25

$$Y12(v) = \frac{1}{\frac{1}{Y4(v)} + \frac{1}{Y11(v)}}$$

$$G11(v) = Y1(v) + Y5(v) + Y9(v) + Y10(v) + Y12(v) + Y21(v)$$

$$G22(v) = Y1(v) + Y2(v) + Y3(v) \qquad G44(v) = Y6(v) + Y7(v) + Y8(v)$$

$$G33(v) = Y5(v) + Y6(v) \qquad G55(v) = Y21(v) + Y22(v) + Y23(v)$$

$$G12(v) = -Y1(v) \quad G21(v) = G12(v) \quad G23(v) = 0 \quad G32(v) = G23(v)$$

$$G13(v) = -Y5(v) \quad G31(v) = G13(v) \quad G24(v) = 0 \quad G42(v) = G24(v)$$

$$G14(v) = 0 \quad G41(v) = G14(v) \quad G34(v) = Y6(v) \quad G43(v) = G34(v)$$

$$G15(v) = Y21(v) \quad G51(v) = G15(v) \quad G25(v) = 0 \quad G52(v) = G25(v)$$

$$G35(v) = 0 \quad G53(v) = G35(v) \quad G45(v) = 0 \quad G54(v) = G45(v)$$

Calculations for the elements of current source matrix:

Point 1

12-phase converter 5MVA ϕ=30

$$J11(v) \boldsymbol{=} if\left[(v = 11) + (v = 13) + (v = 23) + (v = 25), \frac{0.05}{v} \cdot \left(\cos\left(30 \cdot v \cdot \frac{\pi}{180}\right) + j \cdot \sin\left(30 \cdot v \cdot \frac{\pi}{180}\right)\right), 0\right]$$

Point 2

6-phase converter 15MVA ϕ=10

$$J22(v) \boldsymbol{=} if\left[(v = 5) + (v = 7) + (v = 11) + (v = 13) + (v = 17) + (v = 19) + (v = 23) + (v = 25), \frac{0.15}{v} \cdot \left(\cos\left(10 \cdot v \cdot \frac{\pi}{180}\right) + i \cdot \sin\left(10 \cdot v \cdot \frac{\pi}{180}\right)\right), 0\right]$$

Point 3

$J33(v) = 0$

Point 4

10 6-phase converter 0.2MVA ϕ=20

$$J44(v) \boldsymbol{=} if\left[(v = 5) + (v = 7) + (v = 11) + (v = 13) + (v = 17) + (v = 19) + (v = 23) + (v = 25), \frac{0.002 \cdot 10}{v} \cdot \left(\cos\left(20 \cdot v \cdot \frac{\pi}{180}\right) + i \cdot \sin\left(20 \cdot v \cdot \frac{\pi}{180}\right)\right), 0\right]$$

Point 5

$J55(v) = 0$

Solution of the equation of main potentials

$j = 1..8 \qquad i = 0..4$

$$A(v) = \begin{bmatrix} G11(v) & G12(v) & G13(v) & G14(v) & G15(v) \\ G21(v) & G22(v) & G23(v) & G24(v) & G25(v) \\ G31(v) & G32(v) & G33(v) & G34(v) & G35(v) \\ G41(v) & G42(v) & G43(v) & G44(v) & G45(v) \\ G51(v) & G52(v) & G53(v) & G54(v) & G55(v) \end{bmatrix}$$

$$B(v) = \begin{bmatrix} J11(v) \\ J22(v) \\ J33(v) \\ J44(v) \\ J55(v) \end{bmatrix} \qquad n_j = \begin{array}{|c|} \hline 5 \\ \hline 7 \\ \hline 11 \\ \hline 13 \\ \hline 17 \\ \hline 19 \\ \hline 23 \\ \hline 25 \\ \hline \end{array}$$

$$\phi(v) = isolve(A(v), B(v))$$

$$Kns_i = \sqrt{\sum_{j=1}^{8}\left(\left|\phi\left(n_j\right)_i\right|\right)^2} \qquad \phi(v,i) = \left|\phi(v)_{i-1}\right|$$

Coefficient of non-sinusoidality in the circuit point

$$Kns = \begin{bmatrix} 6.671 \\ 7.755 \\ 3.686 \\ 12.919 \\ 40.987 \end{bmatrix} \cdot \%$$

HH voltage in point 1

	$\phi(n_j,1)$
$v=5$	0.051
$v=7$	0.038
$v=11$	$7.451\cdot10^{-3}$
$v=13$	$6.529\cdot10^{-3}$
$v=17$	$5.289\cdot10^{-3}$
$v=19$	$5.884\cdot10^{-3}$
$v=23$	0.016
$v=25$	$6.288\cdot10^{-3}$

HH voltage in point 2

	$\phi(n_j,2)$
$v=5$	0.059
$v=7$	0.037
$v=11$	$2.841\cdot10^{-3}$
$v=13$	$2.093\cdot10^{-3}$
$v=17$	$2.238\cdot10^{-3}$
$v=19$	$4.823\cdot10^{-3}$
$v=23$	0.031
$v=25$	0.013

HH voltage in point 3

	$\phi(n_j,3)$
$v=5$	0.034
$v=7$	$8.667\cdot10^{-3}$
$v=11$	$3.983\cdot10^{-3}$
$v=13$	$3.708\cdot10^{-3}$
$v=17$	$3.064\cdot10^{-3}$
$v=19$	$3.295\cdot10^{-3}$
$v=23$	$8.223\cdot10^{-3}$
$v=25$	$3.107\cdot10^{-3}$

HH voltage in point 4

	$\phi(n_j,4)$
$v=5$	0.127
$v=7$	0.026
$v=11$	$2.186\cdot10^{-3}$
$v=13$	$1.226\cdot10^{-3}$
$v=17$	$6.073\cdot10^{-4}$
$v=19$	$4.691\cdot10^{-4}$
$v=23$	$9.867\cdot10^{-4}$
$v=25$	$5.337\cdot10^{-4}$

HH voltage in point 5

	$\phi(n_j,5)$
$v=5$	0.408
$v=7$	0.044
$v=11$	$2\cdot10^{-3}$
$v=13$	$1.157\cdot10^{-3}$
$v=17$	$5.066\cdot10^{-4}$
$v=19$	$4.418\cdot10^{-4}$
$v=23$	$8.23\cdot10^{-4}$
$v=25$	$2.634\cdot10^{-4}$

As it is seen from the calculations, the non-sinusoidal coefficients in four network points considerably exceed the value of 5%, that is why installation of FCD is most desirable. To identify the most rational location for installing FCD, their number and resonant frequencies it is necessary to consider several variants. First, let us consider installation of FCD on general busbars (point 1). Obviously there exist several variants of installing high harmonic filters in point 1.

a) Installing FCD for 5-th harmonic.

To calculate the high harmonic levels after installing the filter it is necessary to evaluate its power depending on the overload power of the capacitor bank. To do this let us define HH currents of all converters from the following equation:

$$I_{conv} = \frac{S_{con}}{\sqrt{3}\ Uv}$$

The results of the calculation are given in Table 1.

Let us assume in the preliminary calculations that main harmonic current and 5th harmonic current flow through the FCD of 5th harmonic.

5th harmonic current flowing through the filter

$$I_{F5} = \frac{I_{con1}(5)}{G_{22}(5)}\cdot Y_1(5) + \frac{I_{con2}(5)}{G_{44}(5)}\cdot \frac{Y_6(5)\cdot Y_5(5)}{Y_6(5)+Y_5(5)} = 194A$$

Table 1

Convector	HH currents, A			
	$v=5$	$v=7$	$v=11$	$v=13$
1	173	124	77	65
2	24	16	10	8
3	—	—	26	22

The preliminary value of the capacitor bank power of the filter of 5th harmonic

$$Q_{bk5} = 1.2K_c \cdot I_{F5} \cdot U = 6.9\text{MVAr}$$

where $K_c = 3$.

Let us assign the following value to the power of capacitor bank of the filter of 5th harmonic $Q_{bk5} = 6{,}9$ MVAr and perform calculations of high harmonic levels on the circuit points after the filter has been installed.

$$k_{ns} = \begin{bmatrix} 7.75 \\ 9.425 \\ 2.904 \\ 5.268 \\ 8.658 \end{bmatrix} \%$$

HH voltage in point 1

	$\phi(n_j,1)$
$v=5$	$4.09 \cdot 10^{-6}$
$v=7$	0.074
$v=11$	0.012
$v=13$	$9.333 \cdot 10^{-3}$
$v=17$	$5.967 \cdot 10^{-3}$
$v=19$	$5.524 \cdot 10^{-3}$
$v=23$	$7.789 \cdot 10^{-3}$
$v=25$	0.013

HH voltage in point 2

	$\phi(n_j,2)$
$v=5$	$6.11 \cdot 10^{-3}$
$v=7$	0.093
$v=11$	0.01
$v=13$	$7.353 \cdot 10^{-3}$
$v=17$	$2.525 \cdot 10^{-3}$
$v=19$	$1.175 \cdot 10^{-3}$
$v=23$	$3.81 \cdot 10^{-3}$
$v=25$	$9.699 \cdot 10^{-3}$

HH voltage in point 3

	$\phi(n_j,3)$
$v=5$	0.017
$v=7$	0.021
$v=11$	$6.104 \cdot 10^{-3}$
$v=13$	$5.011 \cdot 10^{-3}$
$v=17$	$3.396 \cdot 10^{-3}$
$v=19$	$3.121 \cdot 10^{-3}$
$v=23$	$3.558 \cdot 10^{-3}$
$v=25$	$6.517 \cdot 10^{-3}$

HH voltage in point 4

	$\phi(n_j,4)$
$v=5$	0.035
$v=7$	0.039
$v=11$	$2.421 \cdot 10^{-3}$
$v=13$	$1.159 \cdot 10^{-3}$
$v=17$	$5.718 \cdot 10^{-4}$
$v=19$	$4.738 \cdot 10^{-4}$
$v=23$	$4.639 \cdot 10^{-4}$
$v=25$	$5.983 \cdot 10^{-4}$

HH voltage in point 5

	$\phi(n_j,5)$
$v=5$	$3.288 \cdot 10^{-5}$
$v=7$	0.086
$v=11$	$3.318 \cdot 10^{-3}$
$v=13$	$1.654 \cdot 10^{-3}$
$v=17$	$5.715 \cdot 10^{-4}$
$v=19$	$4.148 \cdot 10^{-4}$
$v=23$	$3.388 \cdot 10^{-4}$
$v=25$	$5.352 \cdot 10^{-4}$

Let us estimate the minimal power of the 5th harmonic filter [1] taking into account source currents of all points for $v = 5;7;11;13;17;19;23;25$.

Calculation of minimum value of FCD power

$K_c = 3$

$$IF5 = \sum_{j=1}^{8} \phi(n_j)_0 \cdot Y13(n_j)$$

$$|IF5| \frac{S_b}{\sqrt{3} \cdot U} = 0.307\text{A}$$

$$Qp5 = 1.2K_c \cdot |IF5| \frac{S_b}{\sqrt{3} \cdot U} U$$

$$Qp5 = 11.058\text{MVAr}$$

As follows from the calculations the minimal power of capacitor bank (CB) of filter is equal to 11.1 MVAr. To specify on the power value of the filter CB the calculation should be repeated using this power value. It must be stated that to obtain the final value of the filter power you may need to perform a number of calculations. When calculating high harmonics it is also necessary to correct the value of the capacitor bank power Q_{bk3} with consideration of the filter power and the reactive power deficit.

Finite value of the coefficients of non-sinusoidality

$$k_{ns} = \begin{bmatrix} 3.782 \\ 4.765 \\ 2.31 \\ 3.772 \\ 3.219 \end{bmatrix} \%$$

Thus for the operation mode under consideration a reduction of k_{ns} in all points to allowed value is provided.

The results of the calculations for different variants of FCD installation in point 1 are shown in Table 1. In all cases we did not go beyond the second approximation.

When installing FCD in points 2 and 3 the reduction of non-sinusoidality in the network to the allowed value is provided only in the presence of filters F5, F7, F11, and F13.

The results of the calculations are given in Table 3.

As can be seen in Tables 1 and 2 the acceptable result is achieved with installing in point 1 the following filters: filter F5 with power 10.63 MVAr; filters F5, F7 and F11 with total power 24.7 MVAr; filters F5, F7, F11 and F13 with total power 21.88 MVAr. It is evident that the most preferable variant is that of installing one filter F5 in point 1.

In an emergency disconnection of the capacitor bank, the high harmonic levels will change; the values of kns at the network points in this case will be:

Table 2.

FCD	FCD power, MVAr				k_{ns} in network points				
	QF5	QF7	QF11	QF13	1	2	3	4	5
F5	10.63	—	—	—	3.78	4.84	2.35	3.72	2.81
F5 + F7	9.16	11.4	—	—	4.90	8.52	2.84	3.67	1.1
F5 + F7 + F11	7.84	6.45	10.36	—	1.26	3.76	1.83	3.59	0.16
F5 + F7 + F11 + F13	7.62	5.63	4.35	3.60	1.07	3.27	1.8	3.59	0.10

Table 3.

Point	FCD power, MVAr				k_{ns} in network points				
	QF5	QF7	QF11	QF13	1	2	3	4	5
2	6.59	4.31	2.87	8.11	3.18	3.81	2.30	3.31	1.01
3	3.96	4.91	1.29	0.73	7.48	0.32	0.18	3.39	2.05

$$k_{ns} = \begin{bmatrix} 18.74 \\ 18.77 \\ 9.47 \\ 3.78 \\ 3.29 \end{bmatrix} \%$$

The loading coefficient for the capacitor bank for current will be $k_i \approx 1.6$. Thus if only filter F5 is used, the filter should be disconnected together with the capacitor bank.

When F5, F7 and F11 filters are installed, the values of the coefficient of non-sinusoidality at the network points in case if the capacitor bank is disconected are the following:

$$k_{ns} = \begin{bmatrix} 1.63 \\ 1.95 \\ 1.88 \\ 3.59 \\ 0.10 \end{bmatrix} \%$$

In case the load at point 1 is disconnected the coefficient of non-sinusoidality in circuit points is:

$$k_{ns} = \begin{bmatrix} 1.29 \\ 3.76 \\ 1.83 \\ 3.59 \\ 0.16 \end{bmatrix} \%$$

Overload of capacitor bank does not take place either.

Testing the allowed level of non-sinusoidality under other possible conditions is performed in the analogous way, but the results of these tests are not given in this paper.

Thus the installation at point 1 of F5, F7 and F11 filters with capacitor bank power respectively 8; 7; 11 MVAr is accepted. The variant of installing 4 FCD at point 2, despite lesser total power of the capacity bank (21.9 MVAr) turns out to be less appropriate, as it requires more FCD, besides the probability of emergency situations in the cables is higher than on the common busbars.

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