DISTURBANCES IN MV DISTRIBUTION LINES FEEDING DC RAILWAY INSTALLATIONS: CHARACTERISTICS, SIMULATION AND MITIGATION

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ABSTRACT

The paper deals with harmonic supply voltage evaluation of a railway rectifying substation (ESS) connected to distribution feeder and it refers to a real case study.

The main goal of this paper is to conduct a deep frequency analysis in order to evaluate the harmonic distortion of the ESS supply voltage and to outline the resonance frequencies among the reactive elements of the network, establishing also how these frequencies are modified consequently to tuned filter insertion. This analysis has been carried out considering different load conditions and some numerical simulations are performed using the ATP program. Moreover some indications of the filter sizing are provided, after an interesting comparison with the actual standard.

INTRODUCTION

Railway supply is usually made through HV networks due to relevant peak of power delivered during train operation, in particular in the starting phase. On the contrary, metro services and subway are commonly connected to MV distribution system because of the reduced absorbed power and the proximity to the MV substations for supplying industrial, commercial and residential users with relevant limited extension of MV feeders. In the isolated regions, where it is not possible to have a HV network to supply railway lines (it is the case of the Center – South of Italy inside the Apennines region), the MV connection with long feeders is an interesting possibility to connect the ESS.

The ESS supplied in medium voltage gives advantages making the system less expensive considering the costs of installation, maintenance and apparatus, in particular for the power and measurement transformers, circuit breakers and devices insulation.

Anyway, this kind of systems present some problems due to the low short circuit power in the point of coupling. The low short-circuit level available in medium voltage can cause problems for the voltage distortion due to the harmonic currents produced by the rectifier bridges and injected into the line. It is then necessary installing dedicated tuned LC filters in order to reduce the current harmonic content at the lowest frequencies. However, the insertion of the reactive elements changes the frequency response of the network, causing parallel resonances that can increase the voltage distortion.

In this work, a real case of the interconnections between an ESS and a dedicated medium voltage feeder has been analyzed. It is a particular important study on the power quality in distribution networks where railway systems are connected.

After a deep investigation concerning the frequency analysis, an interesting comparison with the actual standard has been conducted in order to validate the sizing of the inserted filters.

ESS POWER CIRCUIT

The train service considered in the paper is of a regional type for connecting small towns and does not require high commercial speed. For this reason a nominal voltage of 3 kV has been chosen for the dc supplying of the traction line. The real plant object of the present study and reported in Figure 1 has been modelled using the ATP program.

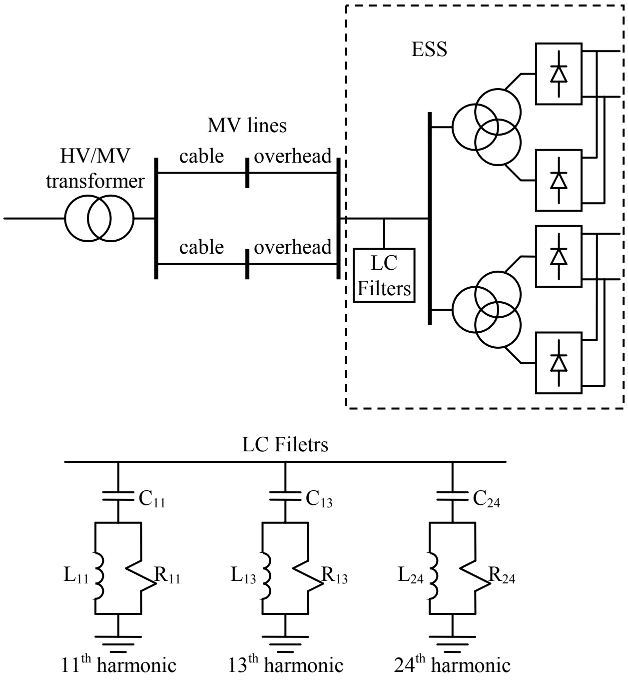

Figure 1 - Electrical scheme of the ESS ad its power supply.

This system is connected to a 150 kV transmission network that supplies a high/medium voltage substation. As it is possible to see from the general scheme, the ac/dc conversion substation for train contact line power supply is supplied by the primary HV/MV substation through two medium voltage lines (both part in cable and part in overhead lines) and it is located near the railway line.

A first purpose is to carry out the frequency analysis of the system, as reported in the following paragraph. It has been used the frequency dependent π model of the lines, both for the cable and overhead lines, in order to underline the possible resonances among the various reactive elements of the network.

First of all it has been considered all the parameters of the supply system, that is constituted by a HV/MV transformer and 2 medium voltage lines in parallel. The transformer presents the following data: A_n: 25 MVA, $v_{cc\%}$: 8%, transformation ratio: 150/20 kV and connection: Y_Ny.

Each medium voltage line is constituted by a part in cable (π model, where: l: 4 km, r: 0.062 Ω/km, x_L: 0.16 Ω/km at 50 Hz, C: 330 nF/km) and part in overhead line (π model, where: l: 12 km, r: 0.11 Ω/km, x_L: 0.25 Ω/km at 50 Hz, C: 8.5 nF/km).

The ESS is constituted by two ac/dc converters of 5,4 MVA each one. In order to reduce the harmonic contents of the current absorbed from the ac network and the voltage ripple on the dc, each rectifier set is constituted by a three-winding transformer and two diode bridges in parallel in order to have a twelve pulse reaction. The ESS main components are 2 rectifiers in parallel (each one constituted by three-winding transformer: A_n: 5.4 MVA, v_{cc}%: 12%, transformation ratio: 20/2.75/2.75 kV, connection: Yyd) and 2 three-phase diode bridges.

The power absorbed by the trains has been simulated taking into account different load conditions. In particular two main cases are considered. In the first one, the ESS absorbs the rated power equal to 5.4 MVA for converter unit, while in the second case an overload of 100% has been considered that implies a double value of the absorbed current. This last critical working condition has to be sustained by the ESS for one hour.

In order to fight the higher voltage harmonic distortion that is typical of the medium voltage connections, due to the minor short circuit level, the installation of LC filters tuned at the characteristic harmonics generated by the ESS has been considered. In particular, two filters tuned at the 11th and 13th harmonic order and a single low–pass filter to cut the components higher than the 24th order have been proposed. These filters, represented in Figure 1, have the following parameters: L_{11}: 35.093 mH, C_{11}: 2.34 μF, R_{11}: 2000 Ω, L_{13}: 25.126 mH, C_{13}: 2.34 μF, R_{13}: 2000 Ω, L_{24}: 15 mH, C_{24}: 1.17 μF, R_{24}: 1130 Ω.

FREQUENCY ANALYSIS

A purpose of the paper is to outline the resonance frequencies among the reactive elements of the network and to establish how these are modified consequently to tuned filter insertion. The result of this analysis is shown in Figure 2, where a comparison between the impedance of the supply network (in the double line case) with and without LC filters up to the 25th harmonic is reported.

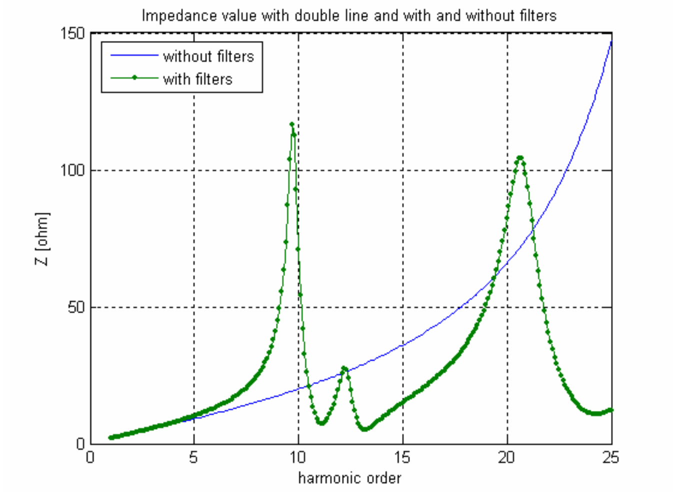

Fig. 2. Comparison between the impedance of the supply distribution network (based on two three-phase lines) with and without LC filters.

The conducted analysis shows that in correspondence of the tuning frequencies of the filters, the impedance value is lower. In correspondence of those frequencies in which parallel resonance phenomena are present the equivalent impedance assumes high values that can bring to a high voltage distortion.

In order to analyze the harmonic distortion of the ESS supply voltage, numerical simulations are carried out, using the ATP program, on the whole system. For the different operation condition, the waveform, the harmonic content and the total harmonic distortion (THD) of the currents and voltages has been calculated. An example is reported in Figure 3 and 4.

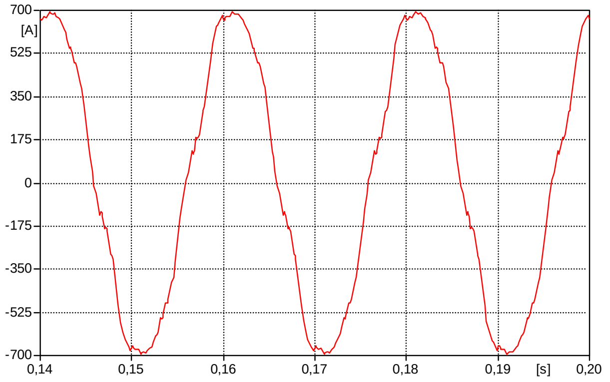

Fig. 3. Waveform of the current absorbed by the ESS with filters in 100% overload conditions.

The filters insertion brings to an apparent improvement of the wave form of the current absorbed by the ESS. In practice the filters have a positive action only on the harmonic components for which they are sized, but a negative one on the 5th and 7th non characteristic harmonic frequencies. The supply voltage benefits of the low pass action of the filters that tends to reduce the harmonic content.

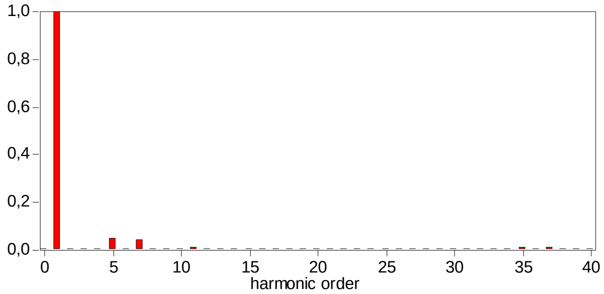

Fig. 4. Harmonic spectrum of the current absorbed by the ESS with filters in 100% overload conditions.

COMPARISON WITH THE STANDARD EN 50160 (CEI 110-22)

It is important to note that the harmonic analysis has been carried out in a 100% overload condition in order to verify the voltage distortion in the worst case, even if the ESS is sized to operate in this condition only for an hour. The use of suitable tuned LC filters allows to obtain a supply voltage that respect the limit imposed by the European Standard EN 50160.

Table 1: Comparison between the harmonic components calculated and allowed by the standard EN 50160 (CEI 110-22) of the ESS supply voltage with an overload of the 100% without filters and with a supply from single line.

Odd harmonics			third harmonics			Even harmonics		
Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated
5	6%	3.9%	3	5%	<0.005%	2	2%	<0.005%
7	5%	3.62%	9	1.5%	<0.005%	4	1%	<0.005%
11	3.5%	4.3%	15	0.5%	<0.005%	6..24	0.5%	<0.005%
13	3%	2.2%	21	0.5%	<0.005%			
17	2%	3.3%						
19	1.5%	2.8%						
23	1.5%	0.074%						
25	1.5%	0.6%						
$\text{THD}_{\text{Max EN50160}}$: 8%			THD_{25}: 8.46%					

Table 2: Comparison between the harmonic components calculated and allowed by the standard EN 50160 (CEI 110-22) of the ESS supply voltage with an overload of the 100% without filters and with a supply from double line.

Odd harmonics			third harmonics			Even harmonics		
Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated
5	6%	2.7%	3	5%	<0.2%	2	2%	<0.1%
7	5%	2.6%	9	1.5%	<0.2%	4	1%	<0.1%
11	3.5%	3.3%	15	0.5%	<0.2%	6..24	0.5%	<0.2%
13	3%	1.9%	21	0.5%	<0.2%			
17	2%	2.6%						
19	1.5%	2.5%						
23	1.5%	0.14%						
25	1.5%	0.1%						
$\text{THD}_{\text{Max EN50160}}$: 8%			THD25: 6.57%					

In all the cases the ESS supply does not show any problem concerning the even harmonics and the third harmonics. This because the Italian MV distribution system has the isolated neutral point, so it does not let the re-closing of the zero sequence currents, with the exception of a little part that can flow through the line-to-ground capacities of the cables.

The supply with single line presents some problems concerning the exceeding of the limit admitted for the 11th, 17th, 19th harmonics and the high TDH values, reported in Table 1. In fact, even if the rectifier bridges installed in the ESS are with a twelve-pulse reaction, there are non characteristic harmonic components due to the commutation and to the inevitable constructive dissymmetry of the bridges.

There is a great improvement, most of all regarding the THD, supplying the ESS with double line (values reported in Table 2) even if the 17th and the 19th harmonics are always a little over the allowed limit.

Table 3: Comparison between the harmonic components calculated and allowed by the standard EN 50160 (CEI 110-22) of the ESS supply voltage with an overload of the 100 % with filters with a recalculated inductance of 24th harmonic and with a supply from single line.

Odd harmonics			third harmonics			Even harmonics		
Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated
5	6%	4.6%	3	5%	<0.01%	2	2%	<0.01%
7	5%	6.7%	9	1.5%	<0.01%	4	1%	<0.01%
11	3.5%	1%	15	0.5%	<0.01%	6..24	0.5%	<0.01%
13	3%	0.4%	21	0.5%	<0.01%			
17	2%	1.9%						
19	1.5%	2.7%						
23	1.5%	0.16%						
25	1.5%	0.11%						
$\text{THD}_{\text{Max EN50160}}$: 8%			THD25: 8.9%					

Table 4: Comparison between the harmonic components calculated and allowed by the standard EN 50160 (CEI 110-22) of the ESS supply voltage with an overload of the 100 % with filters with a recalculated inductance of 24th harmonic and with a supply from double line.

Odd harmonics			third harmonics			Even harmonics		
Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated	Order	Relative Voltage admitted	Relative voltage calculated
5	6%	2.4%	3	5%	<0.01%	2	2%	<0.01%
7	5%	3%	9	1.5%	<0.01%	4	1%	<0.01%
11	3.5%	1%	15	0.5%	<0.01%	6..24	0.5%	<0.01%
13	3%	0.4%	21	0.5%	<0.01%			
17	2%	1.6%						
19	1.5%	2.7%						
23	1.5%	0.04%						
25	1.5%	0.06%						
$\text{THD}_{\text{Max EN50160}}$: 8%			THD25: 5.17%					

The filters insertion reduces the harmonic contents of the components at the frequencies at which they are tuned, but it can cause resonances at lower frequencies that can exalt the lower order harmonics. Referring to the standard EN 50160 and to the results reported in Tables 3 and 4, it is possible to note that the single harmonic components are lower than the allowed values, while the THD is a little higher than the allowed only in the case of supplying from single line. Also the 19th harmonic exceeds the limits only for a little, but at the high frequencies there are other net elements that are not considered in the simulations because of hard evaluation, such as the capacities and the leakage inductances of the cables and transformers and the skin effects that cause a further mitigation of these current components.

FILTER SIZING

From the results of the conducted simulations, reported in Tables 5 and 6, always obtained in the worst case of overload of 100 % of the ESS, it is possible to conclude that the sizing of the 11th and 13th harmonics filters is right for the current flowing through the different filter elements, also maintaining a good security range.

In order to maintain a suitable security level the sizing of the filter elements has to be done considering an overload of 40% compared to the values reported in Tables 5 and 6.

Table 5: harmonic current values (A) in the different filters elements with an ESS supply from single line and with an overload of 100 %.

	11° harmonic filter			13° harmonic filter			24° harmonic filter		
Order	C_{11}	L_{11}	R_{11}	C_{13}	L_{13}	R_{13}	C_{24}	L_{24}	R_{24}
1	7.37	7.37	0.04	7.35	7.35	0.03	3.66	3.66	0.02
5	2.12	2.12	0.06	1.98	1.98	0.04	0.88	0.88	0.02
7	5.7	5.7	0.22	4.81	4.81	0.13	1.88	1.88	0.05
11	12.55	12.53	0.76	2.65	2.65	0.11	0.5	0.5	0.02
13	1.08	1.08	0.08	7.39	7.38	0.38	0.29	0.29	0.02
17	1.8	1.79	0.17	3.55	3.54	0.24	2.4	2.39	0.17
19	1.98	1.97	0.21	3.46	3.45	0.26	4.96	4.95	0.39
23	0.08	0.08	0.01	0.13	0.13	0.01	1.06	1.06	0.1
25	0.05	0.05	0.01	0.08	0.08	0.01	0.77	0.77	0.08
29	0.19	0.19	0.03	0.28	0.28	0.03	1.16	1.15	0.14
Irms	16.04	16.02	0.84	12.94	12.93	0.55	7.18	7.16	0.47

Table 6: harmonic current values (A) in the different filters elements with an ESS supply from double line and with an overload of 100 %.

	11° harmonic filter			13° harmonic filter			24° harmonic filter		
Order	C_{11}	L_{11}	R_{11}	C_{13}	L_{13}	R_{13}	C_{24}	L_{24}	R_{24}
1	8.2	8.2	0.05	8.18	8.18	0.03	4.07	4.07	0.02
5	1.24	1.24	0.03	1.16	1.16	0.02	0.52	0.52	0.01
7	2.84	2.84	0.11	2.39	2.39	0.07	0.94	0.94	0.03
11	15.3	15.27	0.93	3.23	3.23	0.14	0.61	0.61	0.03
13	1.26	1.26	0.09	8.63	8.62	0.44	0.33	0.33	0.02
17	1.69	1.68	0.16	3.34	3.33	0.22	2.25	2.24	0.16
19	2.23	2.21	0.23	3.9	3.89	0.29	5.59	5.58	0.44
23	0.03	0.03	0	0.04	0.04	0	0.34	0.34	0.03
25	0.03	0.03	0	0.05	0.05	0	0.47	0.46	0.05
29	0.35	0.34	0.05	0.51	0.51	0.06	2.12	2.1	0.25
Irms	17.9	17.87	0.98	13.62	13.61	0.6	7.71	7.69	0.54

CONCLUSION

The connection of the ESS railway lines to the MV distribution network is an interesting possibility where the HV lines are not available.

In this paper this chance has been analyzed, considering the problems coming from the connection to a weak short-circuit power point. In fact, beside many advantages, such as minor costs for the apparatus, greater extension of the MV grid and better integration in urban areas, this connection can cause harmonic problems.

The solution proposed in this paper regards the installation of passive LC filters in the MV section for reducing the harmonic content of the absorbed current. In order to prevent resonance phenomena, a frequency analysis on a real case has been carried out simulating the entire system with the software ATP. The results has been compared with the limits suggested by the European standard EN50160.

Finally a preliminary sizing of the filters has been proposed.

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