[24

A. DI GERLANDO - D. ZANINELLI

HARMONIC ANALYSIS IN A.C.-D.C. DISTRIBUTED CONVERSION SYSTEMS

ICHPS V - INTERNATIONAL CONFERENCE
ON HARMONICS IN POWER SYSTEMS

ATLANTA (GA USA), 22-25 SETTEMBRE 1992

ICHPS V

International Conference on Harmonics in Power Systems

September 22-25, 1992

Swissôtel
Atlanta, GA USA

Sponsored by:
IEEE Power Engineering Society

HARMONIC ANALYSIS IN A.C.-D.C. DISTRIBUTED CONVERSION SYSTEMS

Antonino Di Gerlando Dario Zaninelli, Member, IEEE

Dipartimento di Elettrotecnica, Politecnico di Milano
Piazza Leonardo da Vinci, 32 - 20133 Milano, Italy

Abstract - The possibility to use an A.C.-D.C. distributed conversion system aimed at supplying power to underground railway lines is considered: after a description of its structure and of the methodology adopted for the study, the attention is devoted to the harmonic analysis of the waveforms of some electrical quantities inside the converter system.

INTRODUCTION

There is a possibility that, in the medium-to-long term, rectifying materials suited to be distributed over a large surface, are going to become available [1,2,3]. This has suggested the study of the feasibility of a distributed A.C.-D.C. conversion system aimed at supplying power to an underground railway line.

The future objective would be to construct a cable, feeding the contact point, which would carry out the dual task of transporting the A.C. power and of rectifying it to obtain D.C., thus achieving a conversion distributed along the line [4]. This cable would consist of an internal core, made up of A.C. phase conductors, and of a special external sheath using a material exhibiting rectifying properties.

The main advantage of this solution would consist of a considerable simplification of the underground railway power feeding plant, with a significant reduction of the space occupied within the tunnel.

A feasibility study on this subject has been sponsored by the Italian National Research Council as part of the project "Progetto Finalizzato Energetica" and has been carried out in collaboration with, and with the support of, ATM (Milan Municipal Transport Authority).
The primary objective of the study was the identification of conditions for the feasibility of the system.

The fact remains, however, that, at the industrial application level, materials possessing characteristics making them suitable for the construction of an effective busbar (or cable) for distributed A.C.-D.C. conversion are not available. Bearing this in mind, it has been considered that a significant step would be taken by studying, in a preliminary stage, the behaviour of a structure consisting of a sequence of closely-spaced cascaded conversion units.

This "lumped-element" representation of the system can be justified by observing that the results thus derived are an acceptable approximation to a continuous structure. Because of this, it is possible to obtain from these results important informations bearing upon the design of a possible distributed-conversion busbar and on the desirable electrical characteristics of materials to be used in the construction of such a busbar.
At the same time, these results are not only significant from the methodological point of view (system modelling and study of different operation modes), but also have applications in plant design, as we are talking of a solution which could, basically, be constructed even today, by using a sequence of converter units.
As for the latter point of view, it is clear that a complete examination of a system of this type cannot ignore a careful analysis of its behaviour in case of a fault and as regard the required protection and sectioning devices. Such considerations, however, fall outside the scope of the present work.

Fig. 1 shows a schematic representation of a distributed conversion system constructed using a set of cascaded converter units. These units, placed close to each other at regular intervals, are connected on one side to the 3-phase A.C. power feed line, while on the other side they are connected to the D.C. line which serves as the contact line for the underground trains.

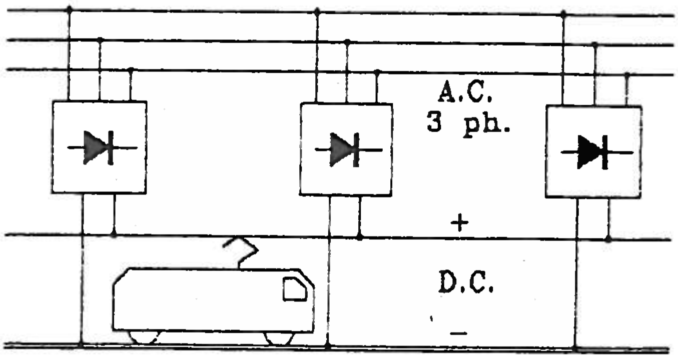


Fig. 1. Schematic diagram of an A.C.-D.C. distributed conversion system for an underground railway contact feed line. Construction using cascaded converter units.

This cascaded arrangement, which represents the distributed conversion system by means of lumped elements in successive cells, is also a typical configuration of many traditional conversion systems.
In fact, this arrangement can also be found in normal underground railway power systems, where the conversion units consist of convertor substations installed at the stations themselves. The difference, however, lies in the fact that, in the case of substations, the distances between successive units is much greater than that envisaged for the distributed conversion system. In addition, in the case of substations, each converter is often independently fed on 3-phase A.C. side.

Another situation characterised by the use of a cascaded arrangement of converter elements, is that of plants containing converter cabins with a number of rectifying elements in parallel, or rectifiers having branches with several diode rows in parallel. The presence of resistances and inductances associated with the connecting conductors, means that these systems are also composed of cascaded converter units [5].
The difference with respect to the situation considered in the present paper is that, in the case of converter cabins, the position of the D.C. load is fixed relative to the set of cascaded converter units, while in the distributed conversion system this position shifts along the D.C. line with the pantograph pick-off point.

After a description of the structure being studied and of the different methodologies adopted, the subject of the present study is the harmonic analysis of the waveforms of the currents inside the converter system. The influence of resistive and inductive parameters will be considered with respect to the following: the level of collaboration between the converter units, the energy flow and the waveforms of the electrical quantities. This is in order to determine the best conditions for the construction of the system.

DISTRIBUTED A.C.-D.C. CONVERSION SYSTEMS

The analysis of a conversion system of the type shown in fig. 1 requires the setting-up of models at different level of complexity, according to the various objectives considered during the study. A theoretical analysis, aimed at understanding the basic operating mechanisms, has been carried out before the study using numerical simulation, which employs both general-purpose programs and programs designed specifically for this application. In addition, an analogue physical system has been constructed [6] to evaluate the degree of importance of the various circuit elements and their simultaneous effect. Experimental results have also been used as a check on the numerical computer analysis.

Many different configurations could be adopted for a single converter unit. Among these, the types most likely to be employed are the 3-phase Graetz bridge structure and the six-phase star diode structure with a power supply transformer (having a double star connection with an interphase inductor) placed at the start of the line [7].

Considering the need to construct an analogue model, the configuration using a 3-phase Graetz bridge in each unit has been adopted. This choice also makes it possible to obtain general informations about the degree of collaboration between the converter units, losses, waveforms and their respective harmonic content.

The derived equivalent electrical network is shown in fig.2. The electrical parameters appearing in it have been determined by referring to a distributed conversion system consisting of a 2-wire D.C. contact line connected to a 3-phase A.C. line via the Graetz bridges [6].

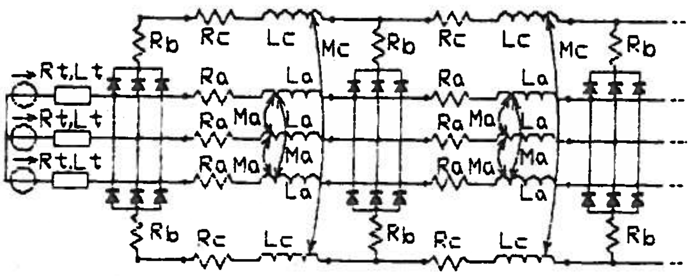


Fig. 2. Equivalent electrical network of the distributed conversion system consisting of 3-phase Graetz bridge-type converter units.

The parameters in fig. 2 have the following meaning:

- R_t, L_t: equivalent phase resistance and inductance of the A.C. power supply network;
- R_a: resistance of an A.C. conductor corresponding to the distance between two adjacent converter units;
- R_c: resistance of a D.C. conductor corresponding to the distance between two adjacent units;
- R_b: transversal resistance of the connection between the anode and cathode stars of the bridges with the D.C. line wires;
- L_a, M_a: self and mutual inductance coefficients relating to sections of A.C. line between adjacent bridges;
- L_c, M_c: self and mutual inductance coefficients, relating to sections of D.C. line between adjacent bridges.

The load (not shown in fig.2) has been simulated by a resistance and an inductance series connected. This load represents the train running along the conversion-power supply line.

The dimensional data of a possible real plant are given in Appendix 1, together with the corresponding parameter values.

An analogue model consisting of eight cascaded Graetz bridges has been constructed on the basis of these parameters. As the values of the real parameters are very low, a scale factor of 200 has been applied to these parameter values in arriving at the component values in the analogue model. This was done to limit the disturbing effect of parasitic elements.

In addition to the arrangement of figs.1 and 2, in which it has been assumed that the system is fed from one end of the line only (single-end feed), experiments have also been carried out on feeding power from both ends of the A.C. line (double-end feed).

In order to obtain some useful informations on the influence which the parameters of the circuit in fig.2 have on system behaviour, two limit parametric conditions have been studied using theoretical analysis. Both refer to the single-end feed case, one assuming a purely inductive system and the other a purely resistive one.

The study of the purely inductive (i.e. lossless) system, carried out by analysing the switching sequence of the diode valves, leads to the following conclusion: among all the bridges present, only the first one, adjacent to the A.C. feeding point, delivers current.

In the case of the purely resistive system, the duration of the switching time intervals, compared with the conducting intervals, is practically zero. Because of this, no appreciable error is committed if, in order to evaluate the degree of collaboration between the converter units, the values of the currents delivered from the bridges are calculated on the basis of performance during conducting intervals only. In addition, the waveform of the bridge currents are practically ripple-free, with the diodes conducting right through 120 electrical degrees.

The study of the complete resistive-inductive system (carried out, because of its complexity, both with the help of the analogue model and by means of numerical simulation, on the computer) shows a behaviour intermediate between the above two. First of all, even with a ripple-free load current, the single bridge currents show considerable ripples around an average value.

Fig.3 shows, as an example, some oscillograms of bridge anode currents and voltages derived from measurements on the analogue model. It can be seen that both the average value and the ripple shape of the currents is different from one bridge to another.

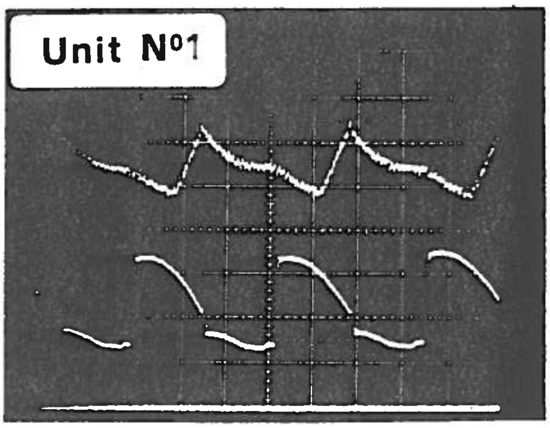
Apart from the waveforms, the analysis of which will be treated more extensively later on, it is of interest to evaluate the degree of collaboration between different converter units. This refers to the number of units active in the conversion process and their contribution, in terms of average current, referred to the total current absorbed from the load. The study has shown how the degree of collaboration depends on the values of the resistive parameters and, in more detail, upon the values of the parametric ratios R_c/R_a and R_b/R_a.

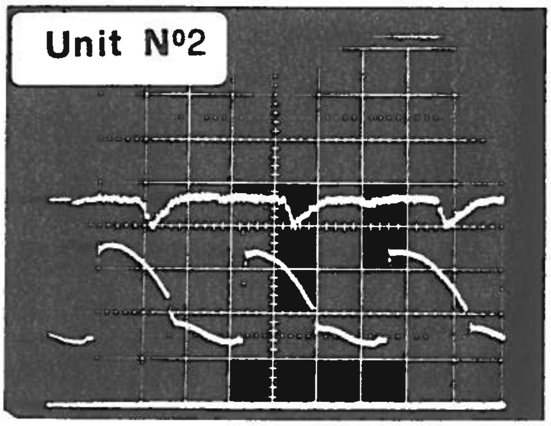
In the case of single-sided feed, the most heavily loaded units (called principal units in what follows) are always those next to the A.C. source (identified with the number 1) and the unit, next to the pick-off point. This collaboration situation is, however, affected by the presence of both self- and mutual inductances, which tend to increase the load on units near the A.C. feed point, at the same time decreasing the load on units close to the current pick-off point.

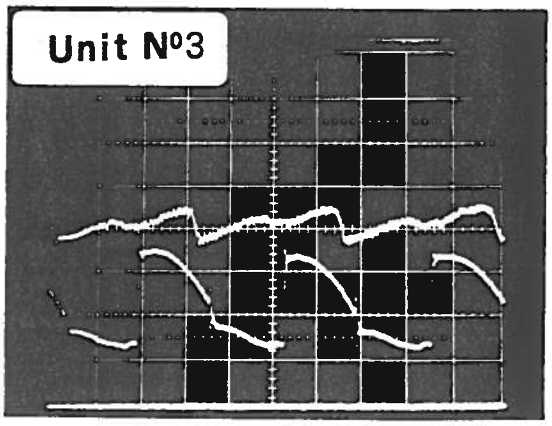
In order to illustrate this influence, Table I shows the average values of the currents delivered from the bridges (in percent of the total load current).

The values have been determined by simulation and by measurements on the analogue model. The feed is single-sided and adjacent to bridge N° 1 while the load is placed at the other end of the line, i.e. under bridge N° 8.

The resistive parameter ratios are: Rc/Ra = 1 and Rb/Ra = 14, while the inductive parameters increase from case a) (purely resistive) to case c) (resistive-inductive, with 200 times the parameter values as given in Appendix 1). In case b), the values of inductances are half those used in case c).
The values in Table I demonstrate how strongly the presence of inductances influences the distribution of current between the converter units, in the direction of creating an unbalance between the principal units. In designing a conversion system, preference should thus be given to those configurations which limit the magnitude of the inductive parameters.
It must however be admitted that, from the point of view of collaboration between units, the study of a conversion system with purely resistive parameters yields significant results.







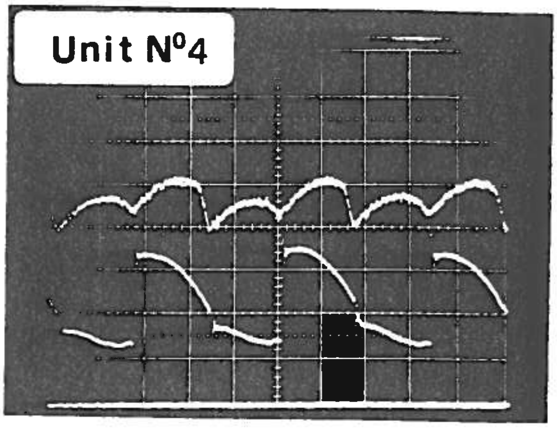


Fig. 3. Oscillograms of voltages and currents obtained from the analogue model under double-sided feed conditions and with a centrally placed load (load between bridges N° 4 and 5) on a line made up of 8 three-phase Graetz bridges: Rc/Ra = 1, Rb/Ra = 18. Given the symmetry in construction and loading, the quantities referring to the other four converter units show an identical behaviour, being a mirror image of bridges N°1, 2, 3, 4. Upper curves: bridge anode currents; lower curves: bridge anode voltages, referred to the centre of the three-phase system star.
Scales: σ_V = 50 V/div; σ_I = 0.2 A/div; σ_t = 2 ms/div.

Table I - Current distribution in a system employing 8 bridges. Power feed is single-sided, adjacent to bridge N° 1, while the load is under bridge N° 8; Rc/Ra = 1; Rb/Ra = 14. (a) system purely resistive; (c) resistive-inductive system with 200 times the parameter values as given in Appendix 1; (b) same as case c), but with the values of inductance halved.

case	Iav1 [%]	Iav2 [%]	Iav3 [%]	Iav4 [%]	Iav5 [%]	Iav6 [%]	Iav7 [%]	Iav8 [%]
(a)	17.6	13.0	10.3	9.0	9.0	10.3	13.0	17.6
(b)	20.2	14.8	11.3	9.3	8.3	9.3	11.9	14.9
(c)	25.6	16.4	11.6	7.5	5.8	7.2	10.5	15.4

For example, Fig. 4 shows the degree of collaboration (in terms of average currents delivered by the converter units) applying in a system made up of 50 units, evaluated on the assumption of purely resistive system.

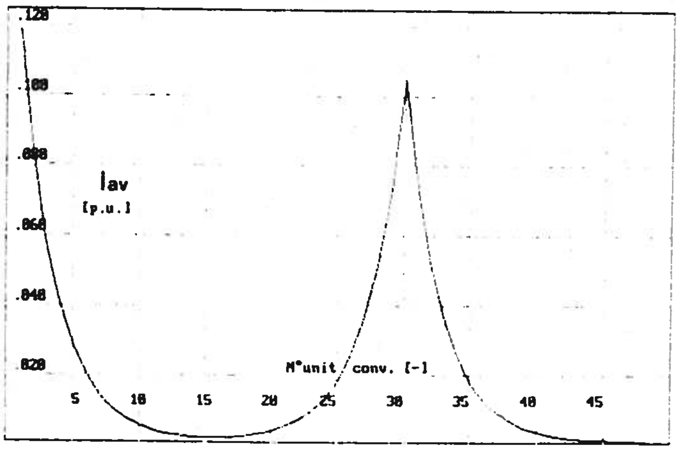


Fig. 4 - Collaboration diagram in a system of 50 units (single-side power feed). Pick-off under unit N° 30. The X-axis shows the converter unit number. The Y-axis shows the envelope curve of the average current p.u. values, referred to the total load current.
Rc/Ra = 1.5, Rb/Ra = 20.

One can observe a cusp-like distribution, with current maxima occurring at the principal units (pick-off point under unit N° 30), with currents then decreasing continuously as the distance from the principal units increases.

As for the influence of the parametric ratios R_c/R_a and R_b/R_a, in the case of a single-side feed, the studies have given the following results.

- The ratio R_c/R_a affects the load distribution between the principal units: an increase in this ratio is accompanied by a reduction of the current delivered from the unit N° 1 (adjacent to the power feed point) and an increase in that delivered from the unit close to the pick-off point. Values of R_c/R_a around 1.5 lead to a substantial equilibrium between the principal units, for any position of the pick-off point. The only exception to the above is the case of pick-off corresponding to the terminal unit, when equilibrium is achieved with a ratio $R_c/R_a = 1$ (see case (a) in table I).
- The ratio R_b/R_a affects the collaboration between units adjacent to the principal ones. As this ratio increases, the number of units collaborating, in the neighbourhood of principal units, increases. At the same time, the individual currents carried by the principal units decrease.

The above clearly demonstrates the opportunity of increasing R_b/R_a in order to reduce the load on each converter unit, thus distributing the total load over a greater number of units as much as possible. This, however, creates a problem associate with losses in the transversal resistances R_b, connected with the adoption of high values for these parameters.

In terms of the simulation [8], still as part of the study of a purely resistive model, the Table II shows how the currents delivered from the principal units (indicative of the degree of collaboration) and the total losses of the conversion system are modified in a system made up of 120 converter units as the ratio R_b/R_a increases.

The total losses of the conversion system (P_L) are expressed in p.u. with respect to the losses which occur when $R_b/R_a = 0$. However, it should be considered that the case corresponding to $R_b/R_a = 0$, assumed as a reference, has no practical significance because only the principal units are loaded.

Table II - System with 120 converter units. As the ratio R_b/R_a changes (at $R_c/R_a = 1.5$), the currents delivered from the principal units are shown, both for pick-off close to the A.C. power feed (unit N° 5) and distant from the power feed (unit N° 60). The table shows the corresponding ratio P_L between the actual losses and the limit values which would occur in the case of $R_b/R_a = 0$.

	pick off under unit N° 5			pick off under unit N° 60		
R_b/R_a	I_{av1} [%]	I_{av5} [%]	P_L [pu]	I_{av1} [%]	I_{av60} [%]	P_L [pu]
10	18.9	16.9	1.74	15.6	14.6	1.04
20	16.2	13.8	2.23	11.9	10.4	1.06
30	14.7	12.4	2.67	10.0	8.6	1.08
40	13.7	11.5	3.06	8.8	7.4	1.09

The observation of Table II shows a general improvement in collaboration as the ratio R_b/R_a increases. However, the currents delivered from the principal units associated with pick-off under unit N° 5, which is closest to the feed point, are higher than the currents found in the case of distant pick-off (unit N° 60) at a constant ratio R_b/R_a.

This phenomenon is linked to interaction between the two cusps of the collaboration curve. This interaction assumes a considerable level when the two principal units are close together.

This unfavourable situation, which occurs when the pick-off is close to the power feed point, is also reflected in the value of losses, as shown by the loss ratio P_L. This assumes significantly different values as a function of the position of the pick-off point. When $R_b/R_a = 40$, the value of P_L increases from 1.09 (when pick-off occurs under bridge N° 60) to 3.06 (when pick-off occurs under bridge N° 5).

It is clear that, from the point of view of overall energy consumption it is better to evaluate not just the losses at a certain fixed position of the pick-off point but the energy lost in the conversion system during the movement of the traction unit along the entire line. In the case of $R_b/R_a = 40$ for the system considered in Table II, the ratio between this energy loss and that of the limit case ($R_b/R_a = 0$) is equal to 1.10. It can be concluded that the comparatively high value of the losses, which occur when the pick-off point is situated near the first units close to the A.C. power feed point, does not significantly affect the overall amount of energy lost. The latter value is associated mainly with the losses which occur when the pick-off point is distant from the power feed point, and this type of loss increases only slightly when the ratio R_b/R_a grows.

Summarising this analysis of the purely resistive model, which is approximate but useful in order to obtain information helping in the choice of optimum system parameters, it can be said that the adoption of high values for the ratio R_b/R_a is convenient, as long as pick-off close to the power feed point is avoided [9].

HARMONIC ANALYSIS OF THE DISTRIBUTED CONVERSION SYSTEM

The study referred to above was concerned with the analysis of the dimensional and parametric conditions needed to obtain a satisfactory level of collaboration between the converter units, without at the same time substantially increasing the overall energy consumption.

An important aspect of considerable interest is the evaluation of the harmonic pollution levels due to the peculiar structure of the conversion system, consisting of cascaded converter units. This question, which is faced only after having considered the intrinsic system feasibility, represents an aspect of considerable importance from the plant design point of view.

The presence of harmonics in the currents delivered by the converter units implies, on one hand, an increase in system losses. On the other, even when the harmonic amplitudes are relatively small, it can cause serious problems due to electromagnetic incompatibility with control equipment and with the plant signaling devices.

The analytical study of these phenomena is very complex, as they depend on the conduction and switching mechanisms between the diodes of the many rectifying units present. Because of this, it has been considered necessary to tackle this analysis making use both of computer simulation and experimental tests. Thus, the numerical simulation has been validated by carrying out suitable measurements on the analogue physical model of the system.

In the computer simulation, the EMTP program has been employed both for the determination of the waveforms of interest and for their Fourier analysis (Appendix 2).

The values of the resistive and inductive longitudinal parameters of the EMTP model are those shown in Appendix 1, multiplied by a scaling factor of 200, similarly to what has been done for the parameters of the analogue model.

The general operating conditions being studied are:

- power feed to the 3-phase line at one end only (single-end feed);
- variation of the transversal resistances (R_b);
- different positions of pick-off along the line.

Analysing the results of all the simulations, the following general observations can be made:

- the resistive-inductive load practically absorbs a direct current (only a slight ripple is present, at a frequency 6 times that of the network. The ripple is caused by the reaction of the set of converters, which

is 6-pulse type);
- the currents delivered by the single converter units can be described as follows:
  - their average value, which is an index of the degree of collaboration between the converter units, depends mainly on the ratio R_b/R_a;
  - the ripple on these currents varies in both shape and amplitude, depending on the line parameter ratios, on the position of the pick-off point and on the position of the converter unit being considered.

The identification of a quantitative relationship between the harmonic spectrum of this ripple and the influencing variables just described is not easy. The following examples illustrate some of the qualitative correlations. On the other hand, the order of the harmonics present can be predicted accurately.
Referring to the harmonic currents delivered by a Graetz bridge, the period of the 1^{st} harmonic equals a third of the mains period. Hence, the harmonics associated to a 50 Hz power supply network, have the following frequencies:

$$f_K = K \times 150 \text{ [Hz]}, \text{ where } K = 1,2,3 \ldots$$

<u>Harmonic analysis of bridge currents</u>

- Case a).

Fig. 5 shows the waveforms of the anode currents in a system consisting of 8 Graetz bridges. The numbering of the bridges normally starts at the point closest to the A.C. power supply. The conditions are:
- single pick-off point, placed in an intermediate position between bridges N° 4 and 5;
- resistive parameter ratios: $R_c/R_a = 1$; $R_b/R_a = 18$.

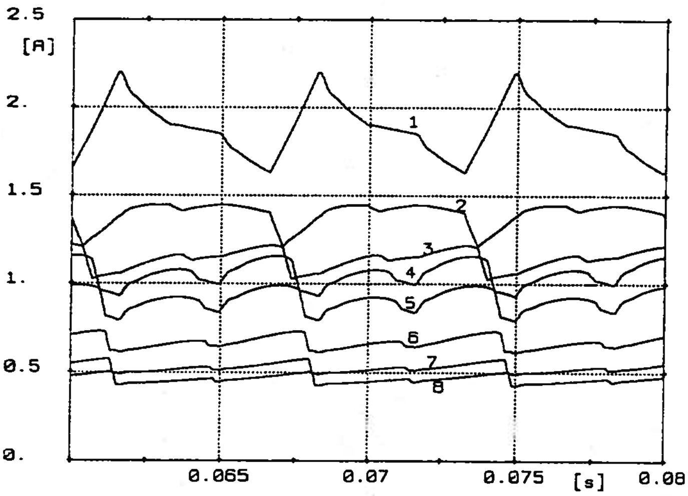


Fig. 5. System with 8 cascaded bridges. Single-side feed, with load pick-off between bridges N° 4 and 5. $R_a = R_c$, $R_b/R_a = 18$. Anode currents of bridges N°1,2,...,8.

The quantitative analysis of the waveforms shows that:
- there exists a degree of similarity between the different current waveforms excepts that of the first bridge waveform; it differs from the others for the slope of the single segments making up the waveform;
- in addition, the currents in bridges N° 4 and N° 5 (between which the pick-off point is situated) have a more rounded shape than in the case of bridges N° 6, 7 and 8.

Table III shows the harmonic analysis of the bridge anode currents, carried out for harmonics up to 1500 Hz (tenth order with respect to the frequency of the first harmonic of the bridge currents).
The numerical values of Table III show that:
- the amplitudes of the first harmonics (I_1) at the various bridges do not exceed few percent of the respective average currents. The highest value occurs at the bridge N° 1, next to the A.C. feed point;

Table III - Average currents (I_{av}) and harmonic currents (I_K, with K = 1, ..., 10) in a system with 8 three-phase Graetz cascaded bridges: $R_c/R_a = 1$, $R_b/R_a = 18$. Pick-off point between units N° 4 and 5.
N.B.: The average values are shown as a percentage of the total load current. The percentage values of the harmonics are shown as the ratio between the RMS value of that harmonic and the average current value at its own particular bridge.

I_K [%]	unit N° 1	unit N° 2	unit N° 3	unit N° 4	unit N° 5	unit N° 6	unit N° 7	unit N° 8
I_{av}	23.4	17.4	13.9	13.2	11.3	8.6	6.5	5.7
I_1	6.55	3.43	3.29	3.15	2.99	2.97	2.87	2.86
I_2	3.94	2.64	2.90	4.80	4.76	3.36	2.56	2.27
I_3	0.94	0.96	0.98	0.88	0.87	0.93	0.94	0.95
I_4	0.39	0.86	0.96	1.56	1.91	1.34	1.19	1.16
I_5	0.28	0.41	0.51	0.51	0.50	0.55	0.56	0.57
I_6	0.54	0.52	0.67	0.43	0.96	0.82	0.82	0.81
I_7	0.19	0.27	0.33	0.35	0.35	0.38	0.40	0.41
I_8	0.14	0.30	0.44	0.37	0.35	0.54	0.62	0.65
I_9	0.10	0.14	0.22	0.25	0.26	0.27	0.30	0.32
I_{10}	0.25	0.18	0.25	0.52	0.17	0.35	0.47	0.54

- generally, the amplitudes of the higher harmonics decrease as the harmonic order increases, except for some limited inversions of tendency;
- the higher harmonics at the various bridges vary, approximately, in the same proportion as their corresponding first harmonic.

The above observations justify the continuation of the analysis limited to the percentage amplitudes of the 1^{st} and 2^{nd} harmonics only. In fact, by doing this, it is possible to estimate both the harmonic energy effects (thanks to the very low amplitude of the higher harmonics) and the harmonic disturbance effects (assuming that the higher harmonics all vary similarly to the 1^{st} and 2^{nd} ones).

- Case b).

Fig. 6 shows the bridge anode currents, with the same parameters as in case a), except that, this time, the load pick-off point is under the bridge N° 2, i.e. substantially nearer the A.C. supply feed point. The behaviour shown in fig.6 is rather similar to that in fig.5:
- also here, a certain similarity exists between the waveforms at all the bridges, excepts at the first bridge, as observed above;
- the observation made for bridges N° 4 and 5 in case a) is valid here for the current at bridge N° 2: the bridge at the pick-off point or nearest to it shows a more rounded current waveform than the others.

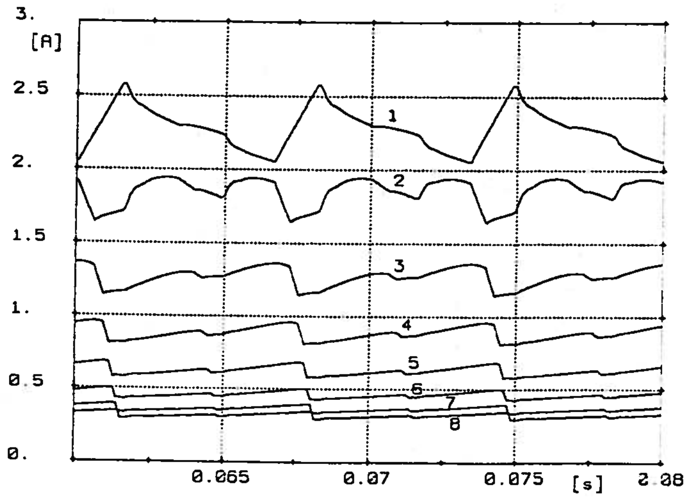


Fig. 6. System with 8 cascaded bridges. Single-side feed, with load pick-off under unit N° 2. $R_a = R_c$, $R_b/R_a = 18$. Anode currents of bridges N° 1, 2 ..., 8.

Limiting the analysis to the 1st and 2nd harmonic only, one obtains the results shown in Table IV, in which the percentage values have the same meaning as indicated for Table III.

Table IV - Average currents and harmonic analysis under the same conditions as in Table III, except that the pick-off point is under unit N° 2 (the percentage values have the same meaning as in Table III).

I_K [%]	unit N° 1	unit N° 2	unit N° 3	unit N° 4	unit N° 5	unit N° 6	unit N° 7	unit N° 8
I_{av}	28.3	23.0	15.8	10.9	7.8	5.7	4.5	4.0
I_1	5.12	2.63	3.23	3.37	3.15	2.92	2.81	2.83
I_2	2.92	3.94	3.31	2.93	2.61	2.36	2.20	2.16

The comparison with the first three lines of Table III shows that, in the face of a worse distribution of the average currents, the amplitudes of the harmonics have remained substantially unchanged.
It can be concluded that the harmonic pollution produced during the passage of a traction unit from the beginning of a contact line to its central zone remains substantially constant as the position of the load pick-off point varies.

- Case c).

In this case, the effect of the variation in the parametric ratio R_b/R_a on the harmonic content is analysed. The power feed is always single-sided and adjacent to bridge N° 1, and the pick-off point is at the other extremity of the line, under bridge N° 8.

- Case c1) Parametric ratio $R_b/R_a = 1$.

Fig.7 shows the current waveforms in the case of a ratio $R_b/R_a = 1$, which is extremely low. As is well known, in this condition the degree of collaboration is completely unsatisfactory. This is also shown by the percentage values listed in the first line of Table V.

Table V - Average currents and harmonic analysis: $R_b/R_a=1$, pick-off under unit N° 8. The percentage values are referred in the same terms as in Table III.

I_K [%]	unit N° 1	unit N° 2	unit N° 3	unit N° 4	unit N° 5	unit N° 6	unit N° 7	unit N° 8
I_{av}	47.8	10.5	2.4	0.6	0.5	1.6	6.8	29.8
I_1	2.86	2.84	2.92	-	-	-	2.60	2.75
I_2	1.87	2.55	2.48	-	-	-	2.39	3.96

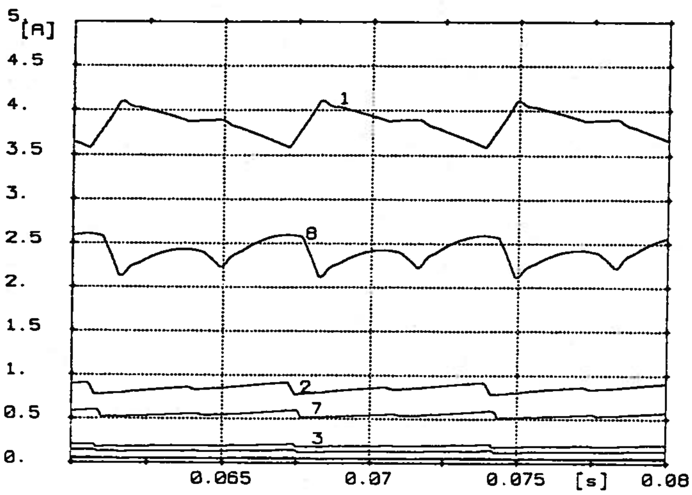


Fig. 7. System with 8 cascaded bridges. Single-side feed, with load pick-off under bridge N° 8. $R_a = R_c$, $R_b/R_a = 1$. Anode currents of bridges N° 1, 2,..., 8.

From the analysis of fig.7, we can confirm the observations regarding the waveform of the bridge currents above reported in cases a) and b).
The appreciable average currents are only those of the bridges N° 1, 2, 3, 7 and 8: hence it makes sense to evaluate only their harmonic content.

- Case c2) Parametric ratio $R_b/R_a = 5$.

Fig.8 shows the current waveforms for this situation.

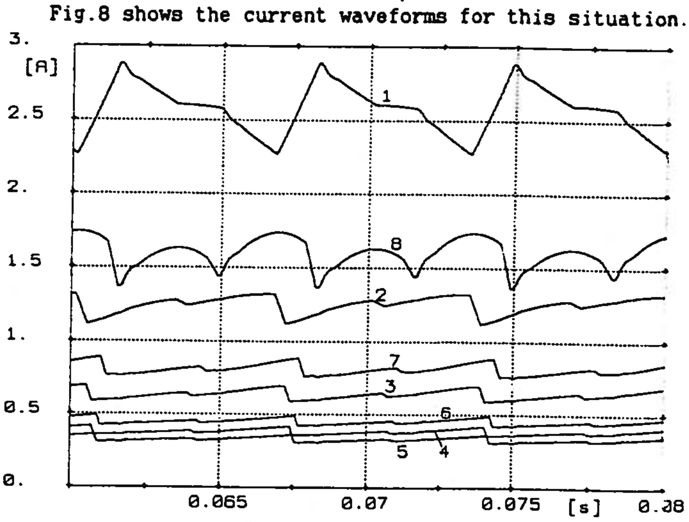


Fig. 8. As in fig. 7, except that $R_b/R_a = 5$.

The qualitative analysis confirms previous observations, while the quantitative study is summarised in Table VI.

Table VI - Average currents and harmonic analysis: $R_b/R_a = 5$, pick-off under unit N° 8. The percentage values are stated in the same terms as in Table III.

I_K [%]	unit N° 1	unit N° 2	unit N° 3	unit N° 4	unit N° 5	unit N° 6	unit N° 7	unit N° 8
I_{av}	32.0	15.6	7.9	4.8	4.1	5.6	10.1	19.9
I_1	5.14	3.17	3.12	2.82	2.71	2.63	2.64	2.83
I_2	3.21	2.72	2.75	2.52	2.39	2.26	2.67	4.71

The transition from the ratio $R_b/R_a = 1$ to the ratio $R_b/R_a = 5$, though resulting in a significant improvement in the distribution of average currents, does not produce a substantial change in the level of harmonic pollution.

- Case c3) Parametric ratio $R_b/R_a = 10$.

Fig.9 shows the waveforms of the bridge anode currents. Table VII shows the distribution of average currents and of the amplitudes of the harmonics.

Table VII - Average currents and harmonic analysis: $R_b/R_a = 10$, pick-off under unit N° 8. The percentage values are stated in the same terms as in Table III.

I_K [%]	unit N° 1	unit N° 2	unit N° 3	unit N° 4	unit N° 5	unit N° 6	unit N° 7	unit N° 8
I_{av}	25.7	15.6	10.1	7.3	6.6	7.6	10.6	16.5
I_1	6.45	3.58	3.43	3.02	2.72	2.62	2.71	2.86
I_2	3.88	2.89	2.92	2.65	2.39	2.23	3.11	5.10

The observation of Table VII shows the known improvement in collaboration as the R_b/R_a ratio increases.
The amplitude of the 1st and 2nd harmonics are substantially unchanged except for the bridge N° 1, adjacent to the power feed point, where the amplitude appears increased. This increase in magnitude is, in practice, only of the percentage type. This is because it corresponds to the reduction in the average current delivered from the same bridge N° 1, to which the amplitude of the abovementioned harmonics are referred.

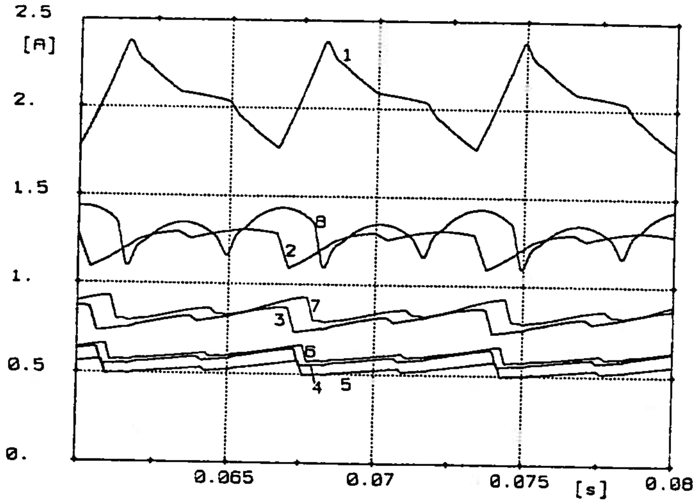


Fig. 9. As in fig. 7, except that $R_b/R_a = 10$.

CONCLUSIONS

The present work has shown the study of a distributed conversion system for the contact feed line of an underground railway. Looking forward to being able to use suitable materials which permit the construction of a continuous feed cable, this preliminary study has been limited to a "lumped component" version, made up of a number of cascaded converter units.

By means of numerical simulation, associated with experimental tests carried out on an analogue model including 3-phase Graetz bridges, parameter ratios have been identified which lead to a favourable situation regarding collaboration between the various units. At the same time, these ratio values assure an acceptable behaviour from the energy point of view.

The study of current waveforms has shown that, under conditions of a smoothed load current, the currents delivered by the single converter units are characterised by a substantial ripple level with respect to their average values.

The harmonic analysis of the currents delivered from the bridges has shown that:

- the magnitudes of the 1^{st} harmonic (150 Hz) are limited to few percent of the respective average values;
- the amplitudes of the higher harmonics generally decrease with increasing harmonic order and are approximately proportional to the respective 1^{st} harmonics;
- the level of harmonic pollution, produced by a traction unit moving along the line, is substantially independent of the position of the current pick-off point;
- as the ratio R_b/R_a (between the transversal and longitudinal resistances of a line cell) increases, the level of collaboration improves. At the same time, the amplitudes of the harmonic components of the current ripple remain unchanged.

APPENDIX 1

The reference data of a possible transmission-conversion system, when assuming a configuration using 3-phase Graetz bridges, are as follows [6]:

- the total cross-section assumed for each of the conductors is 500 mm^2;
- the position of the three A.C. conductors (spaced 50 mm from each other) is symmetrical with respect to the D.C. conductors (spaced 1 m from each other). The A.C. tern is spaced 0.5 m from each D.C. conductor;
- the bridges are placed at a distance of 15 m from each other.

On the basis of the above data, the values of the longitudinal parameters of the circuit in fig. 2 are:

R_t = 2.63 mΩ; L_t = 132 μH; $R_c = R_a$ = 0.558 mΩ;

$L_a = L_c$ = 11.8 μH; M_c = -2.09 μH; M_a = 7.79 μH.

APPENDIX 2

The computer simulation of the distributed conversion system has been carried out employing EMTP program [10] in the following manner:

- integration time step: 2μs;
- mutually coupled R-L elements has been used to represent the interaction between the line conductors;
- a snubber has been positioned in parallel to each diode, with the following values:
  resistance = 7 kΩ; capacitance = 0.01 μF;
  the values has been coordinated with inductances present in the circuit and with the integration time step, in order to eliminate the problem of numerical instability during diode switching;
- Fourier series calculation using 3335 equidistant points in a time interval of 20 ms.

ACKNOWLEDGEMENTS

The authors warmly thank Prof. Ivo Vistoli and Prof. Enrico Tironi for their helpful suggestions during the present study.

REFERENCES

[1] L.Esaki, R.Tsu: "Superlattice and Negative Differential Conductivity in Semiconductors". IBM Journal of Research and Development, January 1970.

[2] G.H.Döhler: "Solid-state Superlattices". Scientific American, Vol.249, N° 5, Nov. 1983.

[3] L.Esaki:"In As-Ga Sb Superlattices - Synthesized semiconductors and semimetals". Journal of Crystal Growth, April 1981.

[4] L.Mazzon, A.Giusti, E.Magni: "Tecniche di ottimizzazione della gestione dell'energia elettrica in una rete metropolitana mediante modellistica per impianti innovativi e supervisione automatizzata di impianti esistenti". Anipla Conference:"L'Automazione nei trasporti", Trieste, Italy, 28-30 Oct.86.

[5] Günter Lehmann: "Ungleiche Ventilbelastungen bei Halbleiterstromrichtern"; Wiss. Ber. AEG-Telefunken 44 (1971) 3, pag.93.

[6] A.Di Gerlando, E.Tironi, I.Vistoli: "Indagini preliminari di un sistema di conversione c.a.-c.c. distribuito"; L'Energia Elettrica N° 4, 1989.

[7] A.Di Gerlando, E.Tironi, D.Zaninelli: "Studio di fattibilità di un sistema di conversione c.a.-c.c. distribuito"; L'Energia Elettrica N° 5, 1989.

[8] A.Di Gerlando: "Doppi bipoli e quadripoli nelle reti a scala"; L'Energia Elettrica N° 7-8, 1989.

[9] A.Di Gerlando, E.Tironi, I.Vistoli, D.Zaninelli: "A.C.-D.C. Distributed Conversion: Feasibility and First Experiences"; International Symposium on "Electric Energy Conversion in Power Systems", Capri, May 1989.

[10] "Electromagnetic Transients Program (EMTP)"; Rule Book, Version M39; Bonneville Power Administration, Portland, Oregon (USA), June 1984.