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A.C.- D.C. DISTRIBUTED CONVERSION: FEASIBILITY AND FIRST EXPERIENCES

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A.C. - D.C. DISTRIBUTED CONVERSION: FEASIBILITY AND FIRST EXPERIENCES

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ABSTRACT

The possibility of the availability of semiconducting resins in the reasonably near future suggested the idea of a study of the feasibility of an a.c.-d.c. continuous conversion system for supplying underground railway contact lines.
The power supply cable would perfom the double function of conveying the power and, at the same time, carrying out the on-line a.c.-d.c. conversion. Since these resins are not currently available it was decided to carry out a preliminary study of the behaviour of a structure consisting of a sequence of cascaded conversion units. This paper explains the methodology used for the analysis of this system and the measures to be adopted to ensure a good level of load sharing between the various conversion units. This is, in fact, an indispensable premise for a hypothetic implementation of such a system.

INTRODUCTION

Today there is continuous and rapid evolution in the field of semiconductor technology.
There is an increment in the power and working frequency of traditional valves, and, in parallel to this, new components are appearing.
Researches directed towards the production of semiconducting resins were initiated in this context [1], [2], [3] and while their production at industrial level cannot be expected in the immediate future, the A.T.M. (Azienda Trasporti Municipali di Milano) decided that it was opportune to begin a study of an a.c.-d.c. continuous conversion system for supplying an underground railway contact line.

Preliminary studies carried out by the A.T.M. demonstrated that, from the technical point of view, it could be interesting to have a power cable which carried out the double function of conveying the power and carrying out the on-line a.c.-d.c. conversion.

If converter cabins can be replaced by transformer cabins this would permit space savings, simplification of the relative operating and switching equipment and, in addition, limit stray currents and this is a specific advantage of such a type of conversion system.
As an example, a hypothetical six-phase cable for continuous power conversion and a scheme of a possible engineering application are shown in fig. 1 and fig. 2.

A research group from the Dipartimento di Elettrotecnica of the Politecnico di Milano was commissioned to carry out a study of the feasibility of the system.

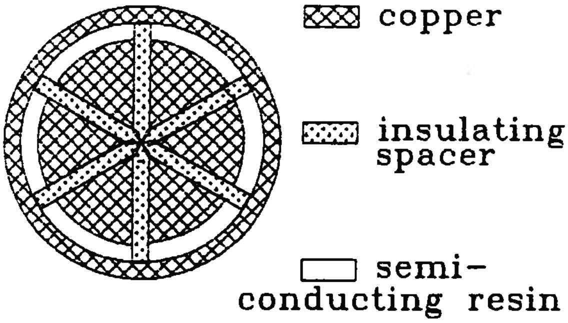

Fig.1 - Six-phase cable for continuous power conversion.

To be ahead of time, it was decided to carry out a preliminary study of a structure consisting of a sequence of cascaded conversion units.

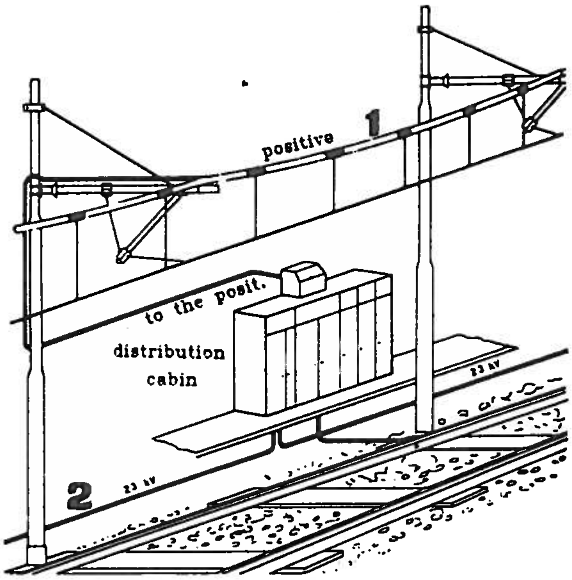

Fig.2 - Scheme of a possible application of the six-phase continuous power conversion cable [4]:
1=six-phase power conversion cable
2=three-phase power supply cable.

This passage from the continuous to the discrete is justified by the fact that a discrete representation can produce results which are representative of the continuous and, at the same time, are significant in view of an intermediate

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solution, already feasible today, with several cascaded conversion units.
As an example, the cross-section of a hypothetical conversion unit with groups of diodes is shown in fig. 3.

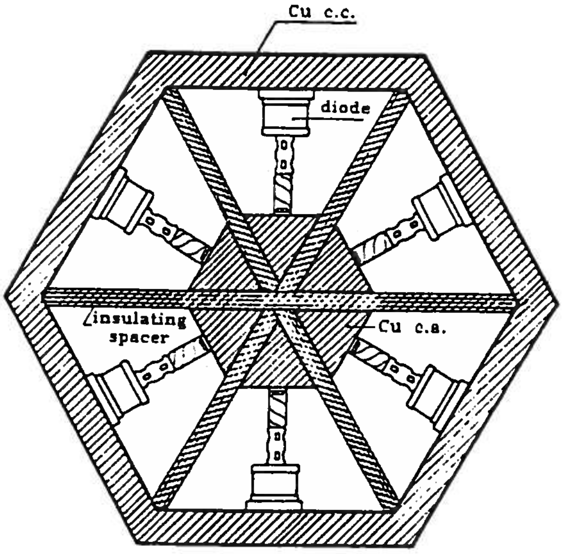

Fig.3 - Cross-section of hypothetical conversion cable with distributed groups of diodes.

An indispensable premise for the implementation of a distributed conversion system is the evaluation of the conditions wich must exist in order to obtain a good level of load sharing among the various conversion units.
From certain aspects, the study presents analogies with the problem to obtain a satisfactory distribution of the load among rectifier bridges in parallel, located in large converter cabins [5]. In the system examined here, the basic difference is that the individual bridges must be located at a distance of some meters apart from one another and the current collector position is not fixed but continuously changes from one end to the other.
The paper also provides a description of the analysis methodology which was used and also provides the results of the first tests carried out on a reduced scale model of the system, on the hypothesis of one-way and two-way supply.

1. ANALYSIS METHODOLOGY

This paragraph summarises the criteria adopted to carry out the research and the results obtained, referring the reader to previous studies for further details [6], [7], [8].
The first step was to carry out a theoretical study in order to identify the main parameters which influence the behaviour of the system and their effects on the current distribution among the individual converters.
In spite of the fact that the plant engineering configurations which can be put forward for the implementation of a distributed a.c.-d.c. conversion system are all quite different, they can all be referred back to the study of cascaded diode stars (three-phase or six-phase connected), when switching between the valves is regular.
Therefore, the analysis was initially carried out with reference to the equivalent circuit of fig. 4 in which, for the take of simplicity, only the pairs of valves which carry out the switching from phase 1 to phase 2 are shown and it has been assumed that the load is fed in at one end of the supply line.
The scheme does not show the inductances and the transversal capacitances since their effect is negligable compared to the other parameters involved.

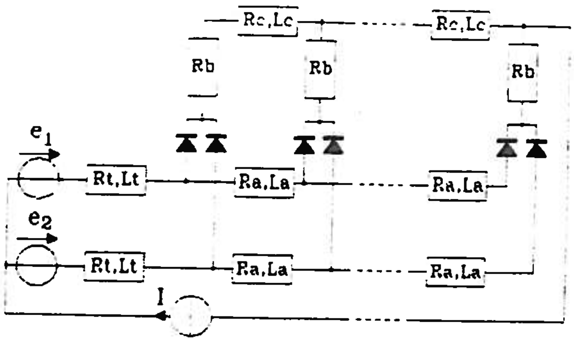

Fig.4 - Equivalent circuit adopted for the analysis of the system, consisting of several cascaded groups of diodes star-connected. The supply is represented by voltage sources with a resistance Rt and an inductance Lt connected in series; Ra-La, Rc-Lc respectively correspond to the resistances and inductances (a.c. side and d.c. side) of the line sections between two successive star-connected diodes; Rb is the transversal resistance of the connection between the centre of the star-connected diodes and the point of connection to the d.c. line. The load is represented schematically by an ideal current source.

In order to obtain an understanding of the basic operation mechanisms, the effects of the inductive parameters and the resistive parameters were considered separately, analysing the behaviour in the two extreme cases of zero resistances and zero inductances.
In both cases, it was assumed that the characteristics of the valves were ideal for the situation.

The analysis of the network led to the following conclusions:

- with a purely inductive system, valve switching ensures that all the converter units do not conduct current and that the only one to be loaded is the one immediately next to the supply;
- with a purely resistive system, given the brevity of the switching time, there is no appreciable error if the evaluation is based on the distribution of the mean values of currents between the various branches as being due to functioning in conduction only

The transversal resistance Rb plays a definitive role in the load sharing level of the cascaded conversion units: the lower the value of Rb with respect to Ra and Rc the more negligible is the contribution of the intermediate star-connected diodes compared to that of the end ones.

The analytical study of the behaviour of the real system, in the simultaneous presence of self and mutual inductances, resistances and real valves, is much more complex.
Therefore, in order to examine the effect of the various circuit components to the distribution of the load among the various conversion units in more detail, an analogue type study was made before the mathematical simulation of the system was carried out.
In addition to providing the inherent advantages of analogue models, the construction of a "physical-analogue" model permitted us to obtain experimental results about the behaviour of the system and also allowed us to prepare an appropriate mathematical model for the computer simulation: this could also be used later for the study of configurations which were different from the one experimentally tested in the laboratory.

The analogue model which was created was based on a conversion system consisting of a twin conductor contact line, connected to a three-phase a.c. line by eight cascaded rectifier units consisting of three-phase Graetz bridges. In spite of the fact that the experimental model necessarily refers to a quite specific situation, the indications obtained have general validity.
Fig. 5 shows an overall view of the analogue model which was constructed.

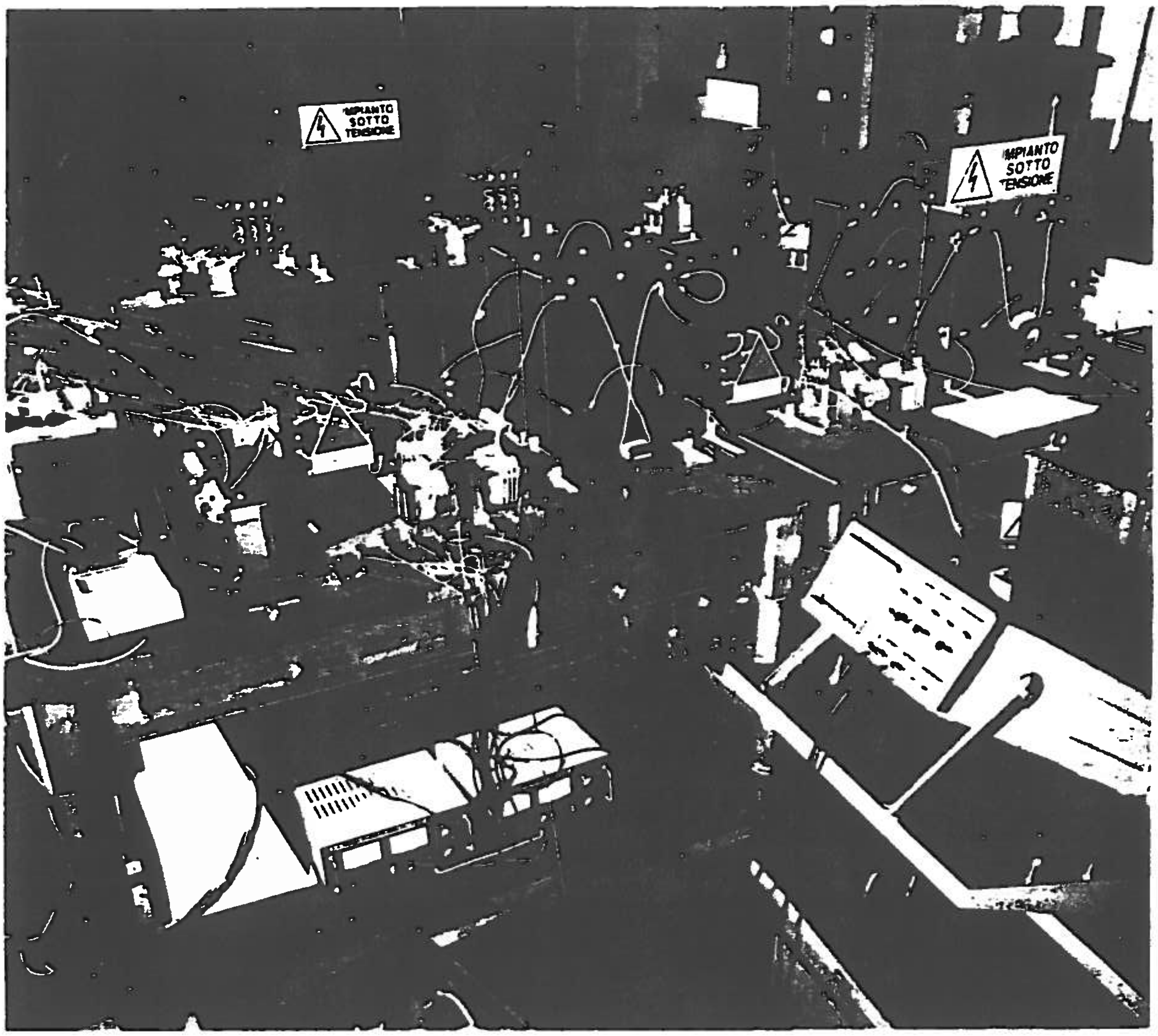

Fig.5 - Full view of the constructed analogue model. The model refers to a conversion system consisting of a twin contact line connected to a three-phase a.c. line by means of 8 three-phase Graetz bridge rectifiers.

The self and mutual inductances of the sections of line between the two converter units, assumed to be 15 meters apart from one another, were simulated by reactances of the type shown in fig. 6 and fig. 7.
Assuming that the a.c. conductors and the d.c. conductors are arranged symmetrically, it can be demonstrated [6] that the inductive voltage drop on a generic conductor is a function of rispectively either the continuous currents only or the alternate currents only.
The load was simulated by a circuit R. L in order to examine the heaviest condition corresponding to that of a train starting up.
When the analogue model was constructed, the level of the electrical quantities and the parameters of the considered real situation were modified in order to reduce the influence of parasitic parameters and to be able to use currents and voltages which were more appropriate for a laboratory model.
The criterion adopted in the construction of the model was to maintain constant the ratio between the system's inductances and resistances and to maintain constant the inductive voltage drops due to the commutating reactances of the various branches of the bridges, normalized with respect to the supply voltage.

The first experimental results were used in the setting-up of the numerical model for the simulation of the system.
The valves were represented in the computer programme as theoretical switches with suitable snubber circuits.
The comparison of the experimental tests and the results of the numerical simulation shows a good equivalence both referring to the waveforms and the values of the quantities, and that the real characteristics of the valve do not have a significant effect on the behaviour of the system.

The simulation also demonstrated that it was possible to obtain a sufficiently indicative answer, with regard to the level of load sharing among the various rectifier units, by evaluating the currents in the various branches of the plant on the hypothesis of a purely resistive system.

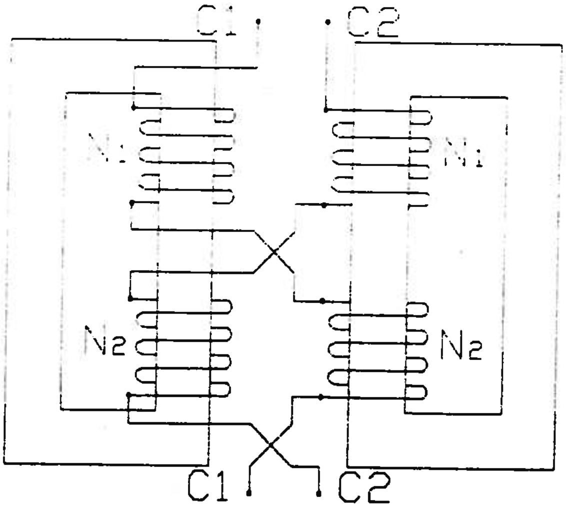

Fig.6 - Principle scheme of reactances which can simulate the inductive voltage drops on the d.c. conductors.

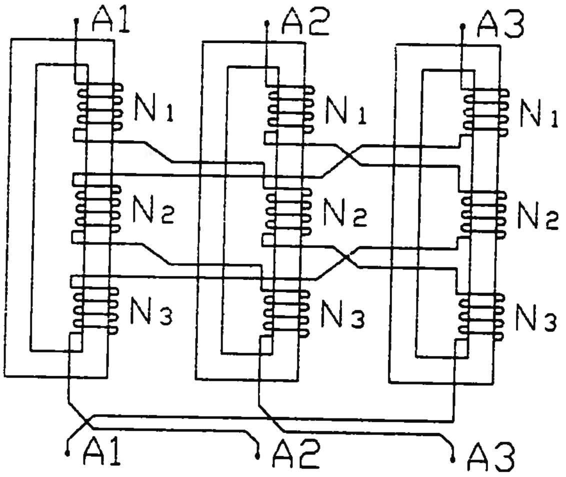

Fig.7 - Principle scheme of reactances which can simulate the inductive voltage drops on the a.c. conductors.

2. LEVEL OF LOAD SHARING AND SYSTEM LOSSES

The analysis was effected on a purely resistive system since this model permits an evaluation of the effect of the parameters on the level of load sharing and the losses.

In addition, the results obtained are very close to those which can be obtained in the case of a complete system, particularly when the inductances of the line cells are modest.

The analysis described here refers to a system with conversion units using three-phase Graetz bridges; however it can also be extended to other configurations as long as suitable equivalent resistive parameters are used [7].

One should first refer to the simplest situation, that of the system fed from one end only (one-way supply).

In addition, it is assumed that there is a single current collector point, whose position can be at any point between the two ends of the line. However, it is assumed these points must coincide with whose exactly under the conversion units only, this representing the most severe situation as regards load sharing. The results have general validity since the level of load sharing, in the case of a current collector point between two units, can also be estimated by interpolation.

The study of the influence of the parameters variation on the load sharing between the conversion units has pointed out the importance of the ratios Rb/Ra and Rc/Ra (fig. 4). When there is a variation in these ratios and in the current collector position, the units with the heaviest load (defined as main units) are always the one adjacent to the power supply and the one next to the current collector point.

The other units become progressively less loaded as one moves way from the main units, according to a graph having a "cuspidal" form as shown in fig. 8. The currents of the conversion units (mean values) are represented as envelope curves and normalized with respect to the total load current.

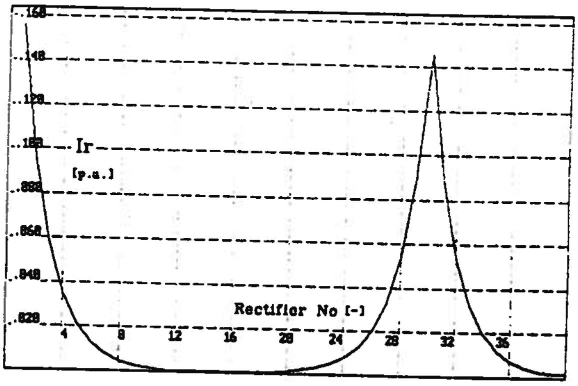

Fig.8 - Diagram of load sharing of a system with 40 conversion units; current collector point under unit 30. X-axis: converter number. Y-axis: envelope curve of the currents Ir of the conversion units (mean values) normalized with respect to the total load current. Rc/Ra=1.5; Rb/Ra=10.

In the case of the current collector position represented in the figure, the bases of the load sharing cusps have a limited width and do not interfere with one another.

The distribution between the main units is a function of the Rc/Ra ratio; as this increases, the load of the main unit on the current collector side increases, while the load of the main unit on the supply side decreases.

With one-way power feed, equilibrium occurs when Rc/Ra=1.5.

An increment in the Rb/Ra ratio reduces the load of the main units, and there is an increase in the contribution of the other units.

There is also a corresponding reduction in the load sharing cusps and a simulataneous widening of their bases.

If current collector point occurs in proximity to the supply section (fig. 9, with current collector point under the 2nd unit) there is a noticeable overloading of the main units.

In fact, under this condition there is mutual interference between the load sharing cusps, with a consequent reduction in the number of working units.

In addition, one can note an unbalance in the loads of the main units, but experience has shown that this can be corrected by assigning a value of Rb1 (which is the transversal resistance of the first unit) suitably incremented with respect to the others (Rb).

The average value of the currents of the main units, as the current collector point changes, is given in fig. 10. One can see that the main units are basically balanced with load values which remain constant as long as the current collector point is not close to the supply.

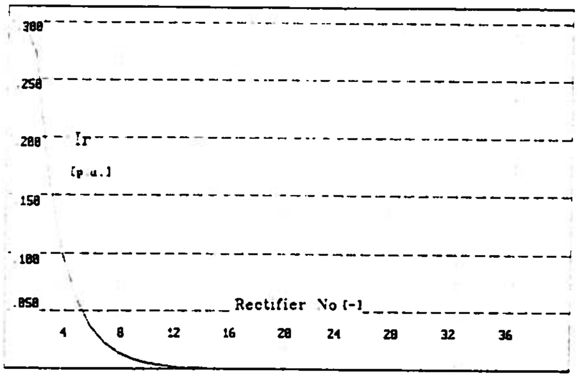

Fig.9 - Diagram of load sharing of a conversion system with 40 rectifiers: current collector point under the 2nd unit. Rb/Ra=10; Rc/Ra=1.5. The main units are overloaded (Ir1 = 30%; Ir2 = 27%).

As the main units come closer together, an overload occurs on them.

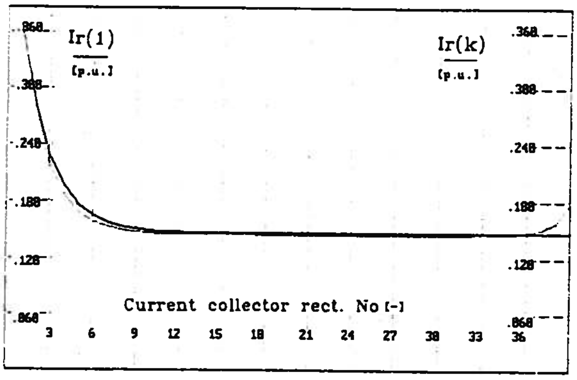

Fig.10 - Average normalized currents of the main units as a function of the current collector point, for a system with 40 conversion units. X-axis: unit number corresponding to the current collector point. Rc/Ra=1.5; Rb/Ra=10; Rb1/Ra=11.

It was to be expected that an increment in the transversal resistance Rb would produce an increase in the losses. Thus the adoption of a high value of Rb is subordinate to a limited increase in line losses on the one hand and to acceptable thermal stresses on the transversal elements with the heaviest load (i.e. the main units) on the other.

An useful parameter of the system losses increase is the ratio of the lost energy on the line during train circulation in the two following working cases: the effective situation (identified by a given Rb/Ra ratio) and the extreme situation, with Rb tending to zero.

This ratio, indicated as Q_E and known as the energy ratio, has been calculated with reference to a train travelling at a constant speed along the whole length of the conversion line.

Fig. 11 shows the energy ratio and the currents in the main units (for current collector point close to and far away from supply) as a function of the ratio Rb/Ra.

The reduction in the load of the main units is more marked for values of Rb/Ra of 5 to 15 and, as it has already been said, the situation is better when current collector point is far away from the supply.

As expected, the increase in the Rb/Ra ratio is accompanied by an increase in the energy ratio Q_E compared to the reference value of the situation with Rb tending to zero.

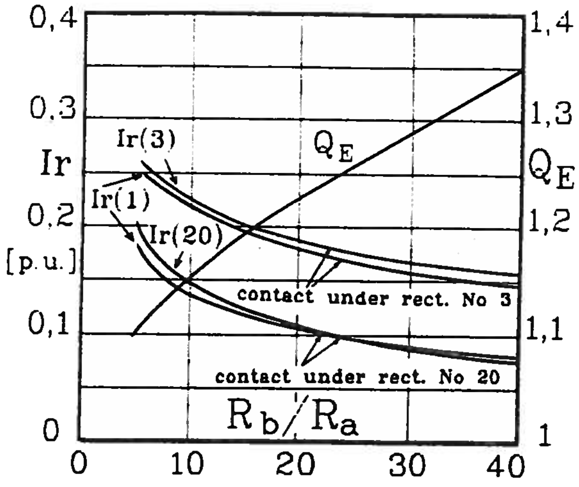

Fig.11 - Normalized current of the main units for current collector point close to and far away from supply (falling curves). Power ratio Q_E=(energy losses)/(energy losses with Rb=0) (rising curve). The curves refer to a system with 40 conversion units under the following conditions: Rb1/Ra=1.2·Rb/Ra; Rc/Ra=1.5.

However, this increase in energy losses is not dramatic for the following reasons: first of all, the reference situation (Rb=0) is not realistic since it corresponds to a situation of unsatisfactory load sharing (only the main units are loaded). Moreover the Q_E has been calculated considering all the positions of the train, including those next to the supply which, as it has been shown, should be avoided.

Finally, since the greatest advantage for the purpose of load sharing is obtained in the low value range of the Rb/Ra ratio, the significant values of Q_E are those between 1.1 and 1.2 where the corresponding loss increment can be eliminated by a reasonable over-dimensioning of the line.

As regards localized losses in the transversal resistances of the main units, it is important to verify that the increase in the Rb/Ra ratio does not lead to overheating of these resistances.

Losses in the main units, for current collector point far away from and close to the supply, as a function of the Rb/Ra ratio are given in fig. 12.

In the case of current collector point far away from the supply, the losses in the main units are basically constant as the Rb/Ra ratio increases: in this situation there is no problem with regard to overheating in the transversal resistances.

The reason for this is that the load on the main units decreases as Rb/Ra increases and, at the same time, the number of working units increases.

When current collector point is close to supply, the interference between the load sharing cusps prevents efficient redistribution of the average currents supplied by the converting units.

Thus an increase in the Rb/Ra produces an increase in the losses in the main units.

One of the possible plant engineering solutions is shown in fig. 13. The T-shaped structure of the conversion system prevents the current collector points in correspondance to the two units located in proximity to the a.c. supply.

3. EXPERIMENTAL TESTS AND SIMULATIONS

The results of tests carried out on the physical-analogue model of the conversion system, consisting of eight cascaded rectifier bridges, are provided below, together with the results of some numerical simulations effected using a complete equivalent circuit of the system.

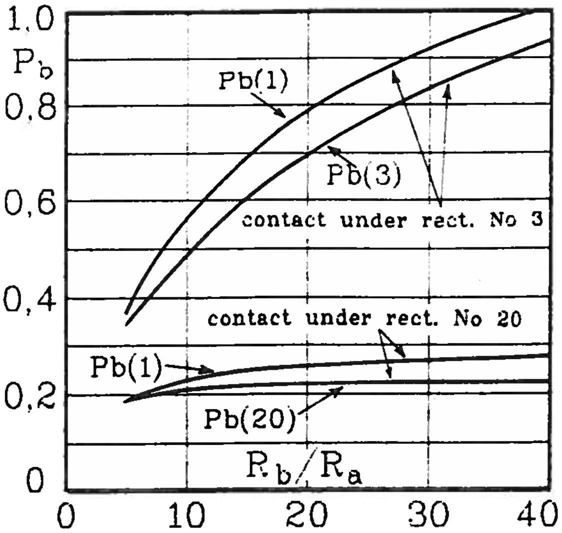

Fig.12 - Losses Pb in the transversal resistances of the main units, for current collector point close to and far away from the supply, as a function of the ratio Rb/Ra. Losses are normalized with respect to the conventional loss $Ra\cdot I^2$.
The curves refer to a system with 40 conversion units under the following conditions: $Rb1/Ra=1.2\cdot Rb/Ra$; $Rc/Ra=1.5$.

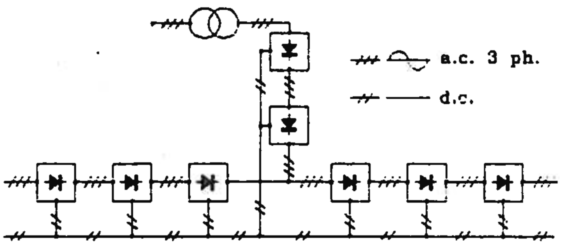

Fig.13 - A possible solution for a distributed conversion system, having a T-shaped structure.

The oscillograms of a first series of tests on the analogue model are shown in fig. 14, carried out with one-way power supply and a current collector point between bridge 4 and bridge 5.
Each oscillogram shows the waveform of the anode current of the bridge and the corresponding anode voltage measured between the positive terminal and the star centre of the three-phase power supply system.
The voltage waveforms show a commutating angle of less than 60 electrical degrees, which is typical of regular operation. With a total load current which is practically constant, the bridge anode currents show a high level of ripple, with considerable differences between one bridge and another.
The average values Ir of the currents supplied by the rectifiers in this situation are shown in the table below, normalized with respect to the total load current.

Rect.No	1	2	3	4	5	6	7	8
Ir [%]	25.3	18.2	14.2	12.5	10.8	7.6	6.1	5.3

This represents further confirmation of the fact that the conversion units with the heaviest loads are those next to the supply and next to the current collector point, while the others show a lesser load sharing. The unbalance between the main units is partially due to the fact that the Rc/Ra ratio in this case is equal to 1 and to the influence of the inductances which tends to increase the load on the units close to the supply.

A numerical simulation, performed using parameters and supply conditions equal to those of the experimental tests shown in fig. 14 (with Rb/Ra=18), gave congruent results both in terms of waveforms and average values; it was also evaluated the power losses in the conversion system, which were found to be equal to 6.9 % of the power delivered by the supply. This result is interesting when it is compared with the losses of the same system, with a value of the transversal resistances Rb tending to zero, under the same supply conditions and the same current collector point. In the latter case, numerically simulated with an Rb/Ra ratio equal to 1/1000 of the previous one, it was shown that the only loaded units were basically the first (Ir1=60.7 %), the fourth (Ir4=18.9 %) and the fifth (Ir5=19.2 %), with an unsatisfactory load sharing level and conversion system losses equal to 4.9 % of the power delivered by the supply.
The increase in the losses as a consequence of the adoption of a ratio Rb/Ra=18 is amply compensated by the improvement in the load sharing level of the rectifiers and the improvement in the distribution of the losses.

Another series of experimental tests, performed with a two-way supply (with the same parameters and load conditions as fig. 14), was carried out to investigate the improvement in the load sharing of the conversion units: the two-way supply was obtained by means of two voltage terns of equal amplitude and phase.
This situation is significant from the plant engineering point of view, since sections of the underground railway line are already fed from a two-way power supply: the primaries of the sub-station transformers located at the ends of each line section are fed from the same medium voltage line.
The results of this test are shown in the table below:

Rect.No	1	2	3	4	5	6	7	8
Ir [%]	14.6	12.2	11.1	12.1	12.1	11.1	12.2	14.6

The good load sharing level among the conversion units can be observed, representing a marked improvement compared with one-way supply.
The symmetry of the values reflects the symmetry of the supply and of the current collector position, which is at the centre of the line.
The advantage deriving from the adoption of a two-way supply is still considerable for other current collector points, as it is shown by the table below: the table gives the values of the average currents of the rectifiers with current collector point under the 2nd conversion unit.

Rect. No.	1	2	3	4	5	6	7	8
(a) Ir [%]	28.3	23.0	15.8	11.0	7.8	5.7	4.5	3.9
(b) Ir [%]	22.6	19.5	13.3	10.5	7.8	7.4	7.6	11.3
(a): one-way supply; (b): two-way supply								

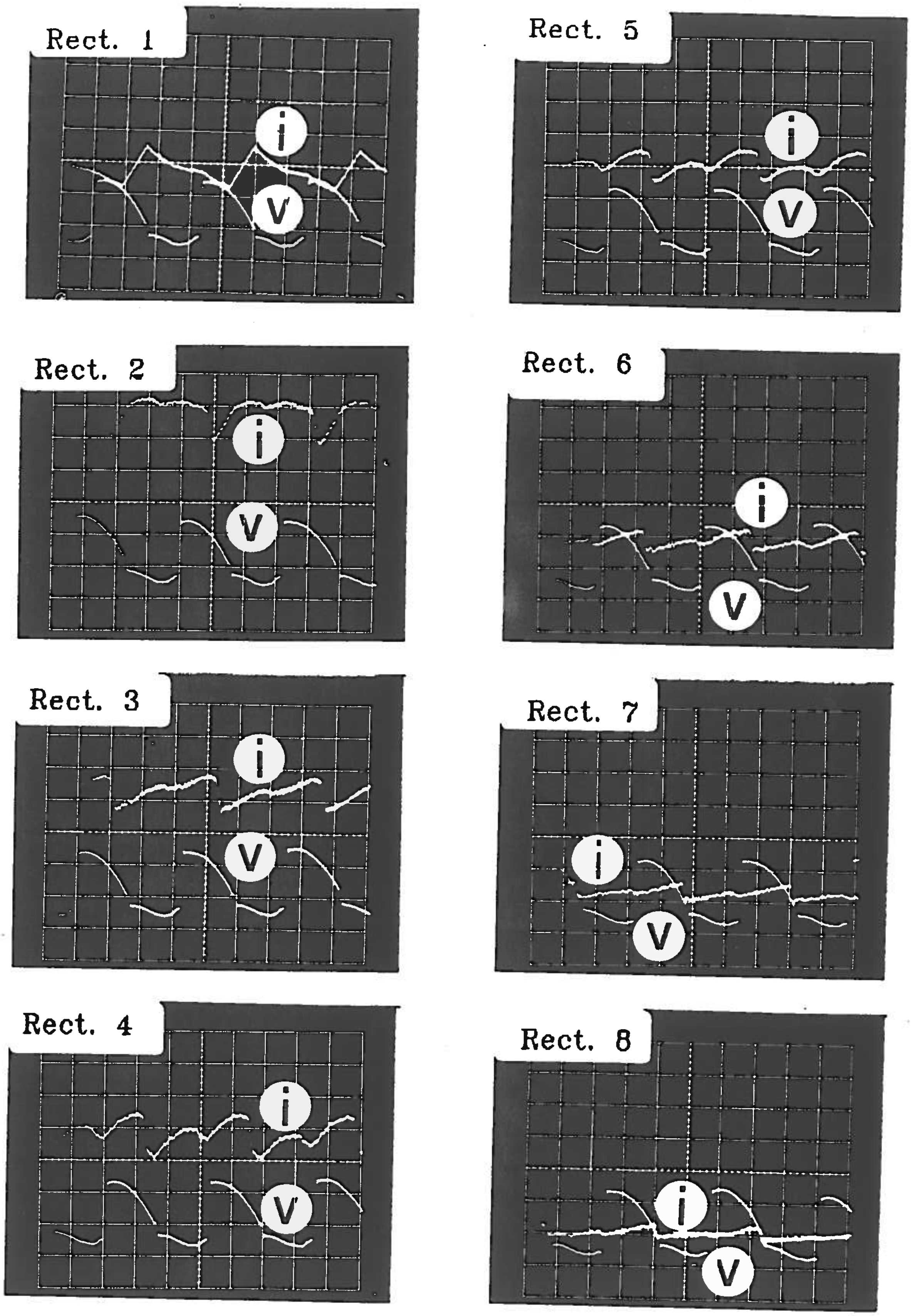

Fig.14 - Oscillograms of the voltages and currents taken on the analogue model with one-way supply and the load in the central position between bridge 4 and bridge 5 (Rb/Ra=18).
- V: bridge anode voltage, referred to the star centre of the 3-phase system (σV= 50 V/div);
- i: bridge anode current (bridge 1: σI= 0.5 A/div; bridge 2, ... , 8: σI=0.2 A/div);
- time scale: σt = 2 ms/div.

CONCLUSIONS

The construction of continuous conversion systems could be interesting for the purpose of providing the power supply for underground railways.

In this case, the power supply line would carry out the double function of power distribution and a.c.-d.c. conversion, thus containing the stray currents and reducing the amount of excavation in tunnels.

Since semiconductor resins are not currently availble and studies are still at the level of basic research, it was decided that an advance analysis of the behaviour of a distributed structure consisting of cascaded conversion units should be carried out.

This system would only be feasible if it is possible to ensure that there is a satisfactory level of load sharing among the various units; otherwise the conversion system will have to be overdimensioned to a level which would be unacceptable.

The results of the first theoretical and experimental studies show that it is possible to obtain an acceptable load sharing of the conversion units.

The main conditions which must be respected are:

- the values chosen for the transversal resistances (including those of the rectifier circuits) must be sufficiently high compared to the longitudinal resistances;
- low inductance circuit configuration must be adopted;
- current collector points must not be located in proximity to the supply sections of the distributed conversion line.

It has been concluded that these conditions can be satisfied without causing serious construction problems and considerable increases in the losses.

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