SUPPLY SYSTEM CHARACTERISTICS AND HARMONIC PENETRATION STUDIES OF THE NEW HIGH SPEED FS RAILWAY LINE "MILAN - ROME - NAPLES"

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INTRODUCTION

The Milan-Rome-Naples, main railway connection of the Italian State Railways (FS) network, is characterized by very intense traffic, with the existing lines already having reached their saturation limit. New lines are to be constructed to increase the passenger and goods transport offer on this connection and to improve the quality of the service. The project will continue the Rome-Florence line quadrupling, now nearing completion.

Essentially, the new lines are designed specifically for the fast intercity links and will use special rolling stock. The infrastructure is planned with line alignment and routing characteristics intended to permit speeds of up to 300 km/h, although it has not yet been established what the best operating speeds actually will be. The sizing of the fixed electric traction installations has also been devised in such a way that high power can be collected from the contact wire; the traction load for the design project has been assumed as trains travelling 15 minutes apart and maximum unit power demand equal to 12 MW.

Since these traction loads lie at the economic technical limit of the practical capacity of the electric traction system (i. e. 3 kV d.c.) adopted for the FS network the question of whether or not it would be advisable to change over to a higher operating voltage system was carefully assessed. Having considered the systems of electrification available today and the inherent problems of both constructing and operating two-voltage locomotives - needed for transit in areas already electrified at 3 kV d.c., and for possible future transformation of the network -, it emerged that the hypothesis of a new d.c. higher voltage system (12 kV level) could be a workable solution as described by Mayer and Ventura [1]. Studies and experiments are underway to prove the feasibility and convenience of this system; in the meantime the project has been developed envisaging use of the traditional 3 kV d.c. system.

The high power to be collected and the high quality service that is to be offered raised a series problems which called for further investigation both of the catenary and of the supply and conversion system.

THE CATENARY

Perhaps the most critical problem to be resolved in the electrification at 3 kV d.c. of high speed lines lies in an optimal design of the overhead line which enables regular and satisfactory current collection. A point of reference is the new Rome-Florence "Direttissima" line, where the overhead line meets collection requirements up to the maximum expected speed of 250 km/h and with only one pantograph. The overhead line of the Rome-Florence line was designed especially to reduce to a minimum its elasticity (ratio between contact wire lifting and pantograph action) by increasing the conductor mechanical tension as much as possible;at the same time, additional measures were taken to attenuate or partially compensate for the non-uniformity of elasticity between suspension and span centre, such as non-uniform spacing between the droppers and positive sag at span centre.

For the new lines the problem is heightened, not so much because of the eventual increase in maximum speed but mainly because it would be difficult for one pantograph alone to support the high total current (4000 A maximum and 3000 A average); moreover, trains formed of trailer cars and two separately supplied (head-end) locomotives are to be used. The most significant improvements anticipated are listed below:

- Further decrease in the elasticity obtained with the increase of the overall tensioning from 5860 to 6880 daN, made possible by the section increase from 460 to 610 sq.mm necessary for reasons of electric capacity. Further increase will be made in tensioning if it is confirmed that copper alloys are more convenient than pure electrolytic copper.Without any noticeable loss in electric conductivity, copper alloys present greater mechanical resistance and better creep characteristics, especially in heat.
- Substantial decrease of the gap between maximum and minimum elasticity, adopting catenary configurations other than the traditional, such as the "Y" and the compound arrangement. These arrangements enable the non-uniformity ratio to be lowered from 3 to 1.2 ÷ 1.4.

In conclusion, to attain optimal results, the following direction is being taken:

- use of a valid numeric simulation model for the pantographic-catenary dynamics, which enables an outline of the most promising configurations and solutions to emerge;
- performance of tests, in all the possible real operating conditions, to confirm, correct and put into practice the results of the simulation. The Modena-Suzzara line, where a speed of 300 km/h may be reached, is also being equipped for this purpose.

ELECTRIC SUBSTATIONS

The dimensioning of the supply system for the new lines essentially is based on a average spacing of 12 km for the conversion substations (ESS). Each ESS will have three conversion groups - see fig. 1 - consisting of one transformer with two secondaries, Y and Delta connection, and by two rectifier units connected in order to obtain a 12-pulse operation, which is particularly favourable with regard to harmonic disturbance. Each group will have a rated power of 10 MVA and a transformer short circuit impedance of 12%. With two groups in parallel, an internal equivalent resistance equal to 0.05 ohm is obtained so that regulation necessary to compensate voltage drops can be overlooked. However, voltage regulation is necessary for primary side voltage variations. In an anomalous situation this regulation can prove useful also to vary the traction load distribution between neighbouring ESS.

The configuration chosen enables a level of operating continuity to be maintained which is more than acceptable, even in the case of total outage of an ESS, and it has been checked with a program of traffic simulation having the following input:

- train performance calculation relative to a train of the expected composition(1 locomotive + 12 cars + 1 locomotive) calculated in the real track conditions and for a maximum speed of 275 km/h;
- time spacing of trains;
- ESS locations and their characteristics;
- traction lines electrical characteristics .

The simulation results showed that supply system meets the trains' power requirements and respects the imposed limits which are maximum train current of 4000 A and minimum line voltage of 3000 V. The check also gave satisfactory results in cases of anomalous systems, such as one ESS in three being out of service. The 12 km spacing of the ESS necessitates the construction of a HV supply line which will run parallel to the railway route and will supply each ESS with an " in - and -out" connection; this layout proved more economical than, and equally as reliable as, direct links to different nodes of the public electric network.

HARMONIC PENETRATION STUDIES

One of the most interesting problems closely examined during the preliminary stage,is the study of harmonic distortion due to the a.c./d.c. converters. In fact, in this case it was expected that this aspect would be more significant than in traditional d.c. electrification because of the amount of power installed in the electric substations and because of the intense traffic conditions expected on the line.

Estimation of the Critical Load Conditions

To pre-determine disturbances created by the railway system on the supply network, numerous experts accept the use of the results of expected traffic simulations (with particular reference to the load curves in the different traction substations). The approach can be defined as "deterministic" since it is linked to evaluations which are closely linked to operation of the system on the basis of laws and fixed procedures (train schedule). Results obtained during anomalous traffic conditions or exceptional and transient power demand peaks are to be regarded as too pessimistic for assessment of harmonic distortion, since the main problems are linked to the duration and repetitive nature of the phenomenon.

The above considerations mainly refer to studies conducted on railway electrification in which substation loading is little affected by short delays with respect to schedule. In other words, the substation spacing and the train speed is such that the critical load conditions for the system (conditions in which the load in one of the substations is maximum) do not change substantially if two trains are closer together or further apart as a result of fairly short delays in schedule.

In the case of high-speed lines, the problem of shifting from deterministically assigned load conditions requires a more thorough analysis in the light of the following aspects:

- delays in departure of the order of several minutes bring about differences in spacing of the order of tens of kilometers between two successive trains;
- it is unlikely that the spacing determined as a result of the schedule or any eventual delay in departure time will undergo further variations, both since it is planned that trains will travel at almost maximum speed and since generally there are no stops or other possible causes for delay along the route;
- in the case of lines electrified at 3 kV d.c., the spacing envisaged for conversion substations is small, particularly if compared with the spaces corresponding to the accumulated delay on departure; the ESS load conditions can be altered considerably even if trains are slightly off schedule.

To take into account the above elements which may drastically alter the overall load conditions and hence the distortion levels, it was preferred when studying the new lines on the Milan-Rome-Naples route to adopt a "combined probabilistic - deterministic" approach. The simulation criteria adopted can be summarized as follows:

- account is taken of the probability of train departure being delayed by means of a simulation which is able to reproduce a pre-set distribution curve for the departure delays;
- the distribution curve for the time delays was introduced by processing data from recent statistical surveys, performed by the FS on Intercity trains (this distribution, which can be exponentially approximated,envisages a maximum departure delay of 5');
- the allocation of delay times to each of the trains is performed with a Montecarlo - type method, carrying out numerous simulations of the different traffic conditions;
- the delay time assigned with probabilistic methods is kept constant during train moving, assuming that moving is the same for all trains, on the basis of only one type of train performance along the entire line.

A high number of simulations (over 100 cases) was performed to determine the power demand values in the different substations, in presence of variations in departure times. The power demand in the ESS was calculated for the minimum expected headway (15 minutes) and for the maximum speed of 275 km/h; the calculation step used was 3 seconds. Figure 2 shows the location of the ESS along the Rome-Naples line and two basic schemes considered for the HV supply system. To give an example of the type of results obtained, Figure 3 shows the peak value of power delivered by one of the 19 ESS (number 4 of Figure 2) for 24 of the 100 cases examined.

The results can be summarized as follows:

- the peak value in several ESS can range from a minimum of 12 to a maximum of 24 MW;
- the peak power demanded by the entire line varies as a result of the different probabilities of the trains being simultaneously in a maximum demand phase; however, this variation is small (no more than 10%) and the peak power can be regarded as virtually constant(about 120 MW).

Figure 4 shows a comparison between the peak power delivered by the 19 ESS calculated by means of a pure deterministic approach (without delays in departure) and the one here defined as "combined deterministic-probabilistic". On the basis of the simulations carried out, it can be said that a purely deterministic approach may prove uncautious.

Because of the presence of 12-pulse converters the harmonic distortion is concentrated on a few characteristic harmonics. Given the radial feeding of the ESS illustrated in Figure 2, it would appear to be of benefit to perform a preliminary "sensitivity" analysis on the electric system by injecting unitary currents (for the characteristic harmonics) into the numerous different substations and checking which ESS determine the greater distortions. Clearly, attention can be focused on the load conditions characterized by the greatest power demands in the few substations which, as a result of their "electrical" location in the system, produce highest distortion levels at the nodes of interconnection with the public network, thereby limiting the number of cases to be examined.

Two schemes for the supply system are referred to in this first phase of the study:

- the scheme A (upper side of Figure 2) having two points of interconnection with the national grid in two stations of the primary transmission system at 380 kV;
- the scheme B (lower side of Figure2) having three points of interconnection with the national network;the two previously hypothesized for scheme A and a third approximately mid-way along the line.

Figure 5 shows the curves of the network equivalent impedance as a function of the frequency - Z(f) -, as seen from 3 different ESS (9, 3 and 2 of the scheme A).The analysis indicated that for the scheme A the disturbance at the frequency of 650 Hz (13th harmonic) is more critical; for the scheme B the resonances shift towards higher frequencies and the most critical characteristic harmonic is the 23rd.

Harmonic Disturbance Characteristics

The harmonic current percentage of the ESS a.c./d.c. conversion group was evaluated on the basis of measurements performed on two ESS presently operating in the FS network, having practically the same characteristics and powers equal to around 60% of those of the future line. The ESS under test were connected to the 132 KV FS line dedicated to ESS supply. The experimental values for the amplitude of the characteristic harmonics are shown in Table I, together with those calculated on the basis of recommendations from the IEC TC 77. As a precaution, values above those found experimentally were adopted for the study (see Table I, column 4). The differences between the values calculated and those measured testify to the fact that, especially for high order harmonics, the constant current injection model is not adequate and there is a reduction of current due to the network impedance, mainly for frequencies near that of parallel resonance.

TABLE I - Harmonic current values (%) of the a.c./d.c. converter groups

Harmonic order	Experimental values (avg)	Calculated (IEC TC 77)	Adopted
11	4.8	5.9	5.3
13	3.0	4.7	3.9
23	< 0.1	2.3	1.6
25	< 0.1	2.1	1.5

For the supply system studied phase differences between the voltages (fundamental) at the different disturbing nodes (FS ESS) can be assumed as being known; in fact , since the 150 kV lines serving the new railway are radially-operated and used exclusively by the FS, once the traction loads are fixed, the phase differences along the lines can be easily calculated. Therefore for the purpose of calculating the overall distortion caused by the numerous harmonic sources acting simultaneously, it was possible to consider the "vectorial values" of the harmonic voltages, namely the values obtained from the vectorial sum of different distorting effects.

Analysis of the Results

The computer program (HARMAN) for harmonic load flow calculation and the criteria adopted for system component modelling have been checked by means of comparisons with numerous field tests carried out in an HV/MV transformer station in which disturbances consisting of a.c./d.c. conversion groups for electric traction were present, as referred by Capasso et al. in [2].

The most significant results of the study are summarized in Table II; in particular it shows the values of Total Harmonic Distortion (THD) and Individual Harmonic Distortion (IHD) obtained in the most unfavourable of the situations examined. Several significant conclusions were drawn from the analysis of the results. The two interconnection point scheme of fig. 2 appears unsuitable in guaranteeing, even in conditions of "all in service", that harmonic distortion levels on the public network is contained within the limits that presumably will be adopted in recommendations and standards; THD do in fact reach values of 10%. Distortion values reached in the HV nodes of the FS ESS appear equally high, such that the convertors, supplied by strongly distorted voltages, may produce non-characteristic harmonics of a lower order, further aggravating distortion at the points of coupling with the public network.

The three interconnection points scheme would seem suitable in guaranteeing that harmonic disturbance on the public network is contained within acceptable limits; the total harmonic distortion values are always found to be contained within 4%. Distortion at the HV nodes of the FS ESS appears to be satisfactorily reduced(below a maximum of approximately 9%), such that the possibility of critical conditions for the immunity of convertors and equipment can be excluded.

In the absence of specific standards from the CEI (Italian Electrotechnical Committee), for the purposes of a feasibility assessment, reference is made to the values indicated by the CIGRE [3]. The CIGRE Report referenced envisages as a compatibility level a maximum of 3% on the high voltage network and distribution at very high voltage and local interconnection, and 7% for medium voltage network and distribution at high voltage. It should be borne in mind that in the Italian network the 150 kV system assumes "combined" characteristics of high voltage distribution and subtransmission. Considering that distortion parameters were calculated in conditions of very high power demand for the whole line, the results obtained by means of the scheme B of Figure 2 can definitely be accepted.

REFERENCES

1. Mayer L. and Ventura O., September 1987 "The evaluation of the feasibility of a 12 kV DC railway system", IEE Int. Conf. on "Electric Railway System for a new Century", London, UK.

2. Capasso A., Lamedica R., Manigrasso R., Superti Furga G. and Tironi E., 1987, "Analytical-experimental identification of a network model for harmonic penetration studies", (in italian), 89th AEI Annual Conference, Capri, Italy.

3. CIGRE WG 36-05, 1981, "Harmonics, characteristics, parameters, methods of study, estimates of existing values in the network", ELECTRA, n. 77, 35÷54.

TABLE II – Maximum values of voltage harmonic distortion at interconnection points with public network
THD : total harmonic distortion (%) IHD : individual harmonic distortion (%)

CRITICAL LOAD CONDITION	SCHEME A				SCHEME B					
	ROME		NAPLES		ROME		CEPRANO		NAPLES	
	THD	IHD (HARM. ORD.)	THD	IHD (HARM. ORD.)	THD	IHD (HARM. ORD.)	THD	IHD (HARM. ORD.)	THD	IHD (HARM. ORD.)
MAX. INSTANT. POWER DEMAND AT ESS.	10.1	7.6 (13)	8.8	6.9 (11)	3.9	3.2 (13)	1.7	1.2 (23)	2.5	2.0 (13)
MAX. RMS POWER DEMAND (10') AT ESS.	10.3	7.8 (13)	10.6	8.3 (11)	4.1	3.5 (13)	2.2	1.5 (23)	3.4	2.8 (13)
MAX. INSTANT. POWER DEMAND OF THE SYSTEM	9.2	7.0 (13)	7.8	6.2 (11)	2.6	2.2 (13)	2.6	1.7 (23)	2.8	2.3 (13)

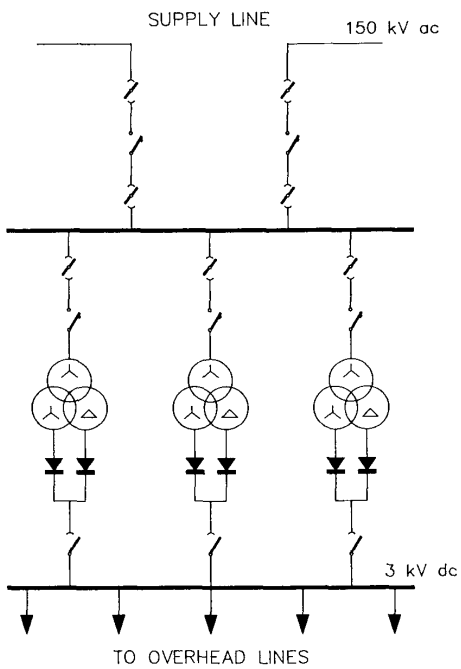

Fig.1-Electric Traction Substation scheme.

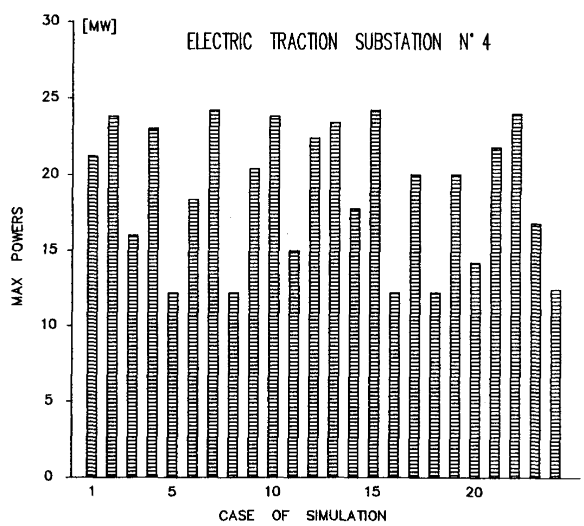

Fig.3-Maximum instantaneous powers for different departure time delays.

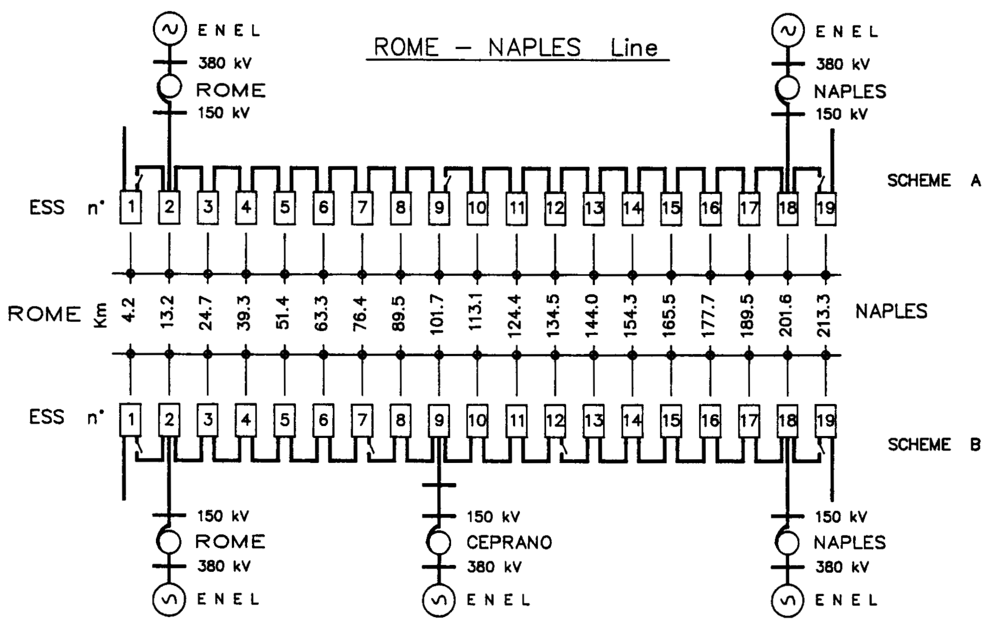

Fig.2-Traction Substation location along the railway line and HV supply line schemes.

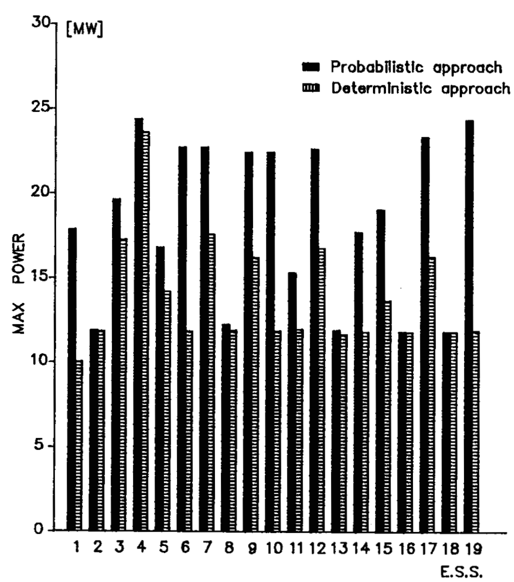

Fig.4-Peak power demand at the 19 ESS.

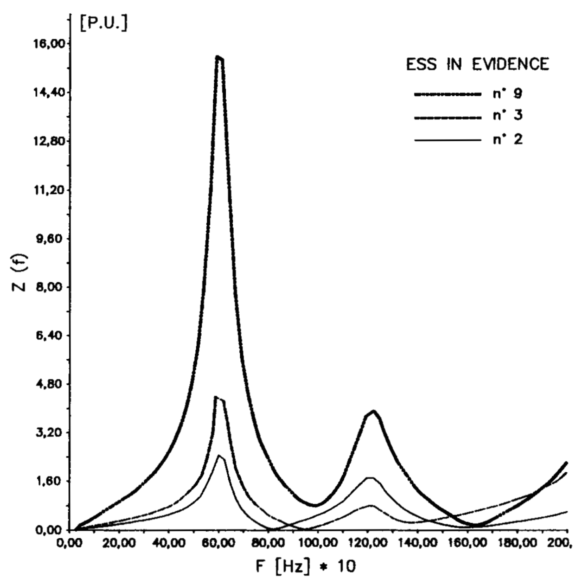

Fig.5-Network equivalent impedance.