ISSN 1401-6176

DC Distribution System for Home and Office

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Chalmers, Gothenburg, Sweden, 2001.

Report No. 20R

Title
DC distribution system for home and office.

Title in Swedish
DC distributionssystem för kontor och hushåll.

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Publisher
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ISSN	Report No	Date	Report Language
1401-6176	20R	30 October 2001	English

Approved by
Ambra Sannino

Abstract
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This report analyzes the feasibility of low-voltage dc distribution systems for homes and offices and evaluates advantages and drawbacks with respect to the existing ac distribution.
The work has focused on the analysis of a “case study”, i.e. an existing system taken as example and used for calculations. For this system, a detailed monitoring of the loads has been carried out to get an understanding of the characteristics of the loads in the system under consideration.
Data obtained from the measurements have been used for the calculation of voltage drops and power losses for the existing system, when dc is substituted to ac, but loads and cables are the same. Different dc voltage levels, ranging from 48 V to 326 V, have been considered in order to choose the most suitable for the proposed application. Results indicate clearly that a very low voltage, like 48 V, cannot be used, as the corresponding voltage drops in the cables would be too high. On the other hand, higher voltage levels like 230 V and 326 V are feasible, with the former being more suitable to households and the latter to offices, because of the massive presence of electronic loads.
Moreover, a back-up supply for the dc system, consisting of a large battery block, has been designed by using commercially available lead-acid batteries. It has been demonstrated that the cost of this back-up system is much lower as compared with the current solution, consisting in a number of small UPS.
The same circuit breakers as for low-voltage ac distribution may be used for protection of the dc system, although with slightly higher interrupting rating.
Finally, an economical evaluation of the dc system has been done, by considering both initial and operational costs. It has been demonstrated that, with proper choice of the rectifier at the entrance of the system and of the voltage level, the choice of the dc system leads to savings in both installation costs and costs of the losses.

Keywords
direct current, distribution system, voltage drop, power losses, uninterruptable power system (UPS).

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Keywords: direct current, distribution system, voltage drop, power losses, uninterruptable power system (UPS).

Preface

The work presented in this report has been carried out at the Department of Electric Power Engineering at Chalmers University of Technology, Gothenburg, Sweden. The thesis will be presented as M.Sc. Thesis at the Department of Electrical Engineering at the University of Naples, “Federico II”. The financial support from Göteborg Energi AB, “Stiftelsen för forskning och utveckling” has been greatly appreciated.

I would like to thank my supervisor, Dr. Ambra Sannino, for her essential help and his invaluable advice during the development of this report. Special thanks go to Prof. Math Bollen for his important suggestions about this project.

I greatly acknowledge the support of my advisor in Italy, Dr. Maurizio Fantauzzi, who has followed from Naples the development of the work.

Particulars thank go to Dr. Mario Pagano for having given me the opportunity to come to Sweden and live this great experience.

I would like to thank the staff at the Department for having considered me a member of their big family, since the beginning of my stay here.

Finally, I want to thank my parents for the constant support during these years of study.

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1 Introduction: why DC?

1.1 Background and aim of the thesis

The choice of alternate current as a worldwide standard for power systems has been historical and mainly due to the necessity of using transformers for transferring power between different voltage levels. Another reason was the use of asynchronous (induction) motors, having higher efficiency than the corresponding dc ones, and the use of synchronous generators for producing electrical energy. The choice of 50 Hz in Europe and 60 Hz in USA has been due to the necessity of finding the optimal frequency for lights not to flicker (different types of lighting equipment where used).
Today, the scenario has completely changed with the advent of power electronics in the power system. Recent developments and trends in the electric power industry clearly indicate an increasing use of direct current, at least as an intermediate stage. Loads that need ac for correct operation are today only a few in a typical household or office. More and more loads at home and in the offices have a built-in rectifier, usually preceded by a transformer, in order to convert the ac voltage to a dc voltage at convenient level to power electronic equipment. Newer loads may have this single-phase rectifier directly supplied via the plug and followed by a dc voltage regulator, as shown in Fig.1.

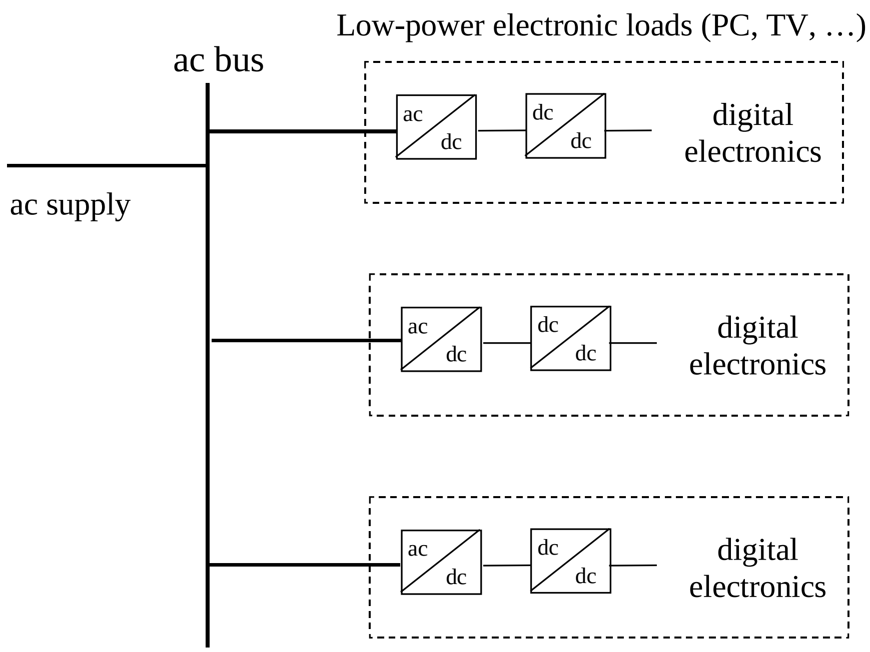

Fig.1 - Scheme of the existing ac supply to electronic loads.

In factories, the same input stage is used for process-control equipment, while directly-fed ac machines have been replaced by ac drives that include a two-stage conversion process (ac power is rectified to a capacitor, which keeps the voltage constant, and then inverted again, Fig.2).

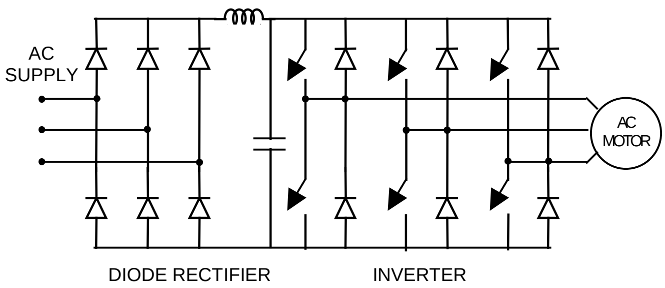

Fig.2 - Scheme of an ac drive.

A drawback is that there are losses in the conversion from ac to dc. Moreover, while newer equipment has an input rectifier followed by a dc-dc converter for regulation of the dc voltage as shown in Fig.1, in most equipment the input stage consists of a transformer followed by a diode rectifier. This input transformer is still powered at no-load, although the equipment is not working (stand-by losses). The total EU domestic power consumption of consumer electronic equipment in stand-by mode has been estimated to be around 36 TWh and it is predicted to increase to 62 TWh by year 2010 [1].
By using dc for distribution systems it would be possible to skip one stage in the conversion in all these cases, with consequent savings due to the lower number of components, as in the system shown in Fig.3. Moreover, energy delivery at dc is characterized by lower losses and voltage drops in lines.

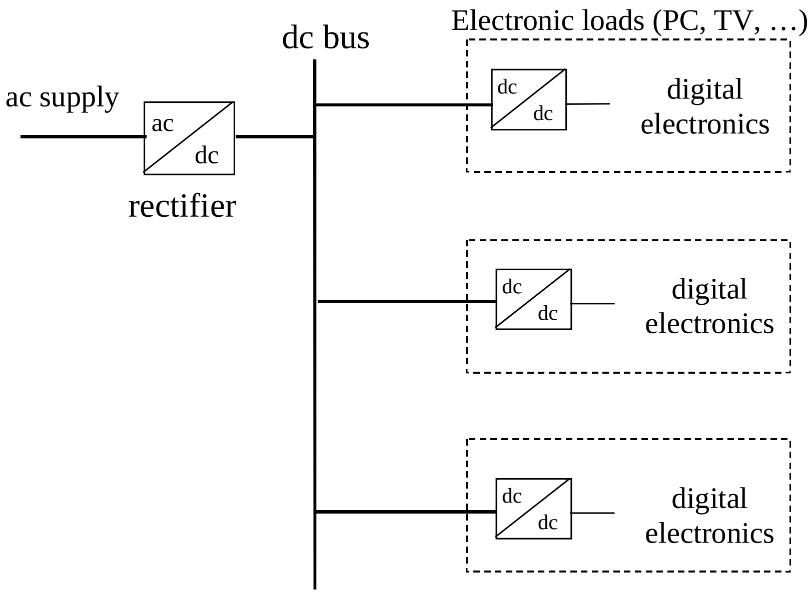

Fig.3 - Scheme of the proposed dc supply to electronic loads.

In this thesis, an alternative power system based on direct current is proposed for supplying homes and offices. Aim of this thesis is to analyze the feasibility of low-voltage dc distribution systems for homes and offices, evaluate advantages and drawbacks with respect to the existing ac distribution, isolate problems and study possible solutions.

1.2 Expected advantages of the proposed dc system

As mentioned above, the use of direct current for low-voltage distribution in homes and offices would make it possible to achieve a high overall efficiency: eliminating the ac/dc conversion leads to lower losses, as well as eliminating the input transformer cancels stand-by losses. Taking away the transformer also leads to smaller and lighter equipment.
Moreover, distributed generation units of all kinds could be directly connected to this lower-voltage dc network. Solar cells [2], which are very suitable to household applications, generate energy directly at dc. This also holds for fuel cells [3], which are considered a very promising technology. Variable-speed wind turbines, connected to the grid via a rectifier, a dc-link and a VSC as front-end stage are becoming more and more common. Natural-gas microturbines rotate at very high speed and produce energy at high frequency: this is injected into the 50 (or 60) Hz system by using the same two-stage conversion. A scheme of the current ac low-voltage distribution system including distributed generation sources is presented in Fig.4: a number of small converters is needed to connect the generators to the ac network.

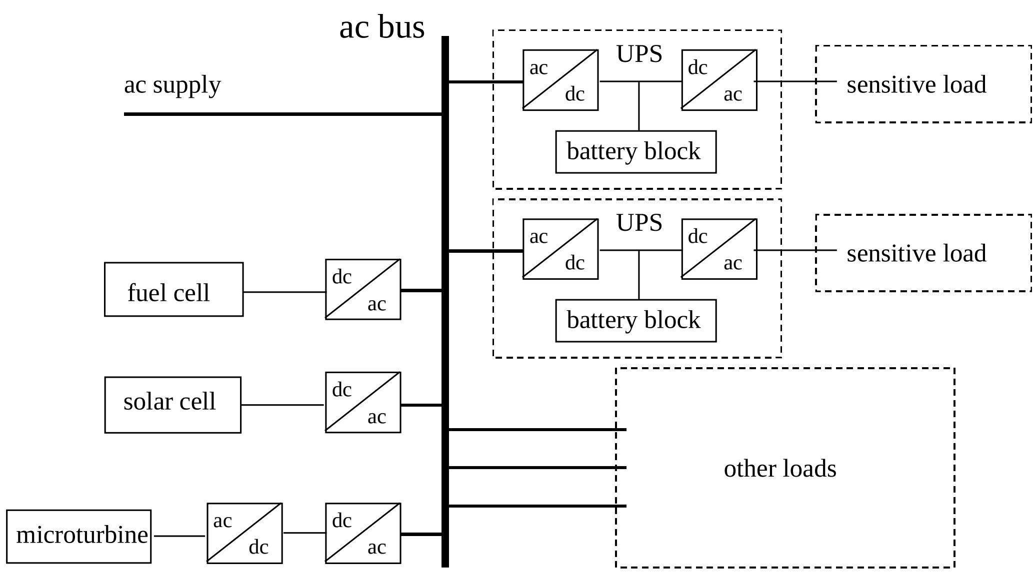

Fig.4 - Scheme of the current ac low-voltage distribution system, including distributed generation sources and sensitive loads.

Note also in Fig.4 the Uninterruptible Power System (UPS), constituted by a rectifier, a battery block and an inverter, which is the typical arrangement used for providing uninterruptible power to low-power loads like computers. A dc distribution system

allows connecting directly the battery block for back-up energy storage to the network, thus saving two conversions in this case. Moreover, by having all computers directly connected to a dc-network together with a larger battery block, the same result is obtained, but the cost is expected to be lower.
In the proposed dc distribution system presented in Fig.5, a much lower number of converters is needed (in principle only a big one at the system entrance, not considering the rectifier for the microturbine). Reliable supply to the sensitive loads is ensured by means of only one big battery block.

Dc networks also offer better possibilities for home automation [4]. This means:

- efficient systems for centrally controlling appliances in the house, which make life easier for people living there;
- possibility of communication with the utility about consumption and tariffs;
- possibility of controlling the consumption by interrupting loads and/or activating them automatically during the night or during hours of low loading/low tariffs (the latter aspect is very important for utilities, see [5]).

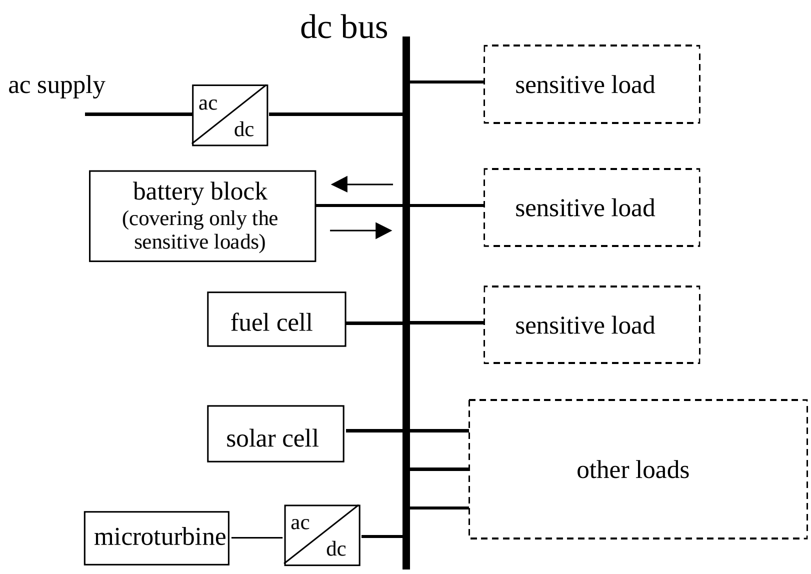

Fig.5 - Scheme of the proposed dc low-voltage distribution system.

Other advantages with such a system may be:
- Safety: direct current is not as dangerous as alternate current for the human body, as it does not lead to involuntary contractions of the muscles. Moreover, a very low voltage could be chosen to design an inherently safe system. This may be of more importance for households than for offices.
- Reduction of electromagnetic fields.
- Improvement of electric power quality: the dc network would be de-coupled from the ac supply, which reduces its exposure to disturbances from the ac network in the form of voltage dips and transients.
- Moreover, since only one rectifier is needed for the whole system, it can be worth spending more to have, instead of the standard diode rectifier, a higher-quality rectifier, such as an IGBT-based PWM-modulated converter. This reduces the

impact of the electronic loads on the ac network by decreasing the harmonic content of the current drawn from the ac supply. Note that the IGBT-converter becomes anyway necessary if renewable sources are connected to the system in such amount that they generate more power than needed in the local system under consideration. If power has to be exported to the ac network, a converter that allows bi-directional power flow is needed.

1.3 Structure of the thesis

Possible advantages with the proposed system have been listed above. Obviously, a number of problems are also likely to be expected, apart from the possible reluctance from the public towards a completely new system and from the manufacturers to change their products. This thesis will try to tackle some of those problems. In particular, it has been chosen from the beginning of this study to first analyze the technical issues connected with this solution, and only later look at a comparison with the existing ac distribution in terms of costs and savings. It is obvious, in fact, that an economical evaluation makes sense only when the technical feasibility has been assessed. This is done in the thesis by analyzing a “case study”: an existing system is taken as example and used for calculations. Later in the thesis, an economical evaluation is presented.

The structure of the thesis is as follows:

- Chapter 2 presents a survey of the loads present in houses and offices and motivates the choice of the office as a case study on the basis of the results of this survey. Moreover, the existing ac system configuration of the office is described and a number of dc alternatives are discussed, together with suitable voltage levels.
- Once the case study had been chosen, a more detailed monitoring of the loads has been done to get a deeper understanding of the characteristics of the loads present in the system under consideration. The results of this monitoring activity are presented in Chapter 3.
- One important question to be answered in this study was if it is possible to substitute the existing ac supply in buildings by dc with minor changes, e.g. by using existing cables. For this reason, the next step has been the calculation of voltage drops and power losses for the existing system, when dc is substituted to ac, but loads and cables are the same. Results are presented and commented in Chapter 4.
- In Chapter 5, a back-up supply for the dc system, consisting of a large battery block, is designed by using commercially available lead-acid batteries. Moreover, the costs of such a system are compared with the current solution, consisting in a number of small UPS.
- A search has been done in the literature and in catalogues for circuit breakers suitable for such applications. Results of this survey are reported in Chapter 6.
- Chapter 7 presents an economical evaluation of the results, by analysing both initial and operational costs.
- Finally, conclusions are drawn in Chapter 8.

2 Choice of The Case Study

2.1 Introduction

Since the beginning of this work, it was decided to carry out the analysis on the basis of a case study. The basic idea was to choose a suitable existing ac system as example, substitute the ac network with a dc one and analyze the results.
This seemed the best procedure to study the possibility of using dc in existing ac system (for instance, by using the same cables) and to find out the advantages and drawbacks, possible technical limitations and also economical aspects (costs and savings). Later, these considerations would have been extended to new systems.

To decide which system was best suited as case study (the choice being mainly between an office or a private house), an analysis of the typical loads in residential systems, with their operating principle and power consumption, has been carried out.
The results are reported in this Chapter. The case study chosen is also presented in this Chapter, with its existing ac configuration and the proposed dc alternatives. Voltage levels for the dc system are also discussed.

2.2 Inventory of Typical Loads

In this paragraph a description of the most common loads in low-voltage distribution is given. The loads are classified according to their functional features, behavior and connection to the network, in three groups:

I. Resistive
II. Inductive and slightly not linear
III. Electronic

For each category of loads, a description is given in the following subsections, and the results of the survey are summarized in corresponding tables (Tab.1 through Tab.3). In each table, the loads that fall under the category are listed, together with the power consumption. The latter is not an exact value, rather a rough evaluation based on observations and on values found in the literature [7, 9]. Power factor and harmonic content are also indicated, but only qualitatively (low/high), without specifying values. Both power consumption and power factor have later been measured for those loads that have been used in the case study analyzed. Results of the measurements are reported in Chapter 3.
Moreover, it is specified if the load is common in private houses and/or in offices. In this respect, the difference between northern Europe (e.g., Sweden) and Mediterranean countries (e.g., Italy) has been taken into account. In fact, it is common to find very high power appliances in Sweden, where the price of the electric energy is very low (among the lowest in the world, probably because the 50% of energy is produced by nuclear plants) and electrical energy is thus used for heating and cooking. In Italy

instead, the price of electrical energy is very high (among the highest in Europe), so alternative forms are used for heating and sanitary uses, e.g. natural gas, and the most common contract with the energy supplier limits the power consumption to 3 kW. This limit is normally trespassed in households in Sweden by only the cooker or the dryer. For these reasons, differences have been highlighted as appropriate in the following analysis of the loads and different results are expected from the study in the two cases.

I. RESISTIVE LOADS

These appliances, listed in Tab.1, are mainly composed by a resistance and their function is warming up water or air for uses like heating, cooking and similar. They generally draw high power, have unitary power factor and are harmonic free. They are usually connected to the system by a simple plug, without any internal voltage regulation. Being “constant impedance” loads, their resulting performance depends on the voltage level. The rms value of the current is what really produces the heat. In low-voltage ac systems the rms voltage is 230 V in Sweden (220 V in Italy), and according to the formula

$$V = Z \times I \tag{2.1}$$

where V is the rms value, Z the impedance and I the rms current, a lower voltage rms will give a lower current, thus a lower performance (a typical example is the luminosity of an incandescent lamp). A higher voltage instead will result in an excessive current, with the risk of breaking the appliance or anyway reducing its life, like for an incandescent lamp.

All loads in this category will in principle work exactly in the same way if supplied by dc, provided that the dc voltage is equal to the rms value of the rated ac voltage. They are very common in houses, not so much in offices, although in Sweden a small kitchen is usually present, including cooker, coffee machine, water heater etc.

About the different diffusion in the two countries considered, it is useful to remark that the common practice in Italy is to use gas for heating functions, which results in the absence of most of the high-power resistive loads used in the kitchen, from cookers to kettles.

TAB.1 - RESISTIVE LOADS MAIN FEATURES AND DIFFUSION

RESISTIVE LOADS							
load	**power [W]**	**Italy**		**Sweden**		**power factor**	**harmonic content**
		home	**office**	**home**	**office**		
electric heating (each radiator)	2000	not common	no	no	no	Inherently unitary	Low or nothing
electric stove	1000	yes	no	no	no		
water heater	1500	yes	no	no	no		
cooker	4500	not common	no	yes	yes		
electric oven	2500	yes	no	yes	yes		
coffee machine	1300	yes	no	yes	yes		
kettle	2200	no	no	yes	yes		
toaster	500	yes	no	yes	no		
iron	1200	yes	no	yes	no		
steam iron	2000	yes	no	yes	no		
incandescent lamp	50÷150	yes	not common	yes	not common		

II. INDUCTIVE AND SLIGHTLY NON LINEAR

Loads of this type are listed in Tab.2. All the motors not controlled by a converter and some fluorescent lamps belong to this category. The motors could be induction motors or universal ones. Refrigerators, washing machines, dryers and pumps are induction motors and require an ac connection. To supply them with a dc voltage, an inverter is needed. Universal motors instead - vacuum cleaners, food processors, hair dryers, electric fan and most high-speed motors – can be supplied by either ac or dc voltage, without any modifications [8, p. 26].

Inherently they do not necessarily require very high power, but in some cases they are connected to a big resistance like for the washing machine or the dryer, so that the load draws high power anyway.

Another common load falling within this category is the fluorescent lamp equipped with choke ballast, i.e. with a big reactor that is used for switching the lamp on. This lamp will not function if supplied directly with dc: in this case, an inverter is required or otherwise a different lamp should be used (for instance the fluorescent lamp with electronic ballast belonging to the third category of loads).

For the presence of the inductance the power factor is quite low while the harmonic distortion is not so high [8, p.1143].

Excluding the clothes dryer that is not common in Italy, the appliances of this category are present in both countries with the same diffusion.

TAB.2- INDUCTIVE LOADS: MAIN FEATURES AND DIFFUSION

INDUCTIVE AND SLIGHTLY NON LINEAR							
load	power [W]	Italy		Sweden		power factor	harmonic content
		home	office	home	office		
Inductive motors						Low	Low
washing machine	2200	yes	no	yes	no		
clothes dryer	4000÷6000	no	no	yes	no		
dish washer	2000	yes	no	yes	yes		
air conditioner	750	yes	no	yes	no		
refrigerator/freezer	100÷150	yes	no	yes	yes		
floor polisher	500	yes	no	yes	no		
Universal motors							
hair blower	1200	yes	no	yes	no		
food processor	50÷200	yes	no	yes	no		
hand dryer	1000	no	yes	no	yes		
exhaust fan	150	yes	no	yes	yes		
vacuum cleaner	1000	yes	yes	yes	yes		
electric fan	50	yes	yes	yes	yes		
Others							
fluo lamps with choke ballast	15÷36	yes	yes	yes	yes		

III. ELECTRONIC EQUIPPED APPLIANCES

These are the loads that "naturally" require dc and usually do not draw a high power. Therefore they are best suited for a dc supply. As pointed out earlier in the Introduction, it is because of the increasing presence of this kind of loads that dc low-voltage distribution has been proposed. These loads are listed in Tab.3.

TAB.3 - ELECTRONIC APPLIANCES: MAIN FEATURES AND DIFFUSION

ELECTRONICS EQUIPPED APPLIANCES							
load	power [W]	Italy		Sweden		power factor	harmonic content
		home	office	home	office		
PC with monitor	180	yes	yes	yes	yes	Low	High
printer	900	yes	yes	yes	yes		
fax machine	450	no	yes	no	yes		
copy machine	1800	no	yes	no	yes		
security system	40	not common	yes	not common	yes		
fire alarm system	40	not common	yes	not common	yes		
microwave oven	1200	yes	no	yes	yes		
TV	50÷100	yes	no	yes	no		
Hi-Fi	60	yes	no	yes	no		
radio	25	yes	no	yes	no		
fluo lamp with electronic ballast	36	no	yes	no	yes		

For appliances like PC, printer, fax, alarm systems and all the “data-handling” machines, dc is necessary for the functional electronic circuits. Controlled motors also fall in this category, since a dc stage is required to de-couple the present network frequency from the one that really supplies the motor (a controlled inverter gives the wanted speed of the motor).
Fluorescent lamps with electronic ballast are controlled to behave as “constant power” loads. It means that they produce a constant lighting, not subordinate to the voltage variability, that in a constant impedance load results in a variable current and power (see also Section I).
Because the current network is ac, it is necessary to create a power supply input stage consisting of a rectifier. The most used ac/dc converter in these cases is the diode rectifier, because of its low price with respect to other ones. It gives as output the peak value of the single-phase voltage (326 V for Sweden, 311 V in Italy) – if a suitable capacitor is used to smooth the output voltage ripple. Due to the presence of the diode rectifier all these appliances draw a current with high harmonic content from the network. The current spectrum includes the odd harmonics (see also measurements reported in Chapter 3).

2.3 The Case Study

On the basis of the previous analysis, it was chosen to analyze the supply to an office as case study. This because the office has a concentration of low-power electronic loads, i. e. loads falling within the third group analyzed above.
This is thus a case in which the advantages of using a dc network should be more evident (reduction of conversion and stand-by losses, simpler system with a smaller number of components). Moreover, since most loads absorb low power, it could even be possible to use very low voltage levels. The supply to an office will be briefly presented in the following section. A more detailed description of the case study chosen will be given in Chapter 4.

2.3.1 The existing ac system configuration

Usually residential distribution systems are structured as in the one-line diagram of Fig.1. From a substation where voltage is transformed from medium to low voltage level (in Sweden from 11 to 0.4 kV), a three-phase cable connects the transformer to the switchgear and several feeders depart from the switchgear to reach different rooms. From every feeder several loads are derived, each with a different power and power factor, three-phase or single-phase type.
The length of the feeders depends on the location of the loads. Their cross-section is chosen so that the total current drawn by the supplied loads does not exceed the maximum allowable current for the cable. Moreover, it has to be verified that the voltage drop on the feeder does not trespass recommended limits (usually 5%).
The cables have the typical cross-sections used in residential applications (1.5 mm^2 and 2.5 mm^2). Usually in ac system with 230 V line-to-ground voltage these sizes allow remaining widely under voltage drop limits.

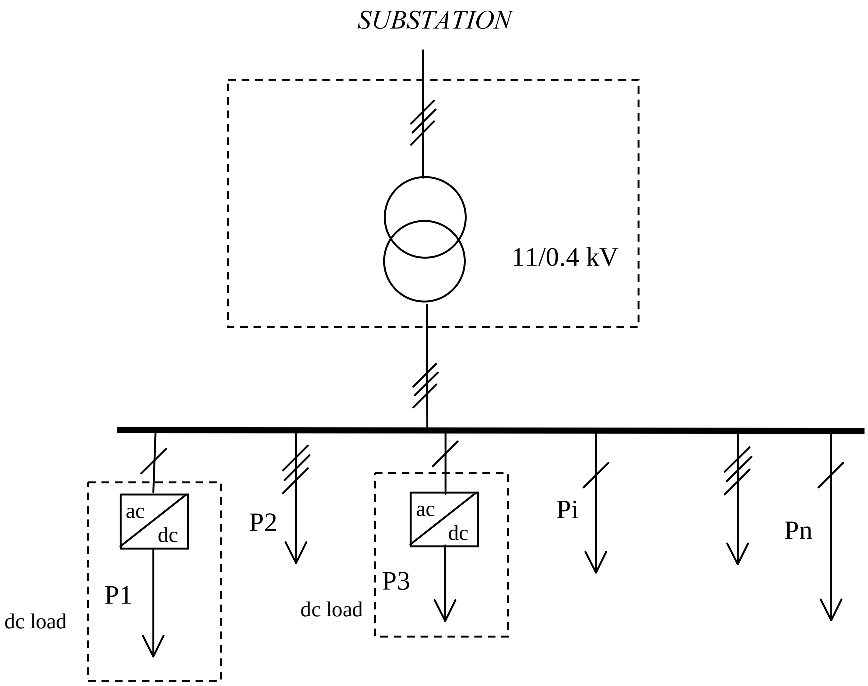

Fig.1 - Ac distribution system.

Three-phase appliances (if present) and ac single-phase loads (like motors, resistive loads, incandescent lamps) can be connected directly to the feeders. Electronic loads instead need a transformer to reduce the voltage further on, followed by a rectifier to change the voltage type from ac to dc, and then usually a dc/dc converter is present to adjust the dc voltage to the level required by the electronics inside. In the most modern appliances, the transformer is not necessary and the rectifier is directly coupled to 230 V ac (as shown in Fig.1).

2.3.2 Proposals for dc configurations

In this section some suggestions for the configuration of the proposed dc system are given. The system has again a transformer in the substation, a switchgear, some feeders and some loads derived. The difference is that in this case a common rectifier for the whole system is required. But since some high-power loads are still fed by ac to take advantage of three-phase supply or because necessary for some appliances, two different options have been considered.

a) The rectifier could be put in the substation right after the transformer. This means that the cable connecting the substation to the switchgear is a dc cable and all the dc loads can be derived directly from the switchgear.
   For the ac loads there are three options:

   - continuing to feed them from the substation in a separate way (not using the same main cable but another dedicated);
   - install an inverter at the switchgear and supplying all the three-phase feeders via the inverter;
   - use a smaller inverter for each load requiring ac supply.

It could be objected that the last solution proposed for the ac loads is the dual of the one currently in use (a main supply in ac and then a rectifier at each load that supplies dc for the inside electronics). But one has to keep on mind that the basic assumption made here is that the number of loads requiring ac is considerably lower than those using dc. The third solution (reported in Fig.2) is thus considered the best among the proposed ones, while the first two would make the system rather complex, as both ac and dc cables would be present at the same time.

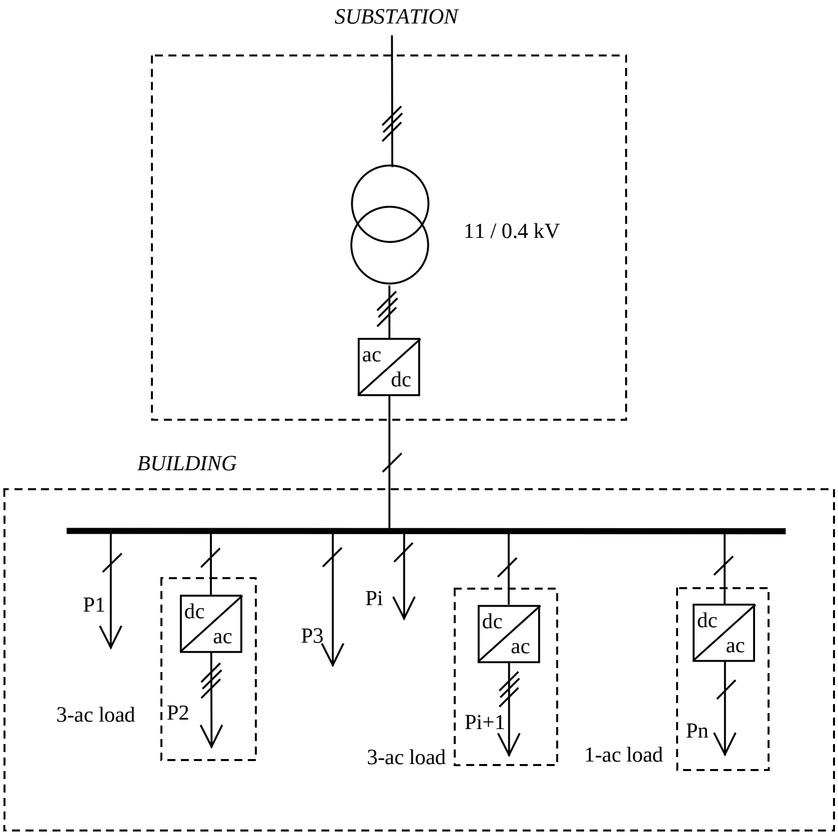

Fig.2 - Dc distribution system. Case a): rectifier in the substation.

b) In Fig.3 the different solution of putting the rectifier not in the substation but at the switchgear (in the building) is presented. This allows using three-phase ac for the connecting cable, thus reducing the current in the cable and then the voltage drop (and power losses) on it. Moreover the ac loads could be easily connected directly to the ac supply, without inverters.
   Two switchgears and two sets of busbars would thus be needed: one for the ac loads and one for the dc loads.

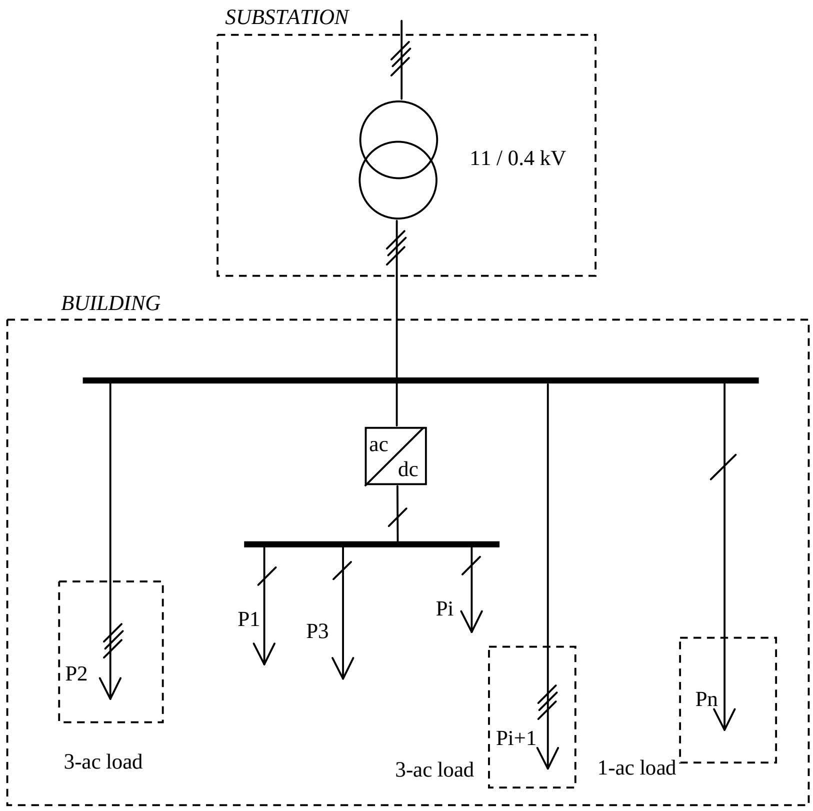

Fig.3 - Dc distribution system. Case b): rectifier in the building.

Both solutions (a) and (b) seem to be feasible, although it will be shown later by the results of the voltage drop analysis that, depending on the dc voltage level chosen, only solution (b) is feasible in some cases.

These solutions accommodate high-power three-phase loads by making the system somewhat complex. Another idea, applicable to all the schemes proposed above, that would simplify the electrical system, could be to improve the use of gas, considering that usually high power loads are resistive and their function is heating (even if in different ways). The cooker can be driven by gas, as it is done in many countries, e.g. Italy, and gas can also be used for warming water for heating and for washing machines, which could take directly hot water instead of warming it up, thus reducing their consumption (the motor inside is not so powerful, usually not more than 400 W). Technology already exists, but the wide application depends on the availability of the energy carrier. For example, gas is not much used in south of Sweden, but there are plans for improving its distribution.

2.3.3 Dc voltage levels

One important point is which voltage level to use in the proposed DC system. For this reason, several different levels will be studied:

- **326 V dc:** this voltage has been chosen because many electronic appliances are fed by an ac-dc single-phase converter (diode rectifier) that supplies them with the voltage peak value. So if the appliances are supplied directly with the peak value (326 is equal to the peak value of the 230 ac voltage), it is possible to remove just the converter keeping the rest of the appliance unmodified.

- **230 V dc:** adopting this voltage should allow the use of resistance equipment (heating, incandescent lights) with no changes, because it has the same rms value as the 230 ac (the currently used line-to-ground voltage).

- **120 V dc**: when using this voltage, no protection against indirect contacts is required. This means that the system could be simpler due to the absence of grounding.

- **48 V dc:** this voltage level does not require any protection at all (not even against direct contacts) since a voltage lower than 50 V is considered inherently safe. Moreover, another reason to use 48 V is that it is the commonly used voltage for telecommunications equipment, therefore system components working with this voltage already exist on the market.

2.4 Conclusions

This first research conducted to understand the behavior of the most common residential loads has resulted in choosing the office as the most suitable candidate for the project.
The reason for this is the massive presence of electronic loads and the lack of high power consumption appliances. This means that it is not expensive to continue feeding some big loads by ac, if necessary, because just a few dc/ac converters are sufficient.
Another point is the reliability and the power quality required by an office and generally not by a house. It will be shown that it is simpler and less expensive to ensure high reliability when using a dc system than ac.

3 Monitoring of Loads

3.1 Introduction

Once chosen the office as a study case for the reasons exposed above, a part of an existing system was taken as example, to collect data about system dimensions (wire length and cross section) and loads.
One of the two switchgears feeding the Electric Power Engineering Department of Chalmers University of Technology was chosen for the analysis. The appliances connected to the switchgear were listed and the most common in offices measured with a Power Quality Monitor (Dranetz PP1). This kind of analysis was deemed necessary to get an understanding of the behavior of the loads and to get exact data for further analysis. Loads typical of a kitchen, even if present and considered in the rest of the project, were not included in this phase.

The appliances have been divided by groups, according to some common characteristics. The groups are:

1) personal computer
2) diode rectified loads in combination with an heating function
3) lightning loads

The first one is the computer, the most common load in every office.

To the second group belong machines like fax, copy machine and printer. Their particular feature is that, although they handle data and thus have a similar behavior to the computer, they also have a heating function to melt the toner before printing and so from time to time draw high power and have linear behavior.

Another category is the lightning. In an office, generally, and this case confirmed it, most of the light are fluorescent ones. But there are several types of them (in this case study three kinds have been found and analyzed) and the only thing they have in common is the function. Their internal structure and way of operation will be shown to be different.

3.2 Personal computer

Measurements have been performed on a personal computer including the monitor and voltage and current waveforms have been recorded in the two cases in which the monitor is off (Fig.1) and on (Fig.2). The resulting waveform of the current is typical of the single-phase rectifier in both cases, only the peak value of the current changes because of the power required by the monitor. During the transient in which the monitor is switched on, the waveforms of Fig.3 have been recorded.

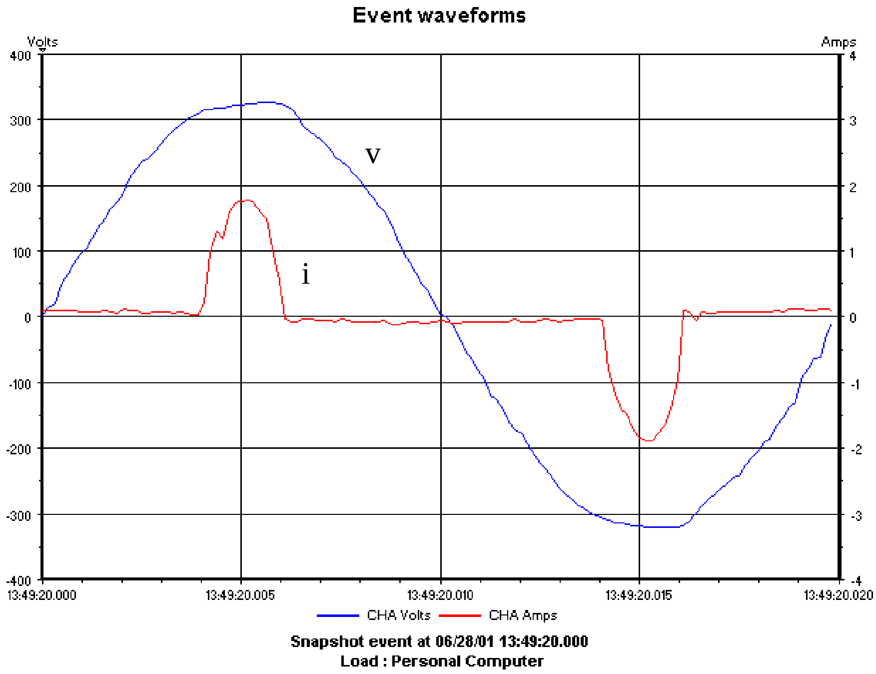

Fig.1 – Recorded voltage and current waveforms for PC with monitor off.

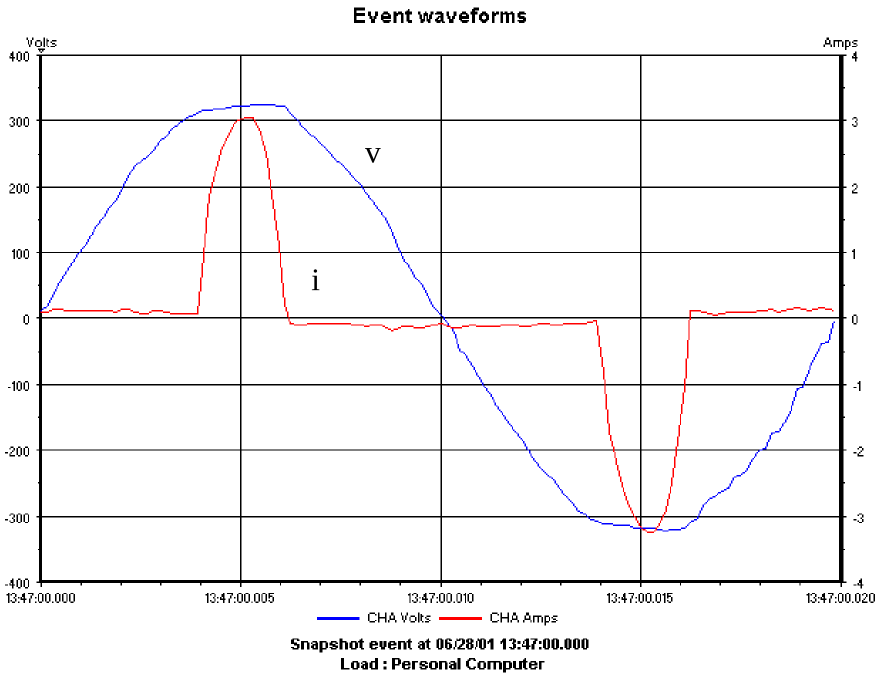

Fig.2 – Recorded voltage and current waveforms for PC with monitor on.

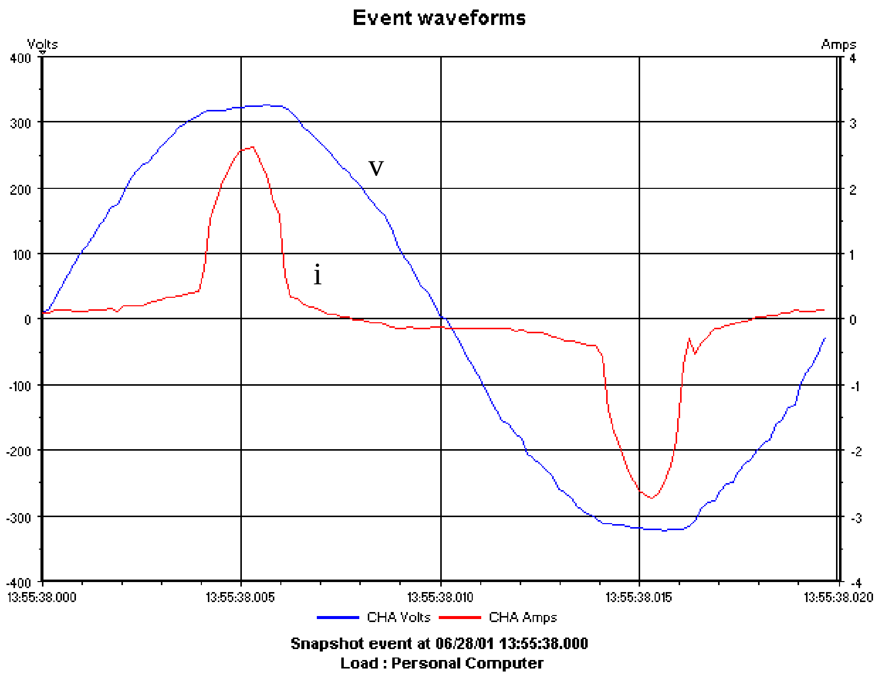

Fig.3 – Recorded voltage and current waveforms for PC during the monitor switching-on transient.

The measured RMS value of the current, shown in Fig.4, clearly does not follow the variations of the voltage RMS value, shown in Fig.5. In particular, the monitor is switched on at about 12:40 and off again at 13:45, and the current drawn while working on the computer with the monitor on is rather constant at a level of about 1.15 A.

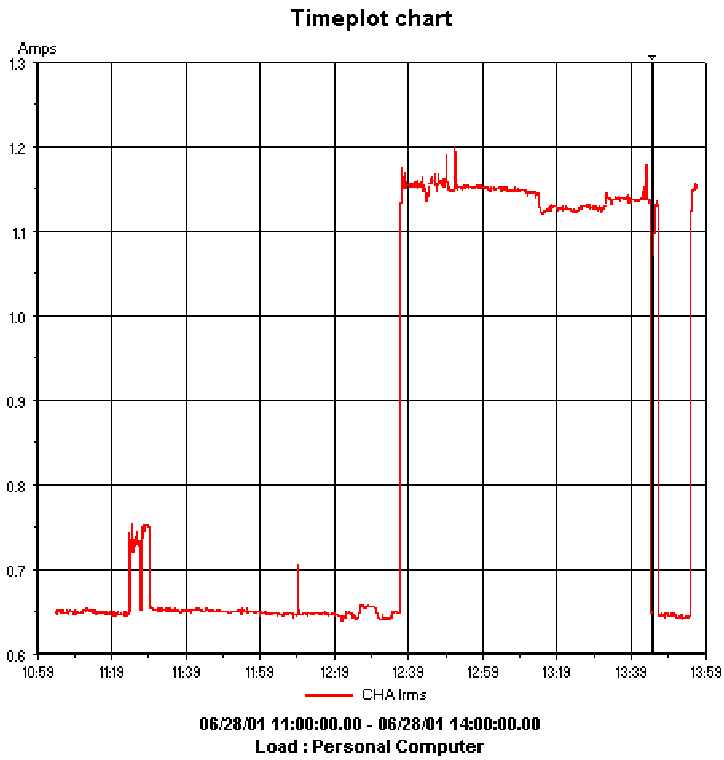

Fig.4 - RMS value of current for PC measured in three hours.

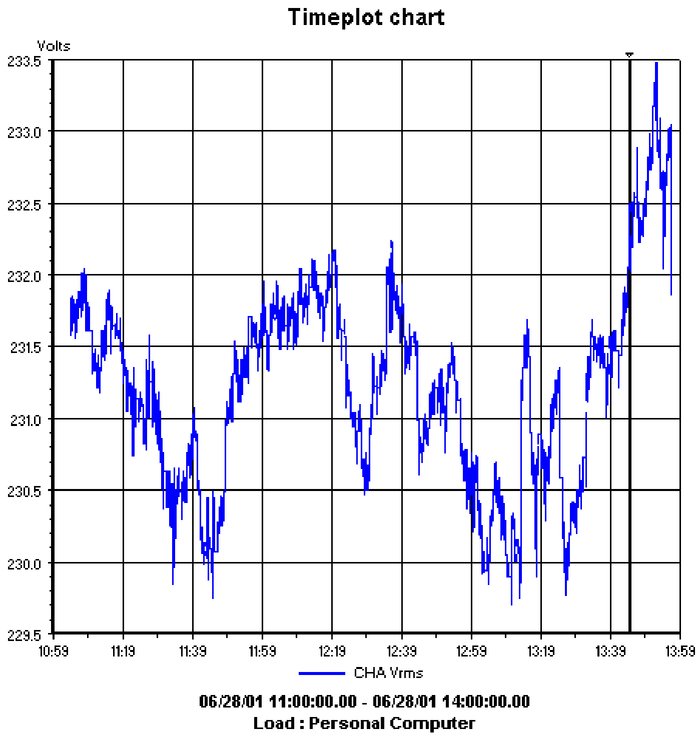

Fig.5 - RMS value of voltage for PC measured in three hours.

When the monitor is off (before 12:40) and the computer is standing by, the current also looks rather constant at a lower level of about 0.65 A, except for a variation of about 0.1 A in a 5-minute period starting at about 11:25. This is probably due to some function performed automatically by the PC (like automatic saving of files, for example). This is also confirmed by the fact that a similar variation is present at the same time and for the same duration in the measured power consumption, shown in Fig.6.

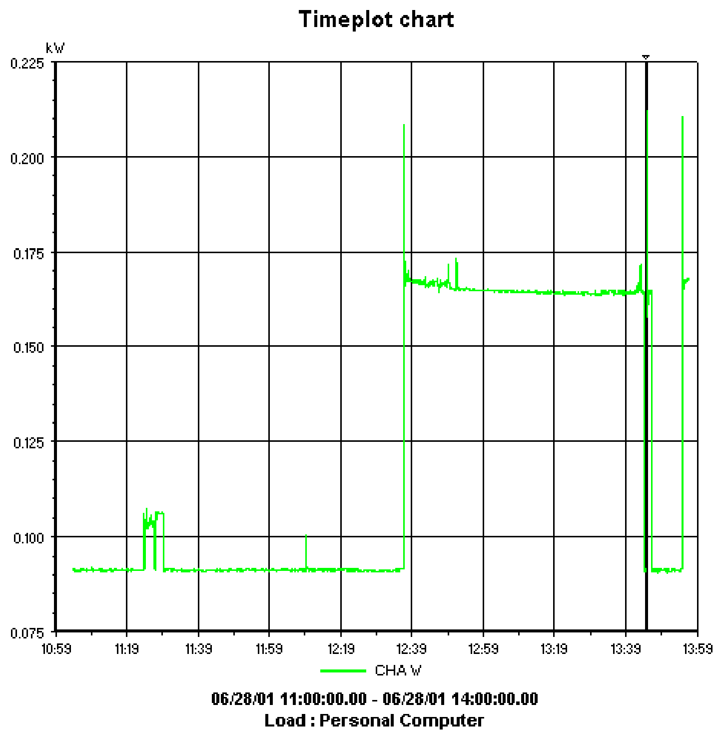

Fig.6 – Power consumption of the PC measured during three hours.

The power drawn by the PC is pretty constant both when the monitor is off (about 90 W) and when it is on (about 165 W). It is difficult to conclude if the load behaves as a "constant-current" or "constant-power" load, especially because the voltage variations are not very large (just about 2 V).
But carefully looking at the plot at the current RMS value in Fig.4 one can see very small variations both with monitor off (current goes up between 12:20 and 12:30) and with monitor on (current goes down between 13:15 and 13:35). These variations do not correspond to power fluctuations, but to inverse variations in RMS voltage value (voltage goes down between 12:20 and 12:30 and up between 13:15 and 13:35). Therefore it can be concluded that the personal computer is definitely a constant-power load. The three-dimensional plot reported in Fig.7 that allows comparing the measured power, voltage and current clearly shows the same trends for current and power. The vertical black line in many of the RMS value plots indicates the instant in which the corresponding waveforms have been recorded.

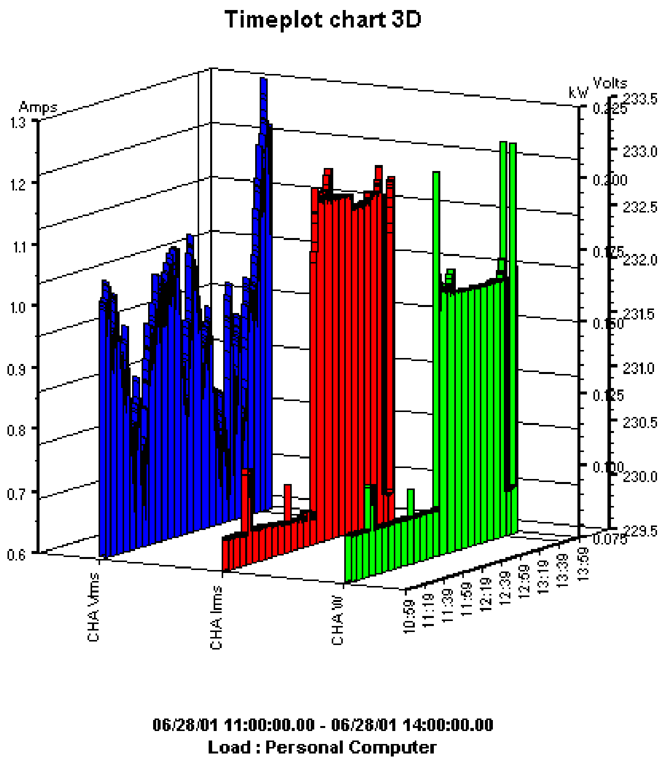

Fig.7 - Three-dimensional plot of RMS voltage, RMS current and power for PC measured in a three-hour period.

The average values of voltage, current and power, in the two cases of monitor off and on, together with the excursion between them, are summarized in Tab. 1.

TAB. 1 – AVERAGE ELECTRICAL PARAMETERS WITH MONITOR ON AND OFF FOR A PC

	Voltage [V]			**Current [A]**			**Power [W]**		
	Off	**On**	**ΔV**	**Off**	**On**	**ΔI**	**Off**	**On**	**ΔP**
Personal Computer	229.7	233.5	3.8	0.65	1.15	0.5	91	165	74

Finally, the harmonic content of voltage and current for the personal computer has been measured and reported in Fig.8 and Fig.9, respectively, for the case in which the monitor was off and the PC in stand by. The THD (Total Harmonic Distortion) of the current up to the 50th harmonic is very high (about 134% of the fundamental). In accordance with the theory, the current harmonics present are mostly of odd order and their amplitude decreases with increasing harmonic order [10]. The behavior is anyway not exactly ideal: there is also a small contribution of even harmonics and odd harmonics appear to increase again between the 15th and 21st. This is because of the background voltage distortion, which is anyway rather small, as shown in Fig.8: the voltage THD is only 2.1% of the fundamental.

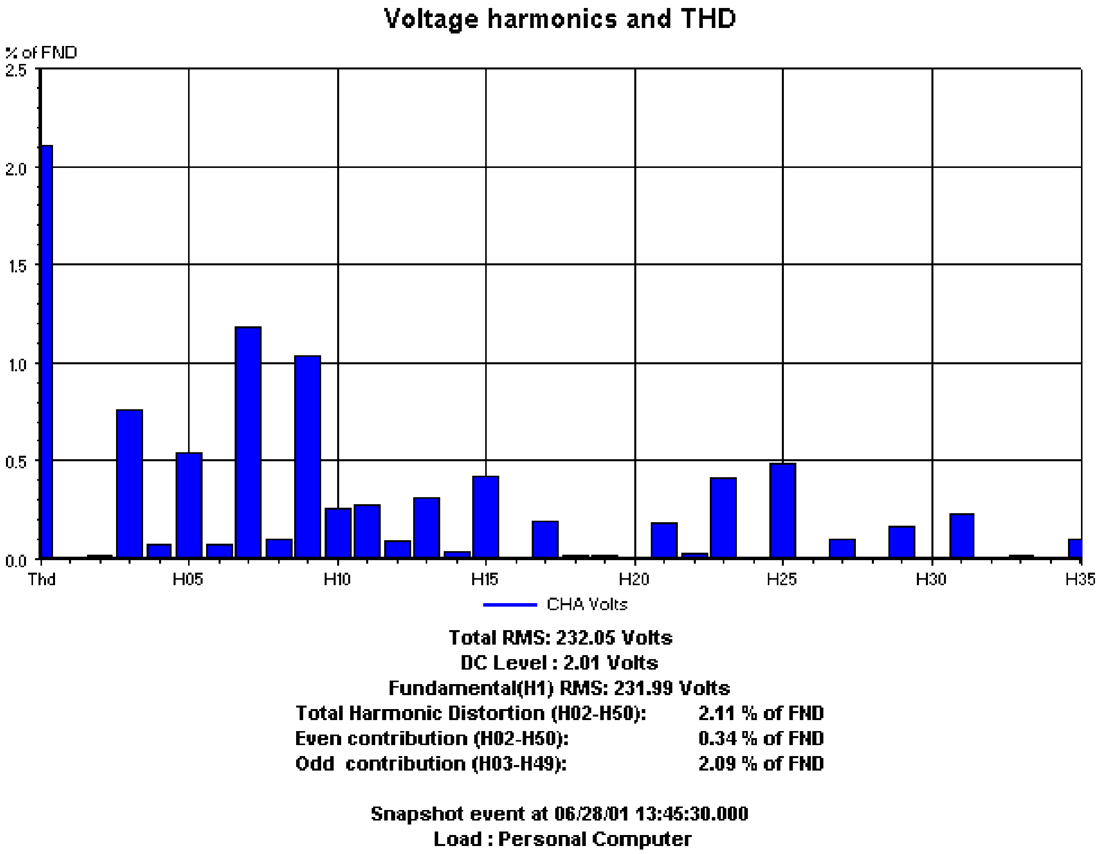

Fig.8 - Voltage harmonic content and total harmonic distortion for the PC.

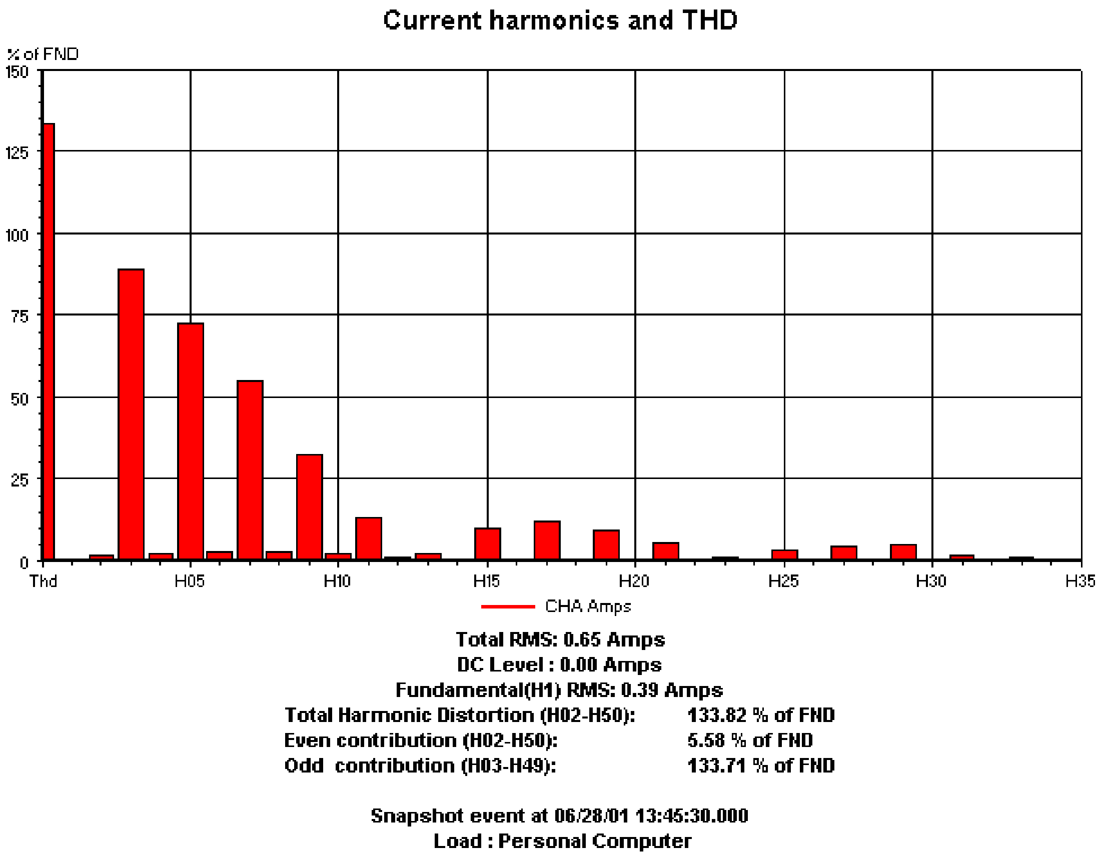

Fig.9 – Current harmonic content and total harmonic distortion for the PC.

Note that these results are valid for all loads including a single-phase diode rectifier as an input stage. In an office where many loads including electronics are present, harmonics may become a concern.

3.3 Fax, printer, copy machine

In this paragraph, the measurements concerning electronic/heating loads are shown. These loads have basically two modes of operation, as it will be explained by considering first the copy machine.

The machine draws normally a very low current, which shows the characteristic waveform of the single-phase diode rectifier (Fig.10). This is typical of the first mode of operation, which is the stand-by position.

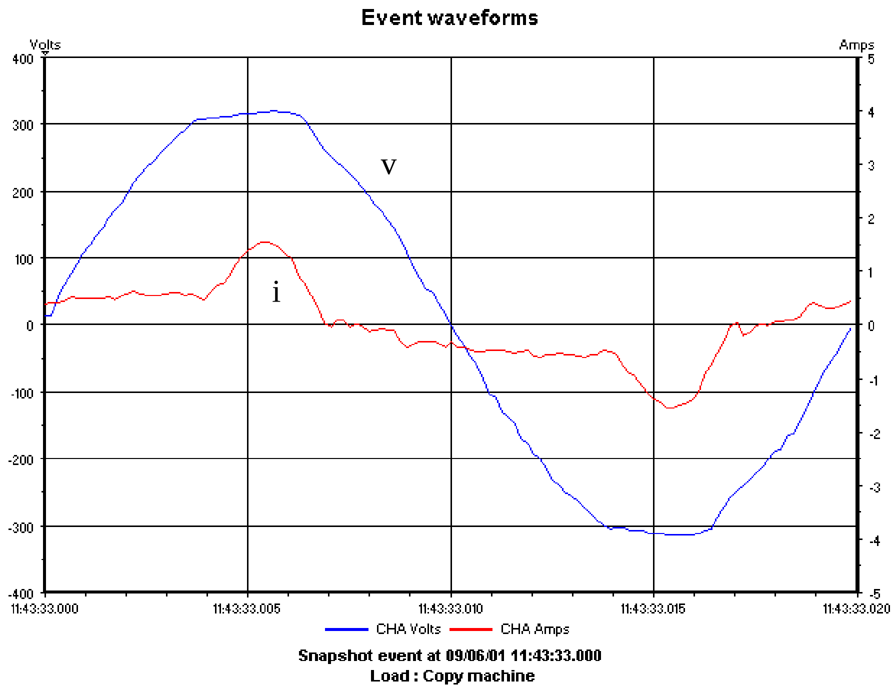

Fig.10 – Recorded voltage and current waveforms for the copy machine in stand by position.

In the second mode of operation, when printing, the machine warms up to melt the toner. The current drawn is sinusoidal and approximately in phase with the voltage, as shown in the plot of Fig.11; moreover, it is much higher, with a peak of approximately 25 A (note that the scale for the current is different as compared with Fig.10). The machine behaves in this phase like a resistance. The transition between the two phases, from stand by to printing, is captured in the plot of Fig.12.

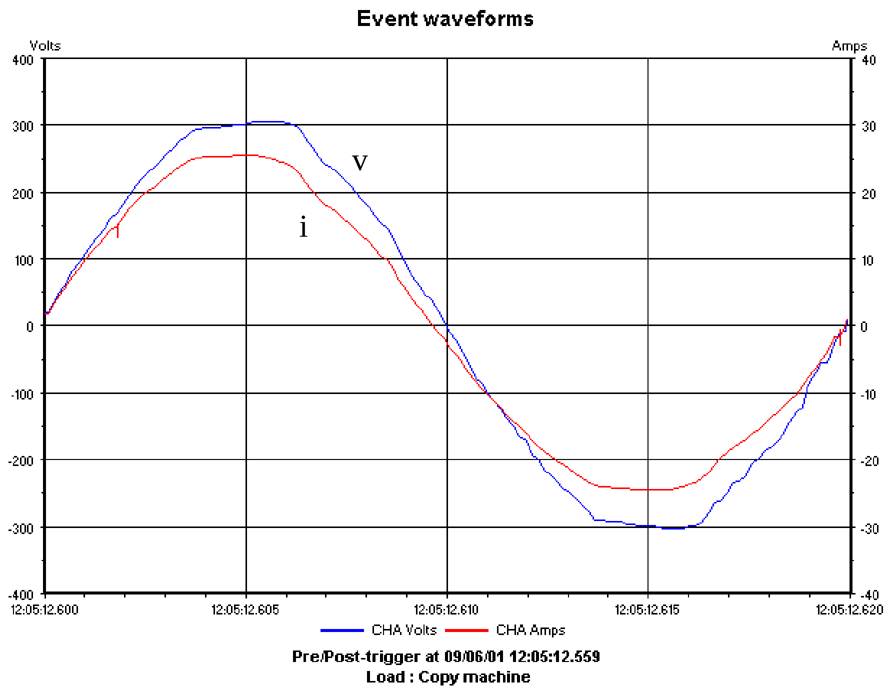

Fig.11 – Recorded voltage and current waveforms for the copy machine during warming up.

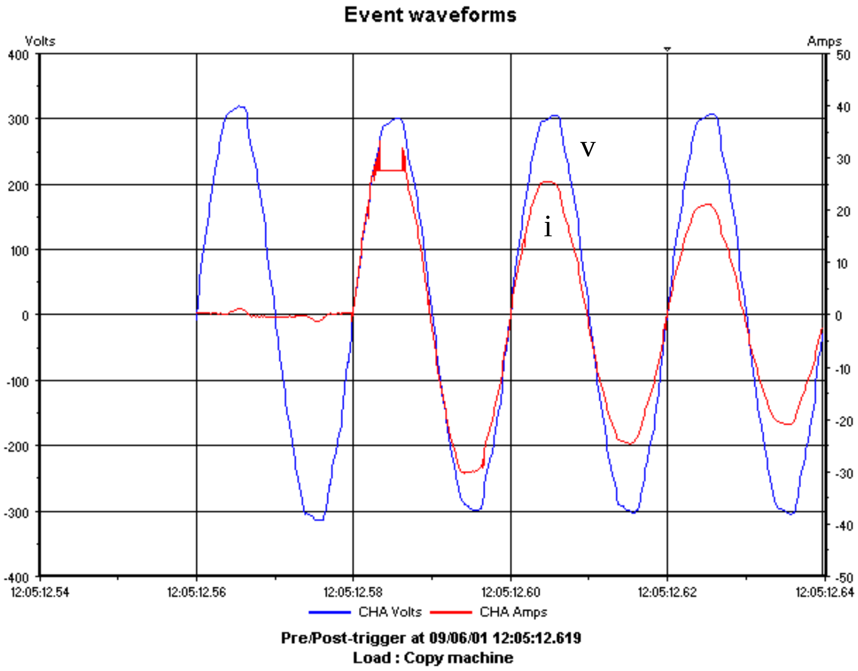

Fig.12 – Recorded voltage and current waveforms for the copy machine when changing operation from stand by to warming up.

The peaks in current due to warming up are evident when measuring the RMS value of the current during one hour (Fig.13). These peaks correspond to peaks in active power drawn by the machine, shown in Fig.14 over the same period. Note that the peaks do not have all the same value, indicating that the machine warms up regularly anyway, even when it is actually not printing. The highest peaks correspond most likely to phases in which the machine was actually copying.

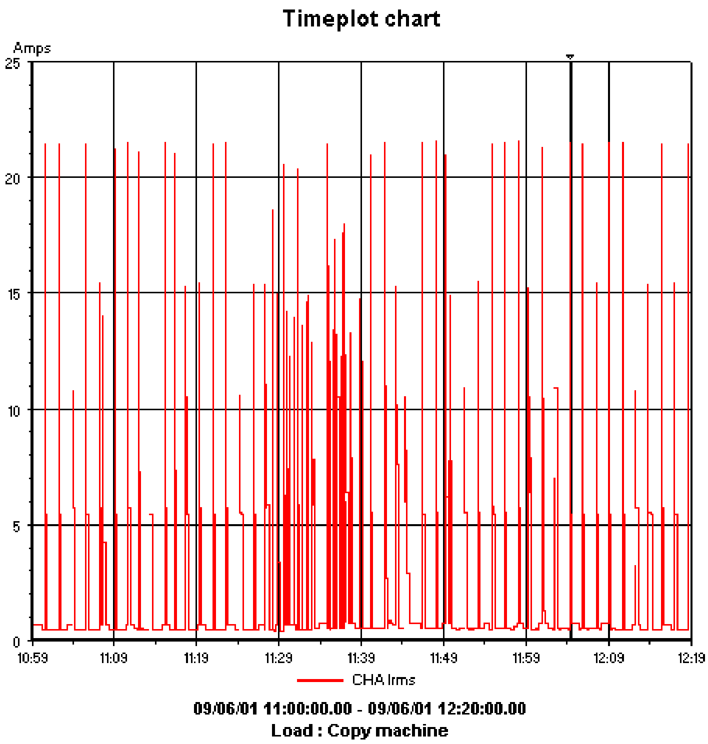

Fig.13 - Current RMS value for copy machine measured during one hour.

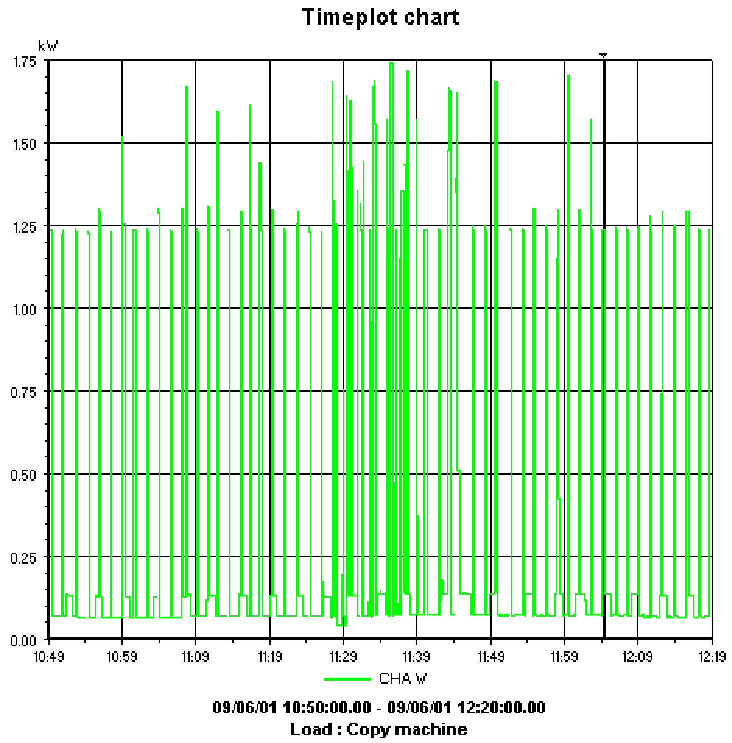

Fig.14 - Power for copy machine measured during one hour.

When a high current is drawn, a corresponding dip in voltage will occur, as can be noticed in Fig.15. These variations in voltage can get as high as 15 V, which may create problems to other sensitive loads connected to the same feeder. The three-dimensional plot reported in Fig.16 that allows comparing the measured power, voltage and current, clearly shows the same trends for current and power. This confirms that this load may be regarded as constant power load in further analysis.

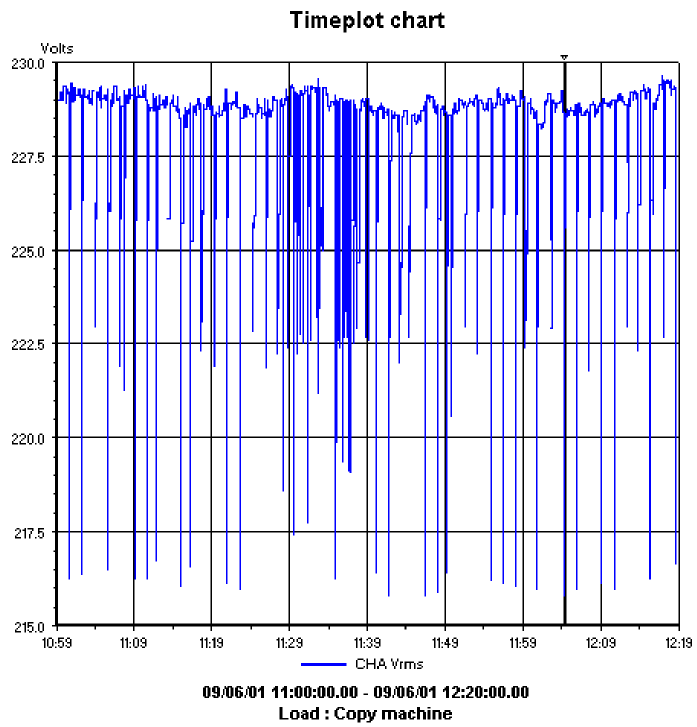

Fig.15 - Voltage RMS value for copy machine measured during one hour.

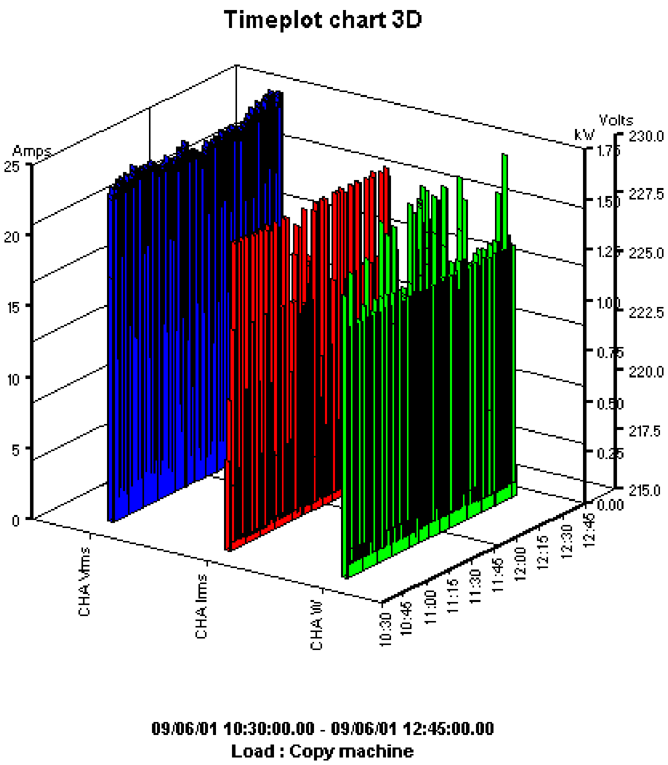

Fig.16 - Three-dimensional plot of RMS voltage, RMS current and power for copy machine measured in a two-hour period.

Similar comments may be given for the fax machine, for which the waveforms of voltage and current are shown in Fig.17 during stand by. The current drawn shows again the typical waveform of the single-phase rectifier, but it is much smaller as compared with the previous case.

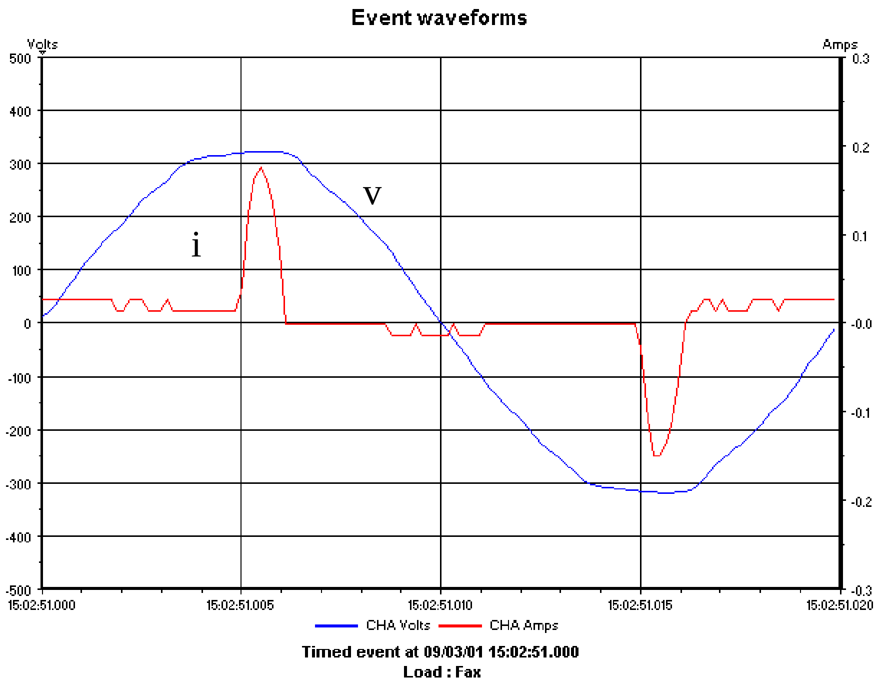

Fig.17 – Recorded voltage and current waveforms for fax machine in stand by position.

This can also be noticed from the plot of the measured RMS value of current in Fig.18 and power in Fig.19: the fax has a much lower power consumption with respect to the copy machine and it does not warm up regularly, but only when actually printing.

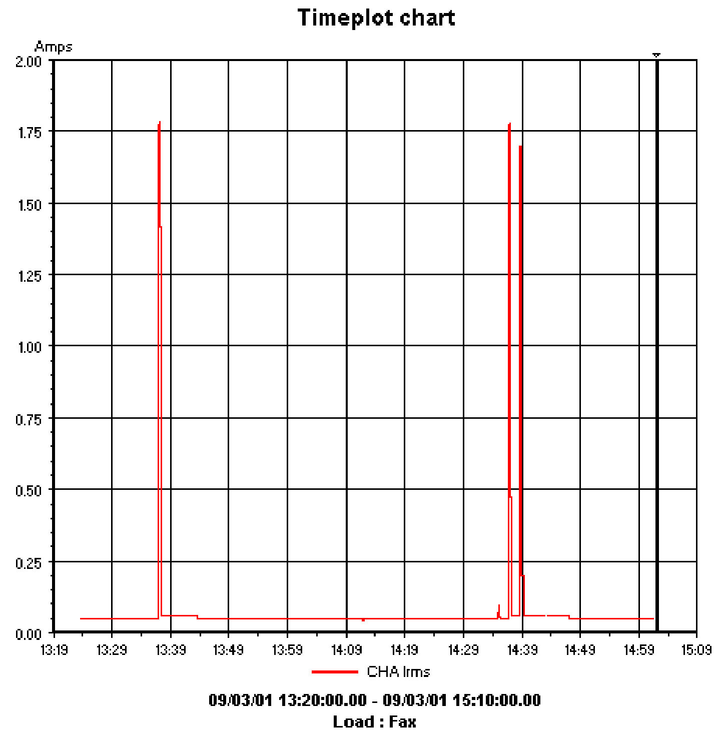

Fig.18 - Current RMS value for fax machine measured in a two-hour period.

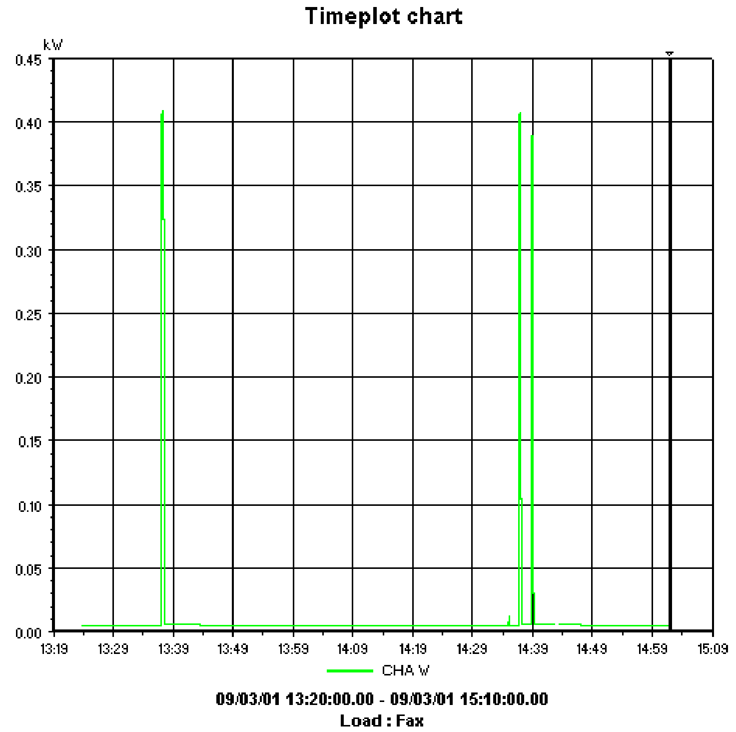

Fig.19 - Power value for fax machine measured in a two-hour period.

The average power consumption is thus expected to be much lower. The minimum power drawn during stand by is about 4.5 W.

The peaks in the current in this case do not appear to influence the variations in the measured RMS value of the voltage, shown in Fig.20.

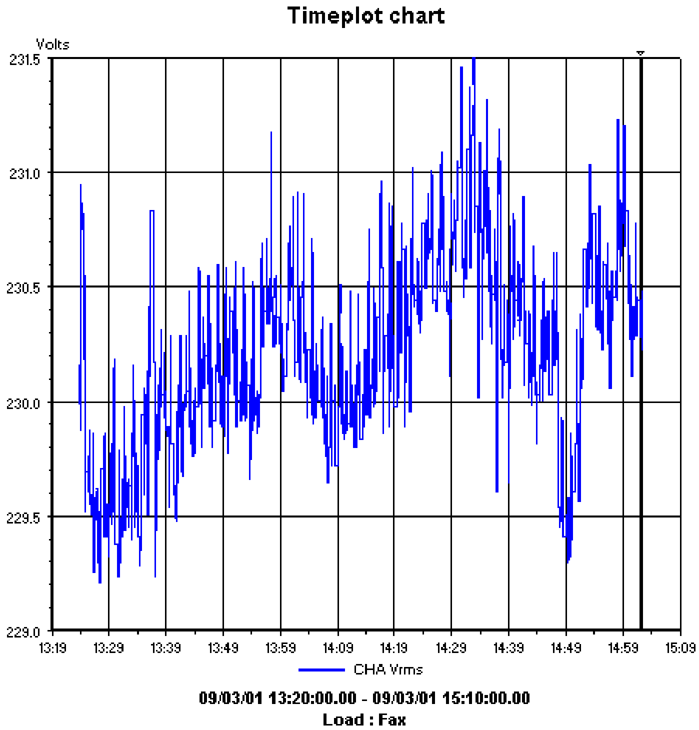

Fig.20 - Voltage RMS value for fax machine measured in a two-hour period.

The three-dimensional plot reported in Fig.21 again shows the same trend for current and power.

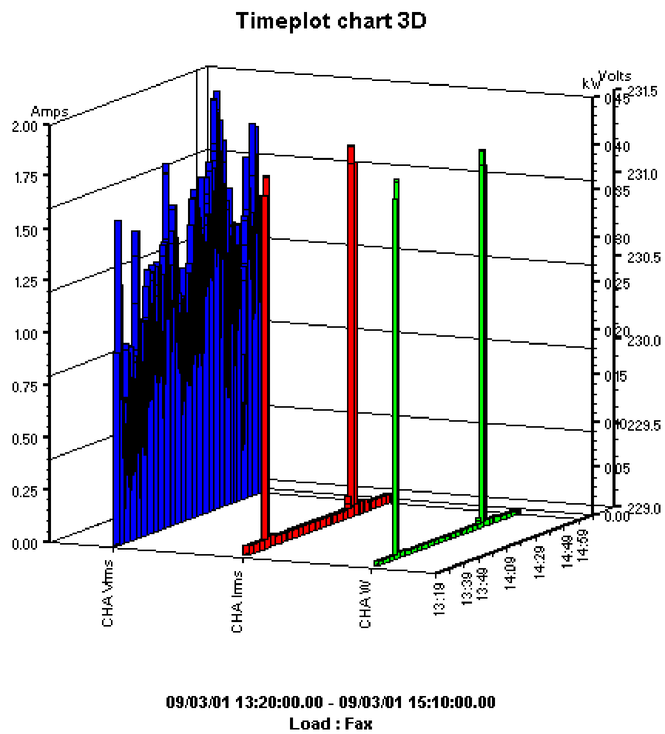

Fig.21 - Three-dimensional plot of RMS voltage, RMS current and power for fax machine measured during a two-hour period.

The third load for which a similar behavior has been noticed is the laser printer. Recorded waveforms of voltage and current for this load are reported in Fig.22.

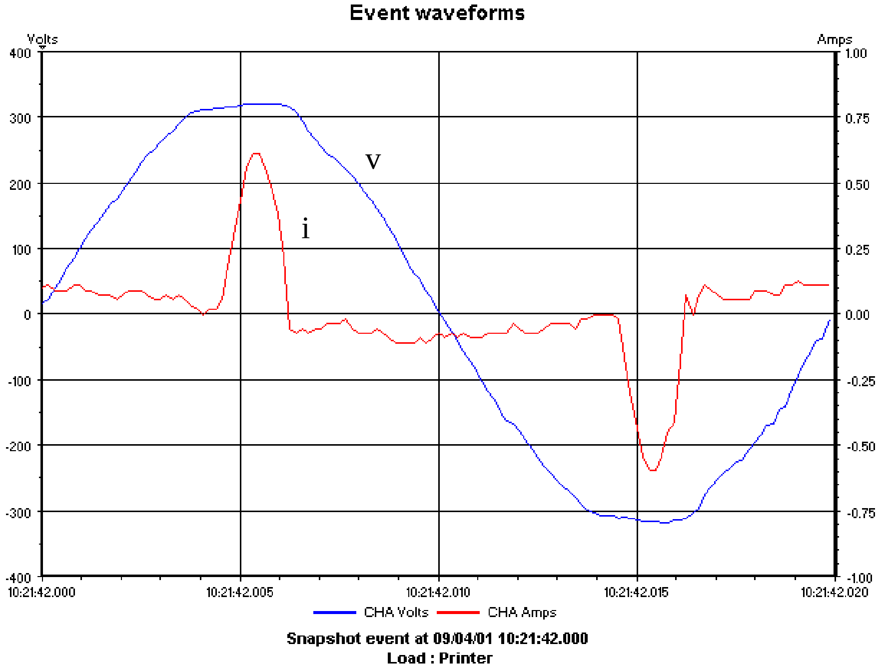

Fig.22 – Recorded voltage and current waveforms for printer in stand by position.

Also in this case there are stand-by periods in which the current and power drawn are very low (Fig.23 and Fig.24, respectively), and peaks of both current and power, corresponding to the phases in which the machine is printing. Note that the peak power drawn is more or less constant at about 600 W, while not all of the current peaks have the same value (most of them reach 2.5 A, but there are some which are as high as 11 A).

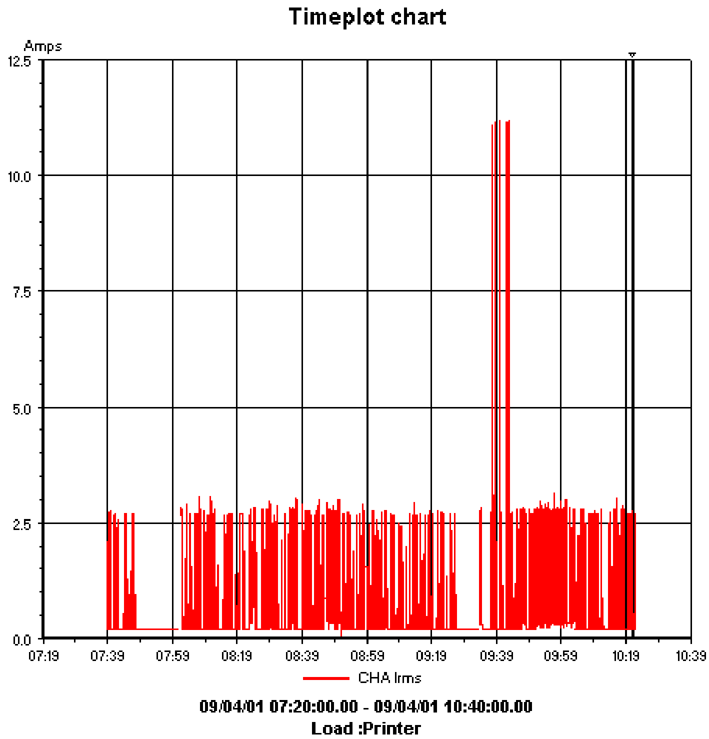

Fig.23 – Current RMS value for printer measured in a three-hour period.

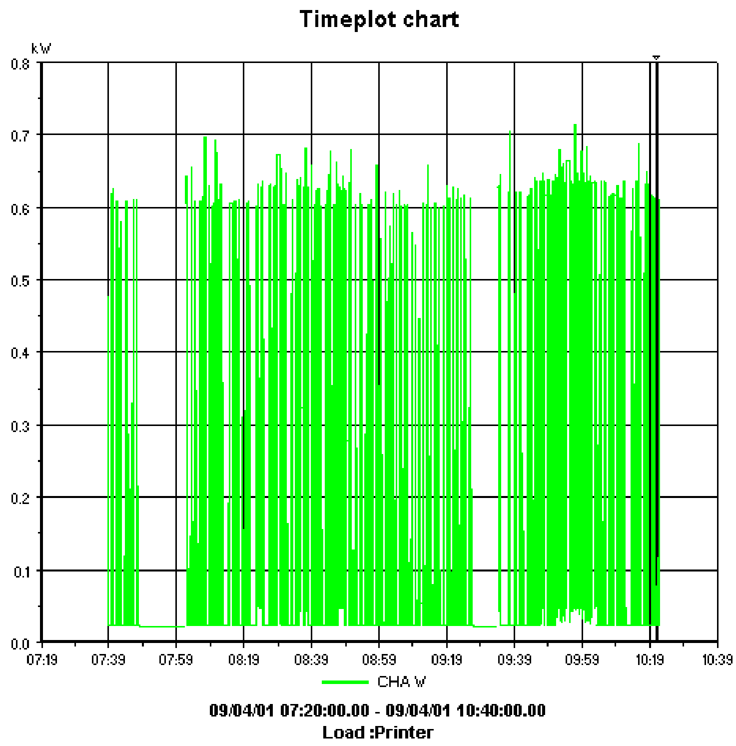

Fig.24 - Power value for printer measured in a three-hour period.

These higher peaks in the current are associated with dips in the voltage, shown in Fig.25.

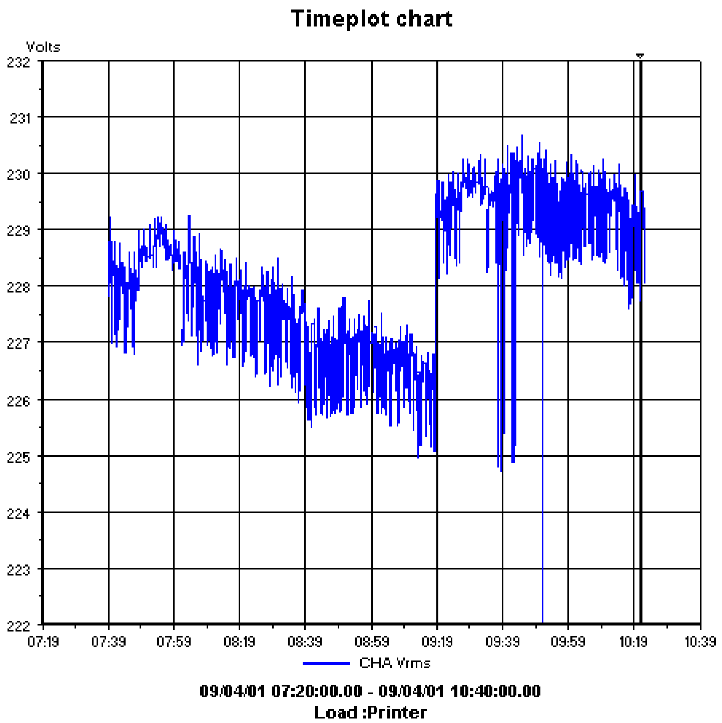

Fig.25 - Voltage RMS value for printer measured in a three-hour period.

The three-dimensional plot reported in Fig.26 shows that there is no evident connection between the variations in voltage and in current. The load behaves as constant-power, which in turn results in "almost constant" current. The negative value in the

RMS value of the voltage is a spurious value, to be considered as a mistake of the instrument. The vertical black line in many of the RMS value plots indicates the instant in which the corresponding waveforms have been recorded.

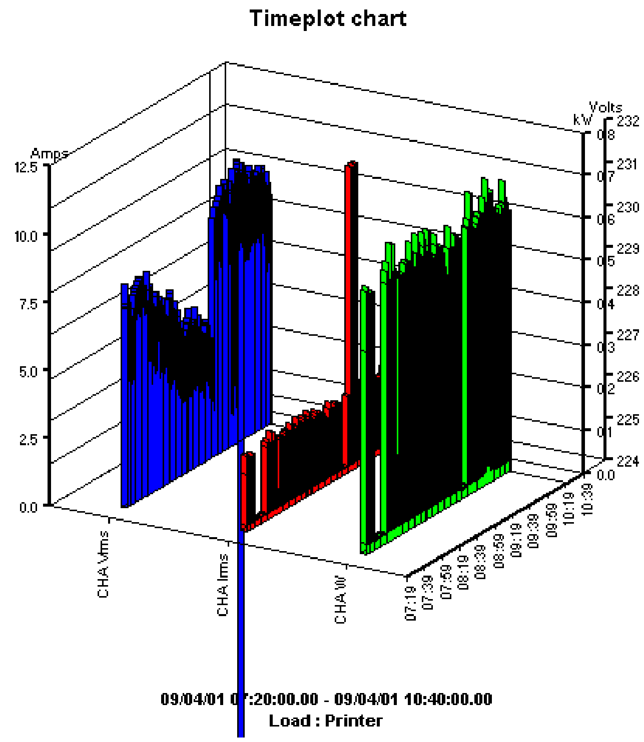

Fig.26 - Three-dimensional plot of RMS voltage, RMS current and power for printer measured in a three-hour period.

In Tab.2 maximum and minimum values of voltage, current and power, together with the excursion between them, are summarized for all three loads analyzed here.

TAB.2 - VOLTAGE, CURRENT AND POWER LIMIT VALUES FOR ELECTRONICS/HEATING LOADS

	Voltage [V]			Current [A]			Power [W]		
	V_{min}	V_{max}	ΔV	I_{min}	I_{max}	ΔI	P_{min}	P_{max}	ΔP
Fax	229.21	231.5	2.29	0.05	1.78	1.73	4.5	410	405.5
Printer	230	228	2	0.15	11.17	11.02	20	710	690
Copy Machine	215.82	229.64	13.82	0.38	21.59	21.21	60	1740	1680

3.4 Fluorescent lamps

Fluorescent lamps are generally used in offices, instead of incandescent ones, due to their higher efficiency. In the case study considered, three different types of fluorescent lights have been found and analyzed. They are:

- desk lamp;
- low consumption lamp;
- ceiling lamp.

The desk lamp is a typical linear appliance with a sinusoidal current lagging the voltage as the waveforms in Fig.27 show.

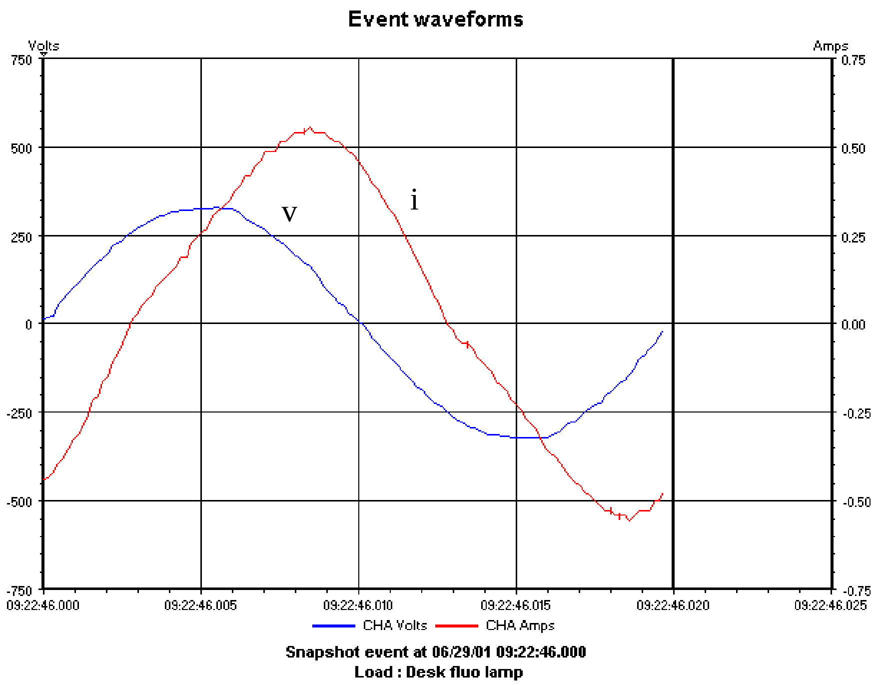

Fig.27 – Recorded voltage and current waveforms for the desk lamp.

The measured RMS value of the current, shown in Fig.28, follows exactly the same variations as the measured RMS value of the voltage, shown in Fig.29, thus implying a “constant-impedance” behavior for the load. Measured power consumption in Fig.30 also shows the same variations as for the voltage plot, since for a constant impedance the power varies with the square of the voltage.
Because of this characteristic, this lamp is potentially not a very good one: the power drawn varies with the voltage, thus giving a continuously variable lighting.

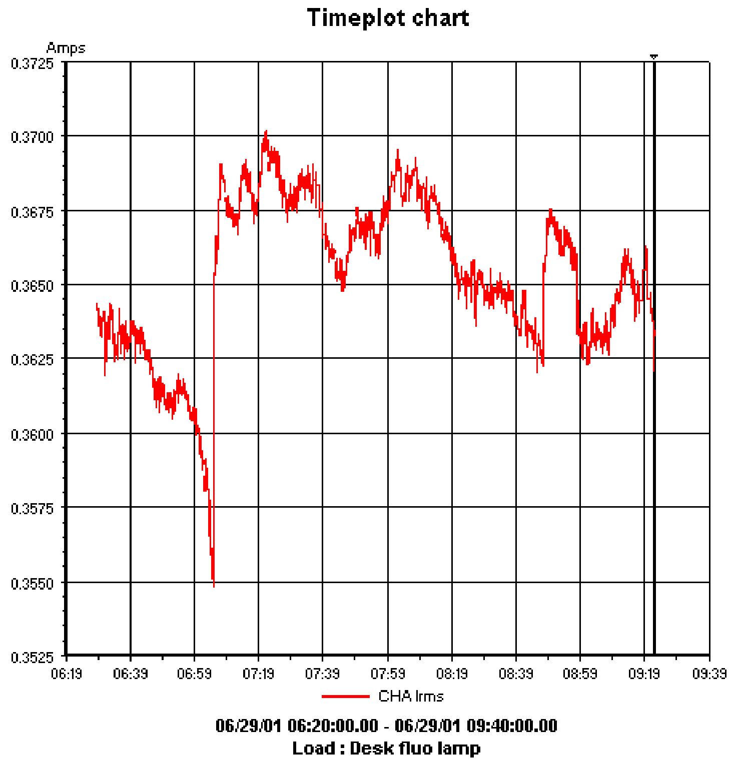

Fig.28 – RMS value of current for desk lamp measured in a three-hour period.

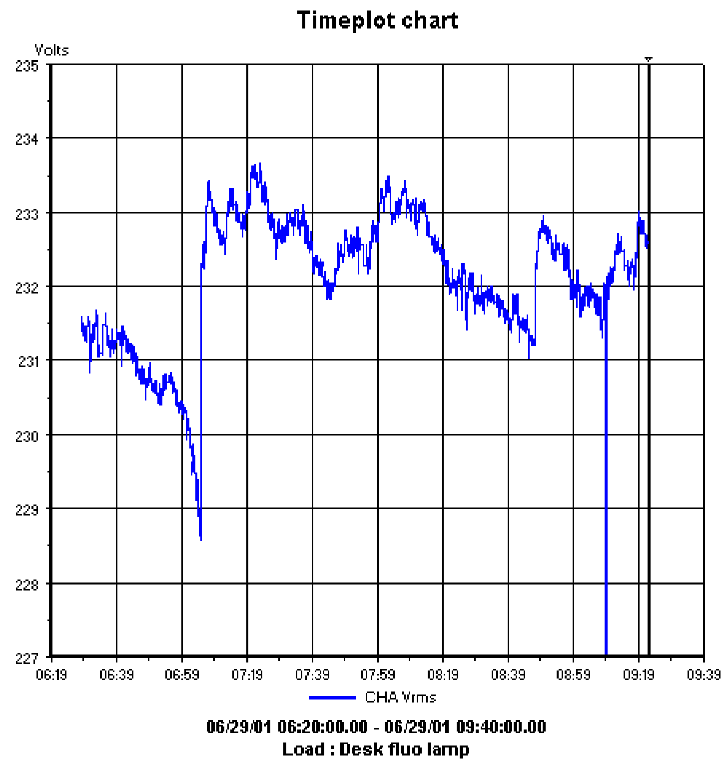

Fig.29 - RMS voltage value for desk lamp measured in a three-hour period.

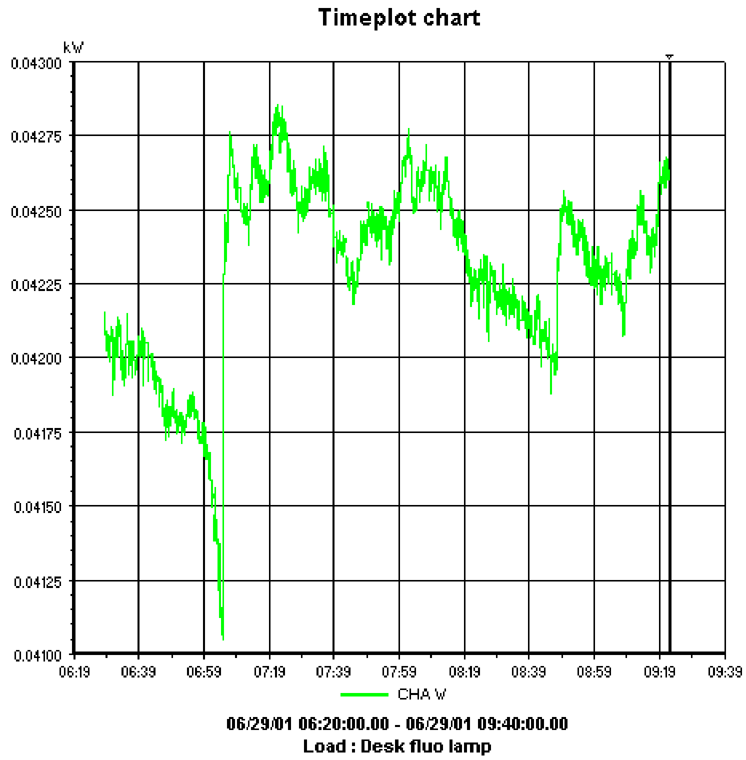

Fig.30 - Power consumption of the desk lamp measured during three hours.

Note the sudden increase in voltage at around 7:00 AM in Fig.29, which is most likely caused by the insertion of capacitors somewhere in the system prior to the transition from the light-load to the full-load period. This is done in order to prevent an excessive decrease in voltage later in the morning, when all loads in the system are switched on.
The three-dimensional plot of voltage, current and power reported in Fig.31 allows a better comparison of the three plots and shows an evident connection between the variations in all three quantities, as pointed out earlier.

Note that the negative peak voltage in Fig.29 and Fig.31 is a spurious value, to be considered as a mistake of the instrument. The vertical black line in many of the RMS value plots indicates the instant in which the corresponding waveforms have been recorded.

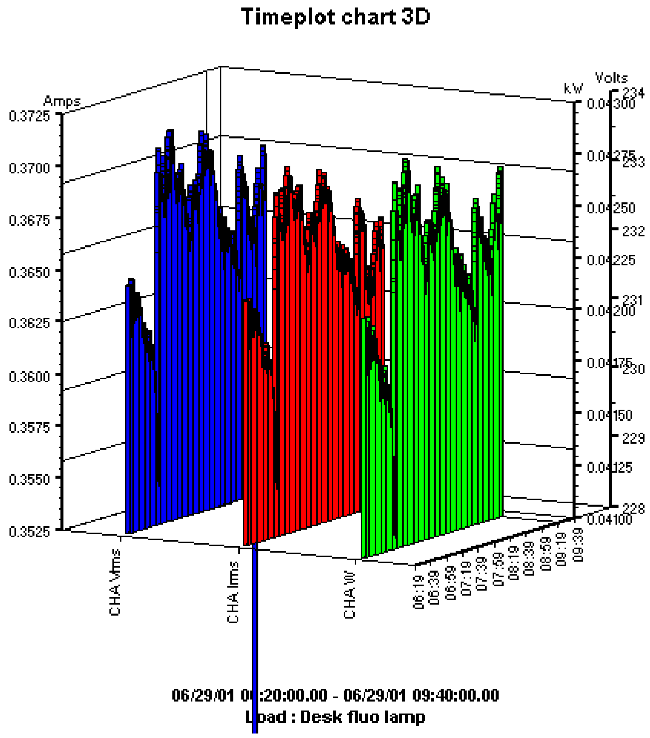

Fig.31 - Three-dimensional plot of RMS voltage,
RMS current and power for desk lamp measured in a three-hour period.

Measurements for the ceiling lamp have shown a very different behavior: the waveform of the current (reported in Fig.32 together with the voltage) is somewhat disturbed, but still looks pretty sinusoidal. This is clear sign of the presence of a high-frequency switched rectifier, which provides a good-quality current if compared with the usual diode rectifier (for example with the current waveform shown in Fig.22). Note that in Fig.32 the current appears to somewhat lead the voltage.

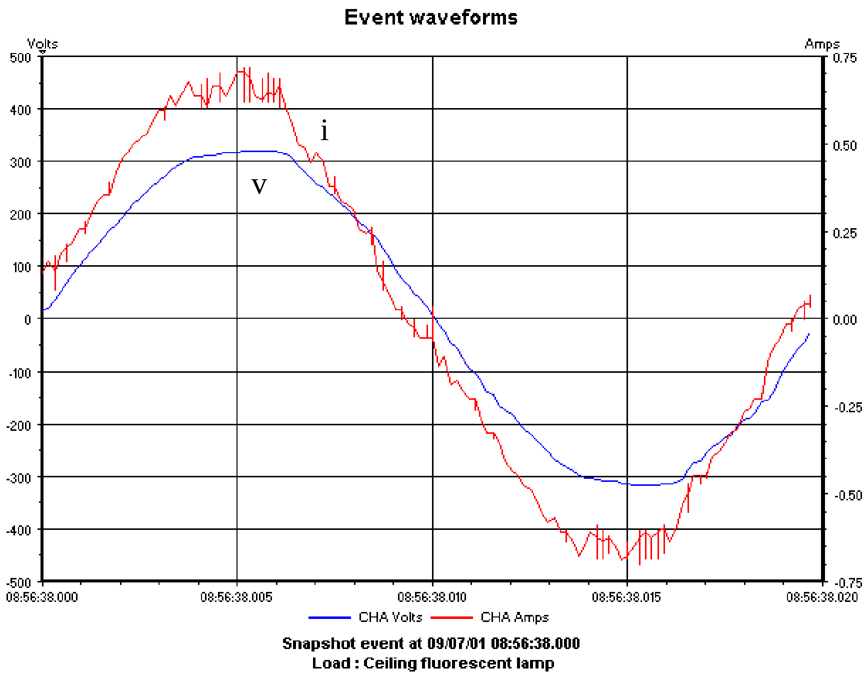

Fig.32 – Recorded voltage and current waveforms for ceiling lamp.

The measured RMS value of the current, shown in Fig.33, appears to vary as the inverse of the RMS value of the voltage, shown in Fig.34. This implies a “constant-power” behavior for the load, which is confirmed by the measured power consumption shown in Fig.35.

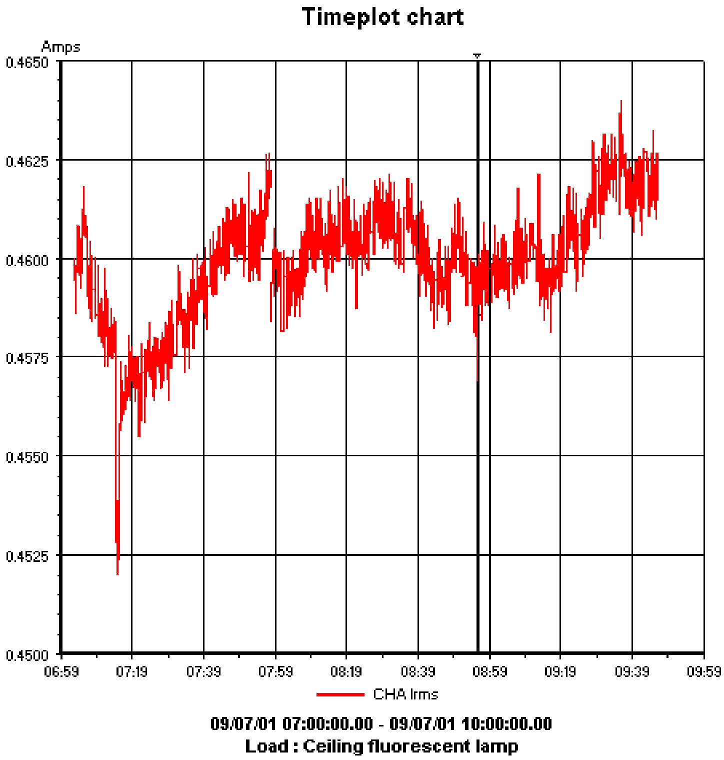

Fig.33 – RMS value of current for ceiling lamp measured in a three-hour period.

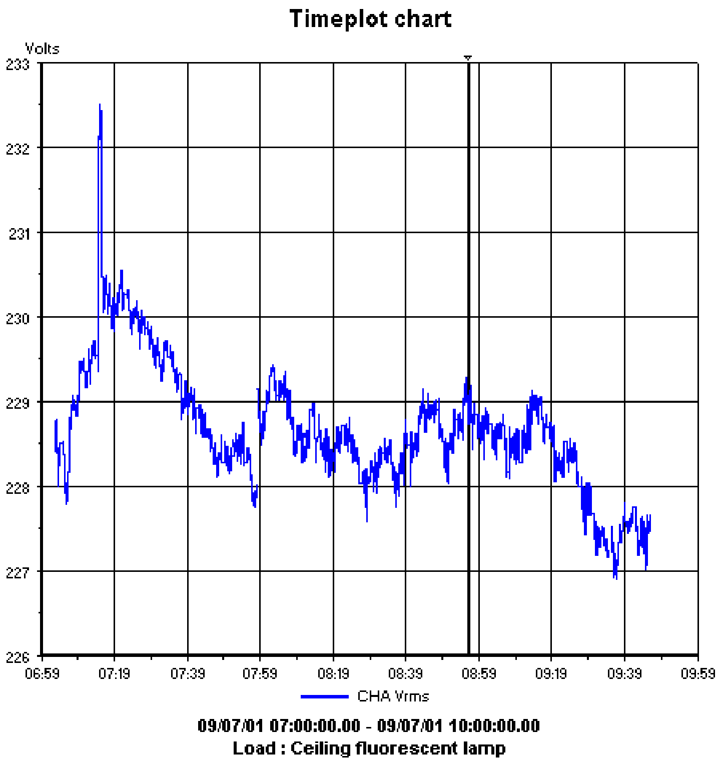

Fig.34 - RMS value of the voltage for ceiling lamp measured in a three-hour period.

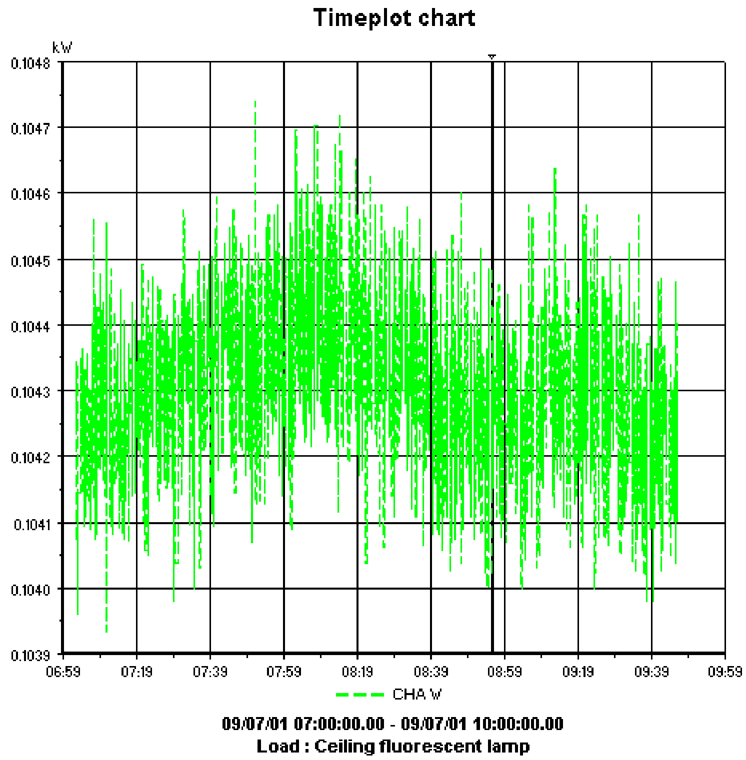

Fig.35 - Power consumption of the ceiling lamp measured during three hours.

This more sophisticated (and expensive) lamp is in fact electronically controlled to mitigate the excursions in voltage by regulating the power consumed, in order to obtain a constant lighting.
For clarity, the three plots are reported once more in the three-dimensional plot of Fig.36.

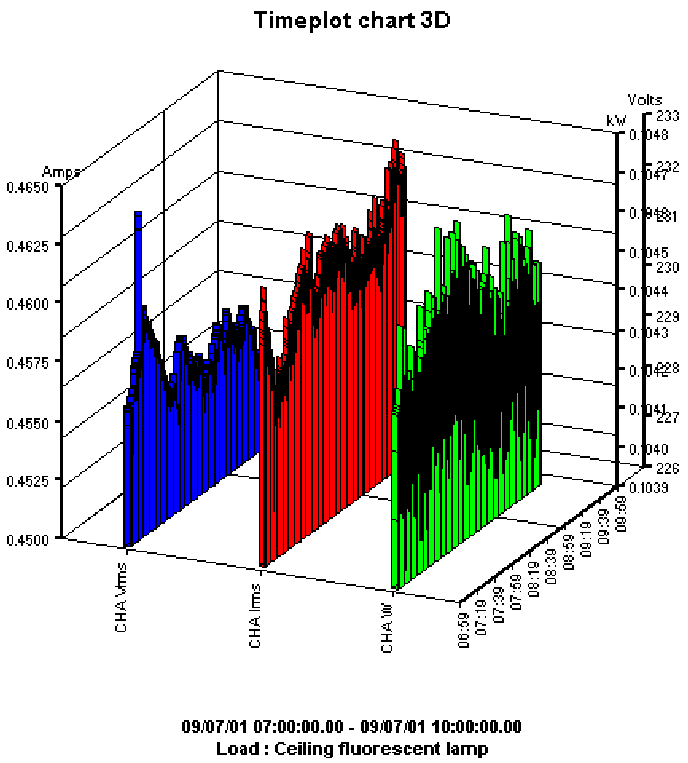

Fig.36 - Three-dimensional plot of RMS voltage, RMS current and power for ceiling lamp measured in a three-hour period.

The third lamp analyzed here is the low-consumption one, for which the waveform of voltage and current are reported in Fig.37. The current is highly disturbed, again most likely because of the presence of a power-electronics converter, and the behavior is somewhat capacitive, with the current slightly leading the voltage.

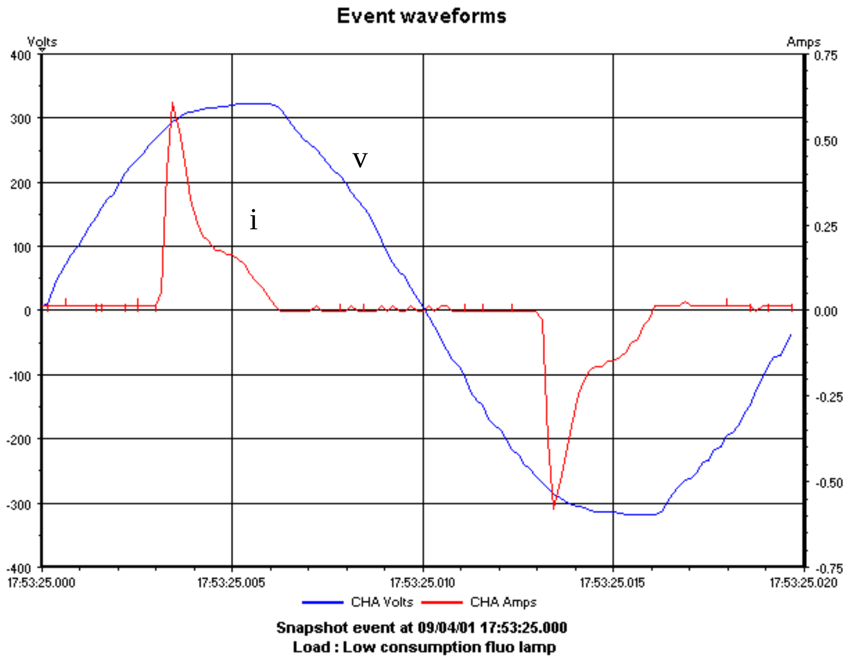

Fig.37 – Recorded voltage and current waveforms for low consumption lamp.

The measured RMS value of the current, shown in Fig.38, appears to be constant regardless of the variations of the voltage RMS value, shown in Fig.39. Unlike either of the previous cases, here the measured power consumption, shown in Fig.40, follows the voltage variations.

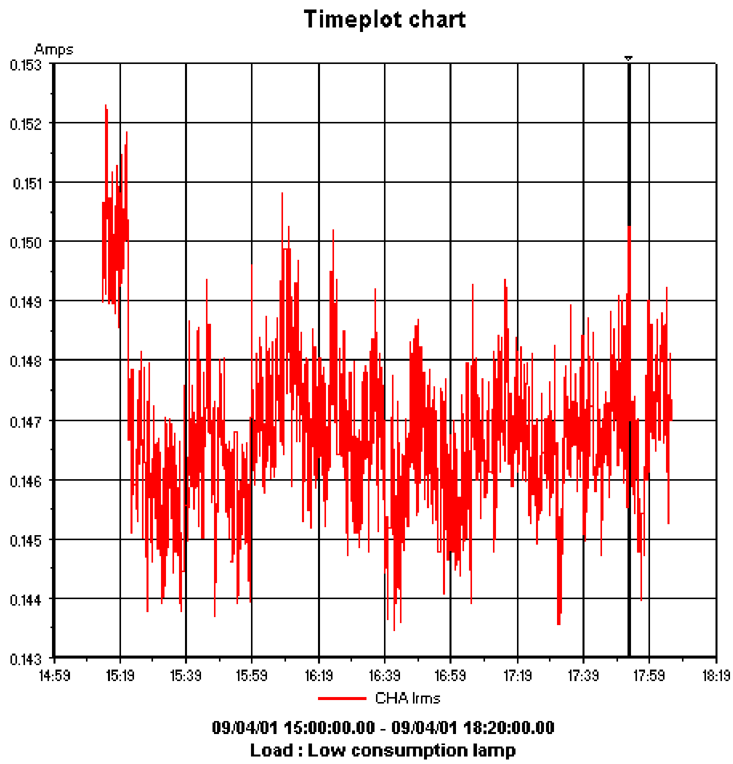

Fig.38 - RMS value of current for low consumption lamp measured in three hours.

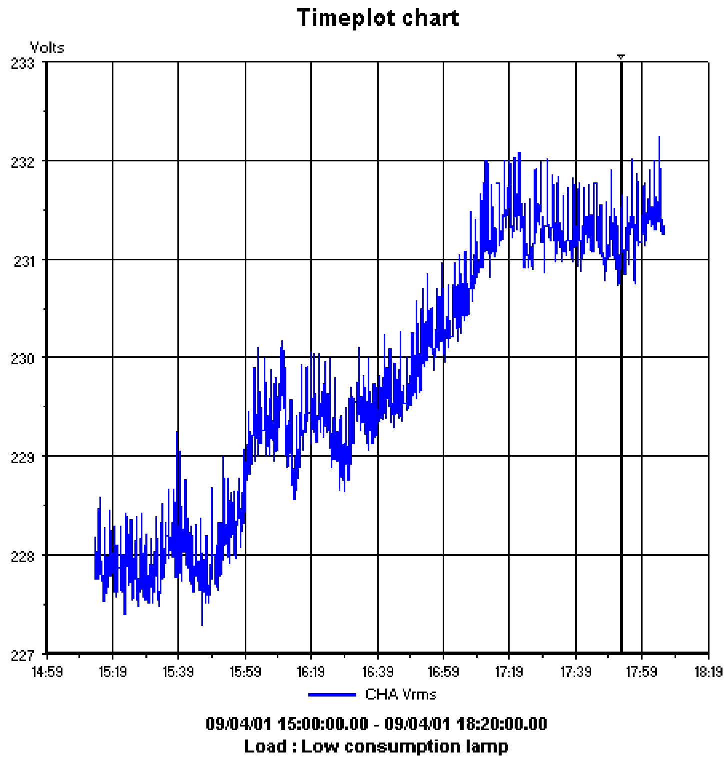

Fig.39 - RMS value of voltage for low-consumption lamp measured during three hours.

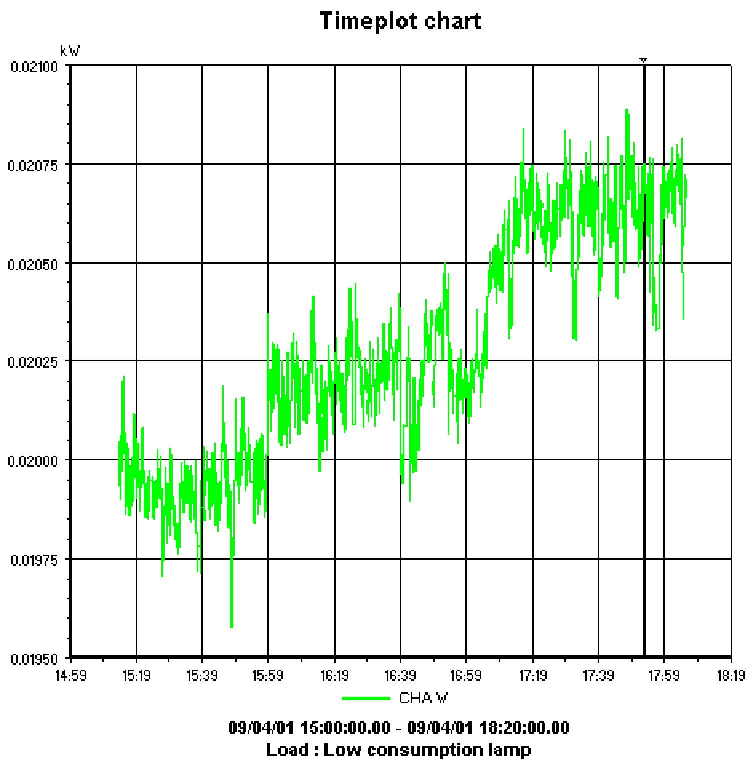

Fig.40 – Power drawn by the low-consumption lamp during three hours.

This is best seen in Fig.41, where the two measurements are plotted together and in the three-dimensional plot (including also the current) of Fig. 42. The behavior of the load can thus be characterized as "constant-current".

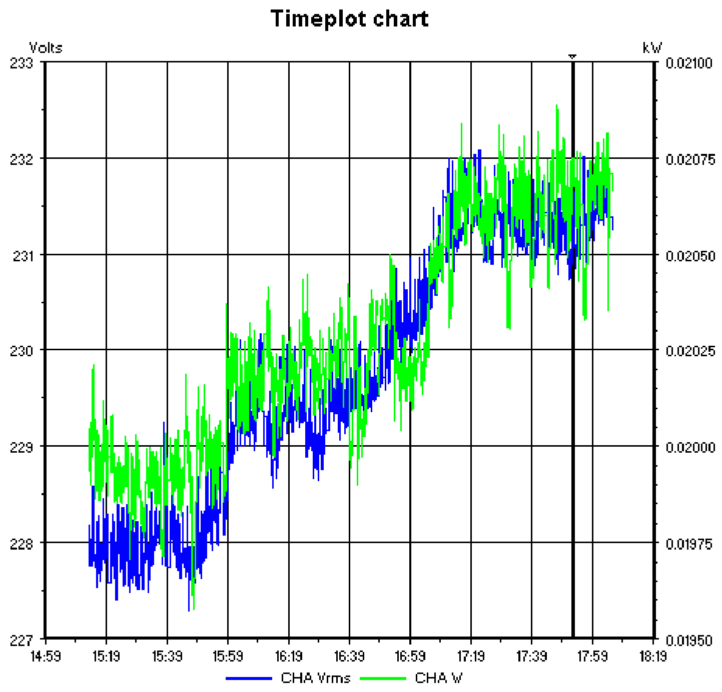

Fig.41 - RMS value of voltage and power for low-consumption lamp measured during three hours.

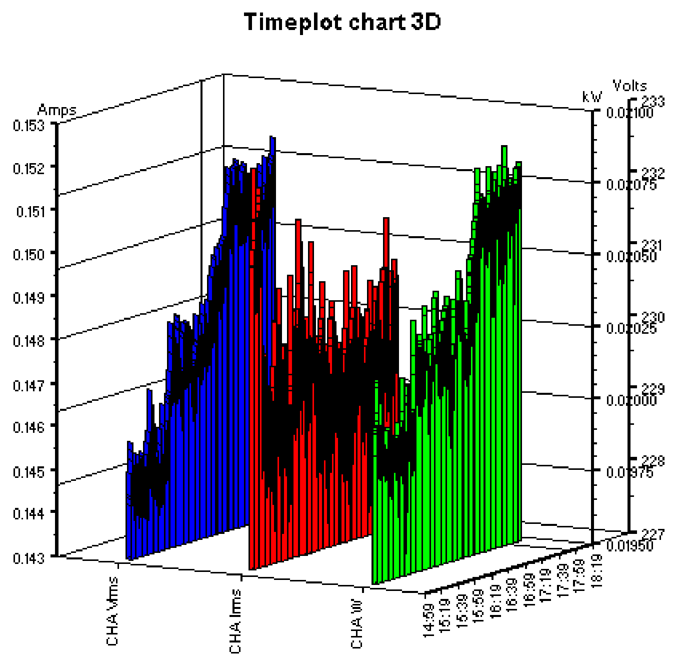

Fig. 42 - Three-dimensional plot of RMS voltage, RMS current and power for low-consumption lamp measured during three hours.

In Tab. 3 maximum and minimum values of voltage, current and power, together with the excursion between them, are summarized for all three loads analyzed here.

TAB. 3 - VOLTAGE, CURRENT AND POWER LIMIT VALUES FOR FLUORESCENT LAMPS

	Voltage [V]			Current [A]			Power [W]		
	V_{min}	V_{max}	ΔV	I_{min}	I_{max}	ΔI	P_{min}	P_{max}	ΔP
Desk lamp	228.6	233.6	5	0.35	0.37	0.02	41	42.8	1.8
Ceiling lamp	226.9	232.5	5.6	0.45	0.46	0.01	103.9	104.7	0.8
Low con-sump.	227.3	232.2	4.9	0.14	0.15	0.01	19.6	20.8	1.2

4 Voltage Drop Calculations for Dc System

4.1 Introduction

In this Chapter, a comparison is made between ac and dc distribution for low voltage as far as voltage drops and power losses are concerned. Comparison is made on the basis of a case study. The system analyzed is a part of the distribution system of the Department of Electric Power Engineering at Chalmers University of Technology (Gothenburg-Sweden). Voltage drops and power losses are calculated for this system with both ac and dc supply and results are compared. For the ac supply the existing voltage level of 400 V line-to-line is considered (voltage currently used in Sweden). The dc voltages chosen for the case study are, as explained in 2.3.3, 326 V, 230 V, 120 V and 48 V.

4.2 System description

4.2.1 General scheme

The one-line diagram of the system is shown in Fig.1. The system considered here includes 15 offices with a total of 26 people, with typical office loads, such as computers and lighting. A copy room is considered, with printer, fax, and copy machine. Moreover, a lunchroom is present, which includes refrigerators, cooker, dishwasher, coffee machine, microwave ovens, a water boiler and an exhaust fan.

Power consumption and power factor for the loads in the case study considered are indicated in Tab.1. The power consumption is known from the load nameplates. The power factor of the first five loads has been deducted from the results of the long-term measurements of voltages and currents reported in Chapter 3. Where measurements were not available, an estimation has been made based on the principle of operation.
A description of the different feeders, with type of load connected, load power, cable length and cross-section is given in Tab.2. For each person working in an office, a total power consumption of 210 W has been considered, which includes computer with monitor (180 W) and a small table lamp (30 W). This is indicated in Tab.2, in the column “load type”, as “office”. The total power supplied by the studied system is ca. 29 kW.
Note that the high-power three-phase loads, like the cooker and the coffee machine, have also been considered in the following calculations. Of course it is assumed that they be replaced by similar loads suitable for being supplied by dc.

TAB.1 – LOADS POWER CONSUMPTION AND POWER FACTOR

LOAD TYPE	**POWER [W]**	**POWER FACTOR [cos φ]**
PC (with monitor)	180	1
Fluorescent lights	15÷36 depending on the type	0.62 ÷ 0.98
Fax	450	0.985
Copy machine	1800	0.985
Printer	900	0.985
Dish washer	2000	0.8
Fridge	100	0.8
Freezer	150	0.8
Exhaust fan	150	0.8
Microwave oven	1300	1
Cooker	4500	1
Water boiler	2000	1
Coffee machine	4700	1

Finally, the impedance "Z" in Fig.1 represents a cable between the substation transformer and the switchgear under consideration. This cable has been considered in both ac and dc calculations. It will clearly emerge from the results that, in some of the dc cases considered, the voltage drop on this cable is too high. Therefore, in these cases, the rectifier will have to be placed at the switchgear and the connection between the transformer and the switchgear will still have to be done using ac (as suggested in 2.3.2, b).

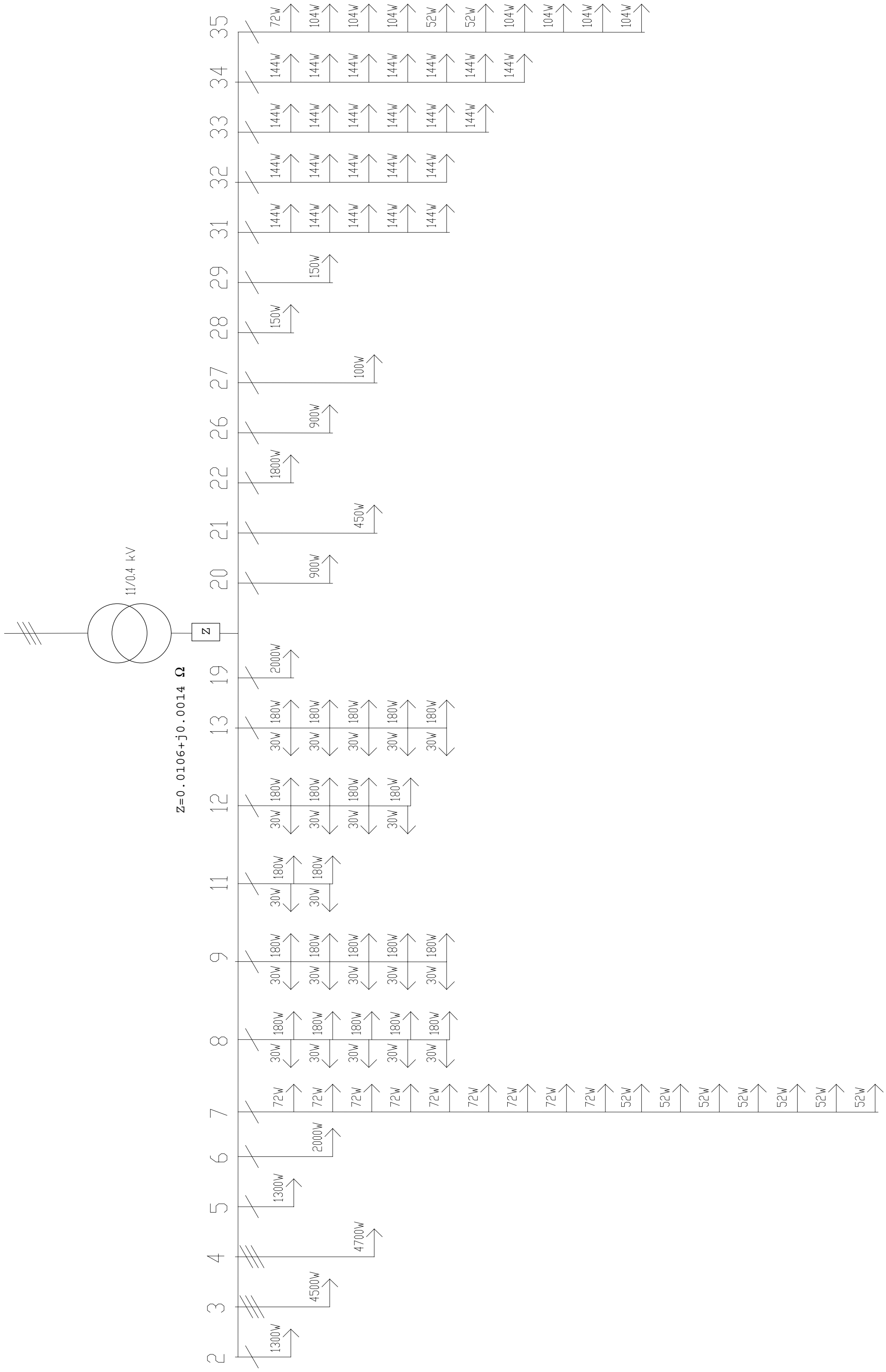

Fig.1 - One-line diagram of the system.

TAB.2 – LOAD AND FEEDER DATA FOR THE EXAMPLE SYSTEM

Feeder number	Load type	Load power [W]	Cable length [m]	Maximum current [A]	Wire cross-section [mm^2]
1	reserve			3x20	2.5
2	microwave oven	1300	15	20	2.5
3	kitchen (cooker)	4500	19	3x20	2.5
4	coffee machine	4700	22	3x20	2.5
5	microwave oven	1300	15	20	2.5
6	water boiler	2000	15	20	2.5
7	corridor lights	1012	80	14	1.5
8	office	1050	22	14	1.5
9	office	1050	40	14	1.5
10	reserve			14	1.5
11	office	420	20	14	1.5
12	office	840	12	14	1.5
13	office	1050	30	14	1.5
14	outlet		22	14	1.5
15	reserve			14	1.5
19	dish washer	2000	21	20	2.5
20	printer	900	14	14	1.5
21	fax machine	450	14	14	1.5
22	copy machine	1800	14	14	1.5
23	outlet			14	1.5
24	outlet			14	1.5
25	outlet			14	1.5
26	printer	900	20	14	1.5
27	fridge	100	20	14	1.5
28	freezer	150	20	14	1.5
29	exhaust fan	150	20	14	1.5
31	office lighting	720	40	14	1.5
32	office lighting	720	40	14	1.5
33	office lighting	864	15	14	1.5
34	office lighting	1008	30	14	1.5
35	kitchen lighting	904	30	14	1.5
38	reserve			14	1.5
39	reserve			14	1.5
40	reserve			14	1.5
41	reserve			14	1.5
41	reserve			14	1.5
42	reserve			14	1.5
43	reserve			14	1.5

4.2.2 Modeling the system for calculations

There are 43 feeders departing from the switchgear and several loads derived from each cable, at different distances along it.
It is common practice in voltage drop calculations for residential systems to substitute the loads along a feeder with a single load equal to the sum of them placed, at the end of the line. In this way, conservative results are obtained. Alternatively, if all loads consume approximately the same power, one can use the well-known formula for loads equally distributed along the feeder:

$$\Delta V = 2\frac{\rho}{S}\times I\ell\times\frac{n(n+1)}{2} \tag{4.1}$$

where ρ is the specific resistance [$\Omega\times$ mm^2/m], S the cable cross-section, I the current drawn by each load, ℓ the distance between two subsequent loads and n the number of loads.
Equation (4.1) results in:

$$\Delta V = 2\frac{\rho}{S}\times IL\times\frac{n}{2} \tag{4.2}$$

with $L = \ell$(n+1) the total length of the feeder.
Both approximations are acceptable for residential 230 V ac systems, because the current flowing is anyway not so high to give either relevant voltage drop or a large percent error between the approximated model and the exact one.

To give an example in the ac case, consider a 40 m long wire with 5 loads derived, each with a rated power of 210 W for a total power of 1050 W. The first load is at 20 m from the switchgear and the other ones are placed at 8, 2, 8, 2 m from each other. The total length of the feeder is thus 40 m. The following results are found:

230 V ac:
- 1.7 % percent voltage drop in the exact calculation
- 2.3 % percent voltage drop in the approximate model

The voltage drop is anyway much below the 5 % limit recommended by the standards. Note that the calculation has been done considering a power factor equal to one.

Completely different is the situation in dc case: for example, for the same feeder of the example above, but considering 120 V dc, the consequent results make impossible any approximation:

120 V dc :
- 6.4 % percent voltage drop with the exact calculation
- 8.3 % percent voltage drop in the approximate model

When considering a dc voltage of 48 V, in the same example it is obtained:

48 V dc:

- 40.2 % percent voltage drop with the exact calculation
- 52.6 % percent voltage drop in the approximate model

We can conclude that exact calculations can be quite important in this analysis. For this reason, a program has been written in Matlab, which calculates voltage drop (and power losses) along the 35 feeder actually in use in the example case, with the correct method. In Appendix A this Matlab program called “voltage_drop”, which calculates voltage drop, is reported together with its subroutine “previous”. They are used both for ac and dc, the difference being in the data matrices. In this study case two 100 x 7 matrices have been used, which are also reported in Appendix A.

4.3 Voltage drop calculations and power losses

4.3.1 Calculations for the ac system

To calculate voltage drops in the ac case, loads are divided into single-phase and three-phase type. Results are shown in 4.3.

- **single-phase loads:**

Known the power consumption, the rms value of the active current I_a drawn by the single-phase loads is calculated as:

$$I_a = \frac{P}{E} \tag{4.3}$$

where P is the active power of the load and E is the rms value of the phase voltage.
The reactive current I_r is calculated as:

$$I_r = I_a \times tg\varphi \tag{4.4}$$

where φ is the load characteristic angle.
The current flowing on the cable impedance produces a voltage drop that can be calculated as

$$\Delta V = 2(RI_a + XI_r) \tag{4.5}$$

where the factor 2 takes into account the voltage drop over the return conductor, R is the resistance of the cable and X its reactance. The resistance of the cable at 80 °C is calculated according to the equation:

$$R = \frac{\rho \times l}{S} \tag{4.6}$$

i.e. the skin effect has not been considered.
In Eq. (4.6)
$\rho = \rho_0 \times \{1 + \alpha \times (T - T_0)\}$ [Ω× mm²/m] is the specific resistance at a given temperature T (i.e. 80°C);
$\rho_0 = 0{,}0178$ Ω× mm²/m is the specific resistance at $T_0 = 20$ °C;
$\alpha = 0.00323$ °C;
S is the cross section and l the cable length.

The temperature has been chosen in the worst case of overload condition, as recommended by standards [6]. The total reactance is equal to:

$$X = x \cdot l \tag{4.7}$$

where a specific reactance x of 0.1 Ω/km has been used.
Power losses are calculated as:

$$\Delta P = 2RI^2 \tag{4.8}$$

where I is the total current flowing into the cable.

- **three-phase loads:**

The active and reactive current drawn by the three-phase load are respectively:

$$I_a = \frac{P}{V\sqrt{3}} \tag{4.9}$$

where V and P are the rated line-to-line rms voltage and power, and

$$I_r = I_a \times tg\varphi \tag{4.10}$$

The voltage drop at the load clamps is:

$$\Delta V = \sqrt{3}(RI_a + XI_r) \tag{4.11}$$

and the power losses are

$$\Delta P = 3RI^2 \tag{4.12}$$

where R and X are calculated as for the single-phase load.

- **substation-switchgear connection**

The parameters of the three-phase cable connecting the switchgear and the transformer are:

S=70 mm^2 cross-section area;
L=20 m length;
r=0.443 Ω/km specific resistance at 20 °C;
x=0.07 Ω/km specific reactance.

Voltage drop and power losses are calculated for this cable by using the same equations as in the three-phase case.

Active and reactive current on the cable are the sum of corresponding currents of all feeders. Current for the three-phase loads can be added up directly, while the single phase loads are assumed to be equally distributed in the three phases, so the current is equal to one third of the total current of the single-phase loads.

4.3.2 Calculations for the dc system

In a dc system there are no reactive currents and voltage drops, therefore the load current coincides with the active current and only resistive voltage drops are calculated.

The current is calculated as:

$$I_{dc} = \frac{P}{V_{dc}} \tag{4.13}$$

and the voltage drop is equal to:

$$\Delta V_{dc} = 2RI_{dc} \tag{4.14}$$

Finally, the power losses are given by:

$$\Delta P_{dc} = 2RI_{dc}^2 \tag{4.15}$$

where V_{dc} is the dc voltage value and R the resistance, again calculated using the same equations as above, at T = 80 °C (to consider the worst case of overload).

Voltage drops and power losses have been calculated and compared for the different voltage levels considered. Results are shown in 4.3.

4.3.3 Results

Results of voltage drop and power losses calculations for the ac case are reported in Tab.3; for the dc case results for 311 V, 220 V, 120 V, 48 V are shown in Tabs.4 to 7, respectively. They are expressed as percent values.

TAB.3 – VOLTAGE DROP CALCULATIONS FOR AC SUPPLY (400 V)

Feeder index	Load type*	Load Power [W]	Feeder Length [m]	Voltage drop % (feeder)	Power losses % (feeder)	Voltage drop % (total)	Power losses % (total)	Feeder current [A]
2	1	1300	15	0.627	0.627	0.828	0.827	5.652
3	3	4500	19	0.458	0.458	0.659	0.658	6.522
4	3	4700	22	0.554	0.554	0.755	0.754	6.812
5	1	1300	15	0.627	0.627	0.828	0.827	5.652
6	1	2000	15	0.964	0.964	1.165	1.164	8.696
7	1	1012	80	2.132	1.487	2.333	1.688	4.492
8	1	1050	22	0.923	0.827	1.125	1.027	4.638
9	1	1050	40	1.757	1.579	1.958	1.779	4.638
11	1	420	20	0.405	0.395	0.607	0.595	1.855
12	1	840	12	0.394	0.340	0.595	0.540	3.710
13	1	1050	30	1.419	1.351	1.620	1.551	4.638
19	1	2000	21	1.362	2.109	1.563	2.309	10.870
20	1	900	14	0.676	0.696	0.877	0.896	3.973
21	1	450	14	0.338	0.348	0.539	0.548	1.987
22	1	1800	14	1.351	1.392	1.553	1.592	7.947
26	1	900	20	0.965	0.994	1.166	1.194	3.973
27	1	100	20	0.108	0.167	0.309	0.368	0.543
28	1	150	20	0.162	0.251	0.363	0.451	0.815
29	1	150	20	0.162	0.251	0.363	0.451	0.815
31	1	720	40	1.155	1.052	1.356	1.252	3.206
32	1	720	40	1.155	1.052	1.356	1.252	3.206
33	1	864	15	0.404	0.307	0.605	0.507	3.848
34	1	1008	30	1.213	1.113	1.414	1.313	4.489
35	1	904	30	1.213	1.146	1.414	1.347	3.994
cable	3	29888	20	-----	-----	0.201	0.200	43.433

* 1 for single-phase load; 3 for three-phase load

Considering ac voltage, the percent value has been referred to the line-to-ground rated voltage for single-phase loads and to the line-to-line rated voltage for three-phase loads and for the common cable.
In dc case the rated dc voltage has been considered as reference value for all the loads. Power losses have been referred to the total load power each feeder, and to the system total power for the cable. Columns 5 and 6 show the results for each single feeder. Columns 7 and 8 show the total drops and losses from the substation, i.e. including the cable connection. Column 9 shows the feeder current. As shown in Tab.2, system feeders have a maximum current depending on the cross-section (S =1.5 mm^2→ I_{max}=14 A; S =2.5 mm^2 → I_{max}=20 A).
Highlighted cells mark feeders in which either the maximum current or the 5% limit for the voltage drop have been exceeded. Note that the maximum current can be exceeded although the calculated voltage drop may remain under 5%. Depending on the voltage level and the feeder length, the maximum current may be a more restrictive condition than the voltage drop limitation. It will be explained more in detail in Sec-

tion 4.4. This is the case for example of feeder 22 in Tab.6, or of the cable between transformer and switchgear (last row in Tab.6).
The cross section of the cable is S =70 mm^2 and the maximum sustainable current is I_{max}=145 A. Note that the power flowing along the cable is the system total active power, which is reported in the second column, last row.

TAB.4 - VOLTAGE DROP CALCULATIONS FOR DC SUPPLY - 326 V

Feeder index	Load Power [W]	Feeder Length [m]	Voltage drop % (feeder)	Power losses % (feeder)	Voltage drop % (total)	Power losses % (total)	Feeder current [A]
2	1300	15	0.312	0.312	0.907	0.907	3.988
3	4500	19	1.368	1.368	1.963	1.963	13.804
4	4700	22	1.654	1.654	2.249	2.249	14.417
5	1300	15	0.312	0.312	0.907	0.907	3.988
6	2000	15	0.480	0.480	1.075	1.075	6.135
7	1012	80	1.063	0.712	1.658	1.307	3.104
8	1050	22	0.459	0.399	1.054	0.994	3.221
9	1050	40	0.873	0.761	1.468	1.356	3.221
11	420	20	0.202	0.190	0.796	0.785	1.288
12	840	12	0.196	0.164	0.791	0.759	2.577
13	1050	30	0.705	0.652	1.300	1.247	3.221
19	2000	21	0.672	0.672	1.267	1.267	6.135
20	900	14	0.336	0.336	0.931	0.931	2.761
21	450	14	0.168	0.168	0.763	0.763	1.380
22	1800	14	0.672	0.672	1.267	1.267	5.521
26	900	20	0.480	0.480	1.075	1.075	2.761
27	100	20	0.053	0.053	0.648	0.648	0.307
28	150	20	0.080	0.080	0.675	0.675	0.460
29	150	20	0.080	0.080	0.675	0.675	0.460
31	720	40	0.576	0.499	1.171	1.094	2.209
32	720	40	0.576	0.499	1.171	1.094	2.209
33	864	15	0.202	0.146	0.796	0.740	2.650
34	1008	30	0.605	0.528	1.200	1.123	3.092
35	904	30	0.604	0.553	1.199	1.148	2.773
cable	29888	20	----	----	0.595	0.595	91.681

TAB.5 - VOLTAGE DROP CALCULATIONS FOR DC SUPPLY - 230 V

Feeder index	Load Power [W]	Feeder Length [m]	Voltage drop % (feeder)	Power losses % (feeder)	Voltage drop % (total)	Power losses % (total)	Feeder current [A]
2	1300	15	0.627	0.627	1.822	1.822	5.652
3	4500	19	2.748	2.748	3.943	3.943	19.565
4	4700	22	3.323	3.323	4.518	4.518	20.435
5	1300	15	0.627	0.627	1.822	1.822	5.652
6	2000	15	0.964	0.964	2.159	2.159	8.696
7	1012	80	2.135	1.431	3.330	2.626	4.400
8	1050	22	0.922	0.801	2.117	1.996	4.565
9	1050	40	1.755	1.530	2.950	2.725	4.565
11	420	20	0.405	0.382	1.600	1.578	1.826
12	840	12	0.394	0.329	1.589	1.524	3.652
13	1050	30	1.417	1.309	2.612	2.504	4.565
19	2000	21	1.350	1.350	2.545	2.545	8.696
20	900	14	0.675	0.675	1.870	1.870	3.913
21	450	14	0.337	0.337	1.533	1.533	1.957
22	1800	14	1.350	1.350	2.545	2.545	7.826
26	900	20	0.964	0.964	2.159	2.159	3.913
27	100	20	0.107	0.107	1.302	1.302	0.435
28	150	20	0.161	0.161	1.356	1.356	0.652
29	150	20	0.161	0.161	1.356	1.356	0.652
31	720	40	1.157	1.003	2.352	2.198	3.130
32	720	40	1.157	1.003	2.352	2.198	3.130
33	864	15	0.405	0.292	1.600	1.488	3.757
34	1008	30	1.215	1.060	2.410	2.256	4.383
35	904	30	1.214	1.111	2.409	2.306	3.930
cable	29888	20	----	----	1.195	1.195	129.947

TAB.6 - VOLTAGE DROP CALCULATIONS FOR DC SUPPLY - 120 V

Feeder index	Load Power [W]	Feeder Length [m]	Voltage drop % (feeder)	Power losses % (feeder)	Voltage drop % (total)	Power losses % (total)	Feeder current [A]
2	1300	15	2.302	2.302	6.693	6.693	10.833
3	4500	19	10.094	10.094	14.484	14.484	37.500
4	4700	22	12.207	12.207	16.597	16.597	39.167
5	1300	15	2.302	2.302	6.693	6.693	10.833
6	2000	15	3.542	3.542	7.932	7.932	16.667
7	1012	80	7.843	5.256	12.233	9.647	8.433
8	1050	22	3.388	2.942	7.779	7.333	8.750
9	1050	40	6.446	5.619	10.836	10.010	8.750
11	420	20	1.487	1.405	5.878	5.795	3.500
12	840	12	1.446	1.209	5.837	5.599	7.000
13	1050	30	5.206	4.810	9.597	9.200	8.750
19	2000	21	4.958	4.958	9.349	9.349	16.667
20	900	14	2.479	2.479	6.870	6.870	7.500
21	450	14	1.240	1.240	5.630	5.630	3.750
22	1800	14	4.958	4.958	9.349	9.349	15.000
26	900	20	3.542	3.542	7.932	7.932	7.500
27	100	20	0.394	0.394	4.784	4.784	0.833
28	150	20	0.590	0.590	4.981	4.981	1.250
29	150	20	0.590	0.590	4.981	4.981	1.250
31	720	40	4.250	3.683	8.641	8.074	6.000
32	720	40	4.250	3.683	8.641	8.074	6.000
33	864	15	1.487	1.074	5.878	5.465	7.200
34	1008	30	4.462	3.896	8.853	8.286	8.400
35	904	30	4.460	4.080	8.851	8.471	7.533
cable	29888	20	----	----	4.391	4.391	249.066

TAB.7 - VOLTAGE DROP CALCULATIONS FOR DC SUPPLY - 48 V

Feeder index	Load Power [W]	Feeder Length [m]	Voltage drop % (feeder)	Power losses % (feeder)	Voltage drop % (total)	Power losses % (total)	Feeder current [A]
2	1300	15	14.388	14.388	41.829	41.829	27.083
3	4500	19	63.085	63.085	90.526	90.526	93.750
4	4700	22	76.292	76.292	103.734	103.734	97.917
5	1300	15	14.388	14.388	41.829	41.829	27.083
6	2000	15	22.135	22.135	49.577	49.577	41.667
7	1012	80	49.017	32.853	76.458	60.294	21.083
8	1050	22	21.176	18.387	48.617	45.828	21.875
9	1050	40	40.286	35.121	67.727	62.563	21.875
11	420	20	9.297	8.780	36.738	36.222	8.750
12	840	12	9.038	7.554	36.480	34.995	17.500
13	1050	30	32.539	30.059	59.980	57.501	21.875
19	2000	21	30.989	30.989	58.431	58.431	41.667
20	900	14	15.495	15.495	42.936	42.936	18.750
21	450	14	7.747	7.747	35.189	35.189	9.375
22	1800	14	30.989	30.989	58.431	58.431	37.500
26	900	20	22.135	22.135	49.577	49.577	18.750
27	100	20	2.459	2.459	29.901	29.901	2.083
28	150	20	3.689	3.689	31.131	31.131	3.125
29	150	20	3.689	3.689	31.131	31.131	3.125
31	720	40	26.562	23.020	54.004	50.462	15.000
32	720	40	26.562	23.020	54.004	50.462	15.000
33	864	15	9.297	6.714	36.738	34.156	18.000
34	1008	30	27.890	24.349	55.332	51.790	21.000
35	904	30	27.875	25.502	55.317	52.943	18.833
cable	29888	20	----	----	27.442	27.442	622.666

4.4 Conclusions

From the results of the calculations it is possible to conclude that supplying with 48 V dc is not feasible (at least in this case study) because both voltage drops and power losses are too high and also the current exceeds the maximum value of the considered cross sections. Considering that 1.5 and 2.5 mm^2 cross sections are the commonly used ones, this excludes the applicability of this voltage level to existing systems.
For the other voltage values (120, 230, 326 V dc), the results show that is possible to substitute ac with dc and still use the same cables. The maximum current is not exceeded and good results are also observed for the voltage drops, with the exception of feeders nr. 3, 4, 7, 9, 13 in 120 V dc case exceeding the 5% voltage drop limit.
Significant advantages are shown in 326 V dc case with respect to the 230 V ac.
Power losses for 230 V dc (shown in Tab.5) are generally slightly lower than corresponding values for 230 V ac (shown in Tab.3). The difference is due to the reactive current and gets higher as the power increases and the power factor decreases. For ex-

ample, a big difference can be noticed for the dishwasher (feeder nr. 19) whose power losses are equal to 1.35 % for 230 V dc, while to 2.1 % for the existing system (230 V ac). An exception must be made for the three-phase loads supplied by feeders 3 and 4, which draw a much lower (three-phase) current in the ac system and therefore power losses are much lower.

About where to put the converter, if in the substation, thus supplying the existing connecting cable by dc, or near the switchgear continuing to use ac, it is useful to remark that with 120 V the dc cable gives too high voltage drops, thus compromising the feasibility of the whole project. By using three-phase ac supply for this cable connection, it could be possible to use 120 V dc in the existing system. For higher voltages the location of the converter results indifferent.

However, to generalize the calculations to other existing systems, the diagrams in Fig.2 to Fig.5 were prepared, which show the maximum power allowed vs. feeder length for all the dc levels analyzed. They clearly show which is the most restrictive condition between cable maximum current and voltage drop limit of 5%. Cross-sections considered are 1.5 and 2.5 mm^2. The maximum current curves are two horizontal straight lines descending from the formula

$$P_{\max} = I_{\max} \cdot V \tag{4.16}$$

where I_{max} is the maximum current allowed by the cable for the insulation not to be damaged (14 A for 1.5 mm^2, 20 A for 2.5 mm^2) and V the rated voltage (constant in each plot).
The voltage drop curves instead derive from the following equation

$$P_{\max} = \frac{0.05 \cdot S \cdot V^2}{2\rho \cdot L} \tag{4.17}$$

where as usual ρ is the specific reactance at 80 °C, S the cable cross-section and L the length. As it can be seen, P and L are in inverse proportion.

These plots could give an immediate idea of the possibility of supplying an existing system by dc voltage, by comparing the existing lengths (room disposition is already fixed in an old building) and the power of the loads.
If the combination of these two elements results in a point remaining under the limit curves, it would be possible to use the desired voltage without any changes. Otherwise, it will be necessary to use a higher voltage level or maybe to redistribute the loads on different feeders. In the worst case, the system will have to be renovated by changing the cables with bigger ones.
According to Eqs. 4.16 and 4.17, the general trend for these plots is that the maximum power that can be supplied under a certain dc voltage is constant and dictated by the maximum current allowed by the cable insulation until a certain value of the length. After this maximum length is exceeded, the voltage drop limit becomes the most restrictive condition and the maximum power that can be supplied goes down.

Note, for example, in Fig.2, that with a voltage of 326 V dc, even a load as high as 6.5 kW may be supplied with a 2.5-mm^2 cable without exceeding the maximum allowed current, provided that the length of the cable is lower than about 47 m.
With a 1.5-mm^2 cable, instead, the maximum power that can be supplied is something more than 4.5 kW for a feeder length lower than about 40 m.
Even the big three-phase loads present in the case study like the cooker (4500 W) and the coffee machine (4700 W) can be supplied in dc by choosing this voltage level, as demonstrate by the results in Tab.4. The limit on the length is not very strict either: in many residential systems (e.g. small apartments) a length of 40 m is exceeded only in exceptional cases.
For higher feeder lengths, the voltage drop limit becomes the most restrictive condition and the maximum power that can be supplied becomes lower. However, in the worst case of feeder length equal to 80 m, a load of about 4 kW can still be supplied by using 326 V dc with a cross-section of 2.5 mm^2 (about 2.3 kW with a cross-section of 1.5 mm^2).

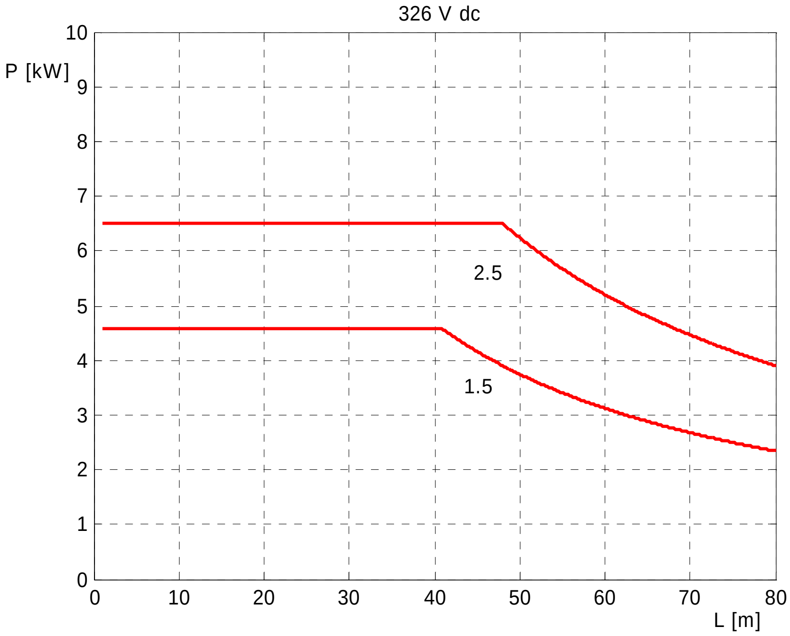

Fig.2 - Maximum power vs. length for cables with cross section S=1.5 and S=2.5 mm^2 (rated voltage is 326 V dc).

In Fig.3, the same plot is shown for a dc voltage of 230 V: the maximum power is now about 4.6 kW (still rather high) for a maximum length of the 2.5-mm^2 cable of about 34 m (respectively 3.2 kW for a 1.5-mm^2 cable shorter than 28 m). Minimum power, corresponding to a length of the cable of 80 m, is equal to 2 kW for a cross-section of 2.5 mm^2 (1.2 kW for a cross-section of 1.5 mm^2).

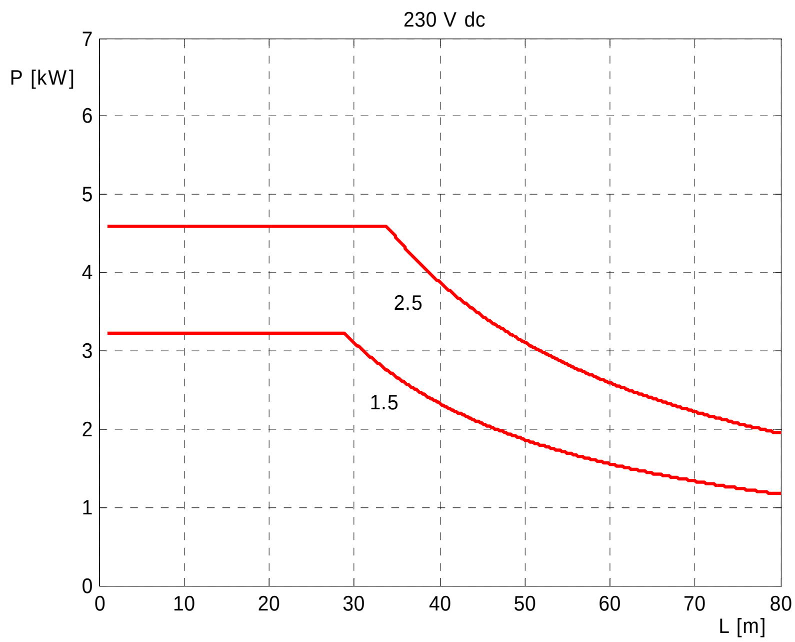

Fig.3 - Maximum power vs. length for cables with cross section S=1.5 and S=2.5 mm^2 (rated voltage is 230 V dc).

When considering a voltage level of 120 V dc, the length under which maximum power may be supplied gets rather low, as shown in Fig.4: 2.4 kW may be supplied for a cable with a cross-section of 2.5 mm^2 only with cables shorter than about 17 m, then the power goes down due to the limit on the voltage drop to only 500 W (at 80 m length). With a cross-section of 1.5 mm^2 the maximum power is only 1.7 kW if the cable is kept shorter than about 15 m, while the minimum power at 80 m length is about 300 W.

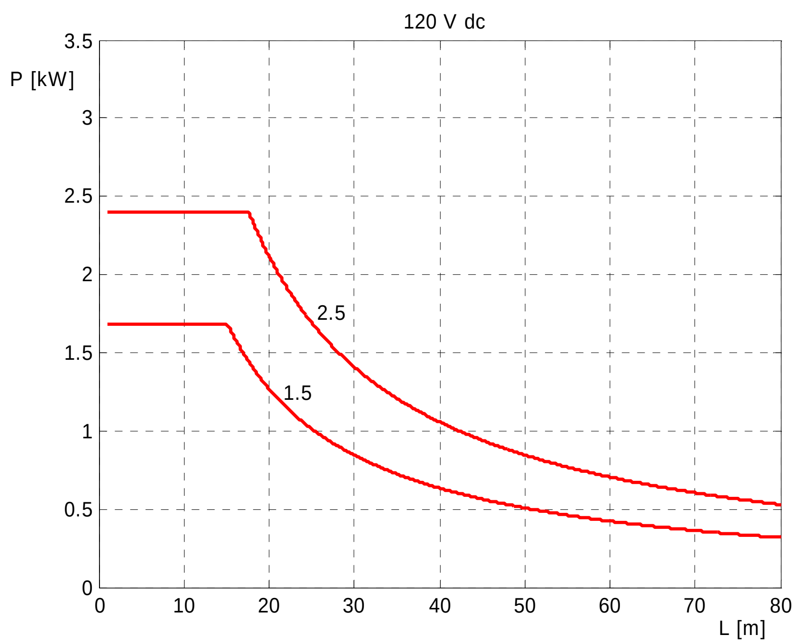

Fig.4 - Maximum power vs. length for cables with cross section S=1.5 and S=2.5 mm^2 (rated voltage is 120 V dc).

Finally, with 48 V dc the condition on the maximum voltage drop is a stronger limitation then the maximum current already at a length of about 8 m (Fig.5). The power that can be supplied, equal to about 950 W for very low cable lengths and a cross-section of 2.5 mm^2, drops down to less than 100 W for 80 m length.

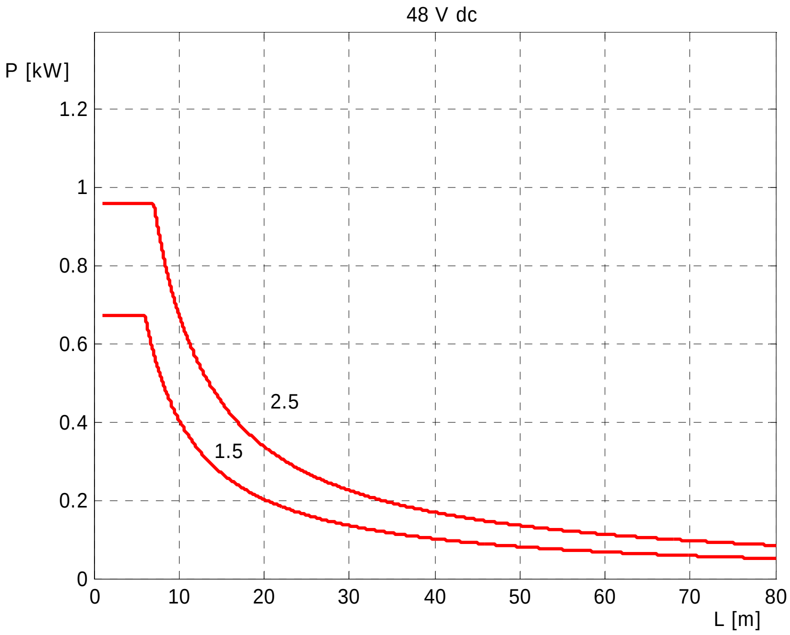

Fig.5 - Maximum power vs. length for cables with cross section S=1.5 and S=2.5 mm^2 (rated voltage is 48 V dc).

For a cross-section of 1.5 mm^2, the maximum power is about 680 W (for cables shorter than 8 m) and then decreases to about 50 W for 80 m length. As an example, the maximum power to be supplied in this case with a 10-m cable is 400 W, which is equal to two computers with screens. At a distance of 20 m, only the power corresponding to one computer could be delivered.

These results seem to exclude completely the possibility to use 48 V dc as a suitable voltage for supplying residential systems. Nevertheless, in specific cases in which load power consumption or cable lengths are very low, it could still be considered. An example could be an isolated house powered by solar cells. As already mentioned, a big advantage with the 48-V level is that it has been used since long in telecommunication systems, which makes it easier to find equipment and system components available for use with this voltage.

5 Back-Up Supply For Dc-Systems

5.1 Introduction

The increasing use of low-power electronic equipment, like PCs, and the growing importance of internet, data exchange via local networks and telecommunications, make many applications in office environments very dependable on the availability and quality of the supply. The main reason is the high sensitivity of low-power electronics to disturbances in the supply voltage, including not only interruptions, but also sudden short-duration drops in voltage, known as voltage dips or sags.
Uninterruptible Power Supply (UPS) systems are the standard solution for this kind of equipment. A UPS (Fig.1) is composed of a battery charger (rectifier), a battery block and an inverter. It supplies the load from the ac supply in normal conditions, from the battery block when the ac supply is unavailable.

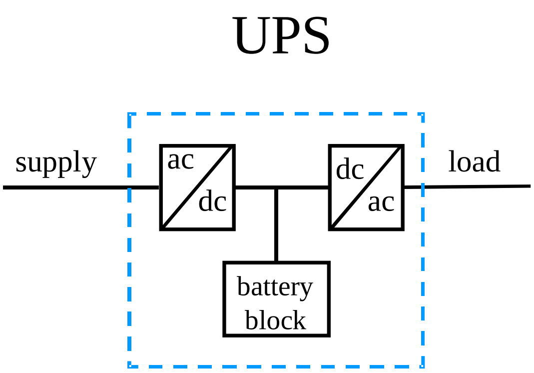

Fig.1 – Scheme of a UPS.

The battery block may be sized to cover the load for different durations. Standard UPSs used for PCs usually have up to half an hour capacity (10 minutes is a very common back-up time). In an office with many PCs and high quality requirements, the power system will look like in Fig.2.
It can be easily noticed that the several AC/DC and DC/AC conversions required by the system in Fig.2, with corresponding losses, make this system not very economical. The system in Fig.3 is a much better alternative: a central rectifier feeds a dc bus, with a big battery block for all the components in the network. Many inverters are still required if the PCs are supplied by ac, but the availability of dc-supplied PCs would lead to higher savings.
The savings could be such that a bigger battery block might be installed at lower cost, thus providing coverage for longer duration. In this Chapter the size of the battery block will be chosen (based on commercially available lead-acid 12 V batteries) for different back-up durations for the example system analysed in Chapter 4.

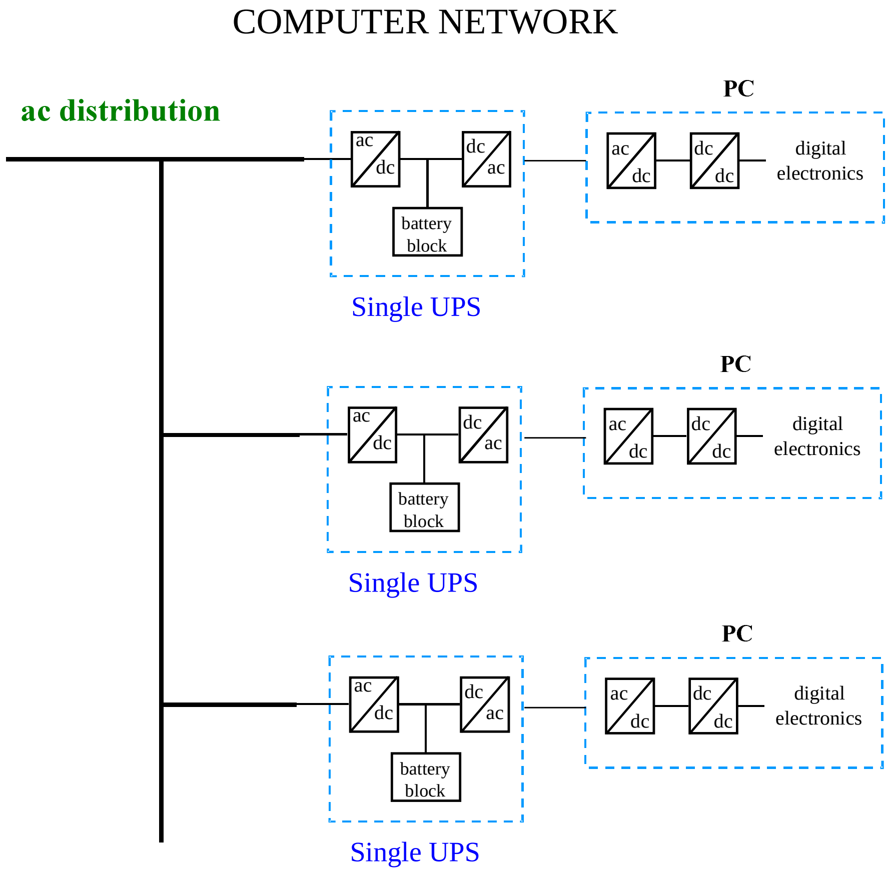

Fig.2 – High-reliability ac supply to an office.

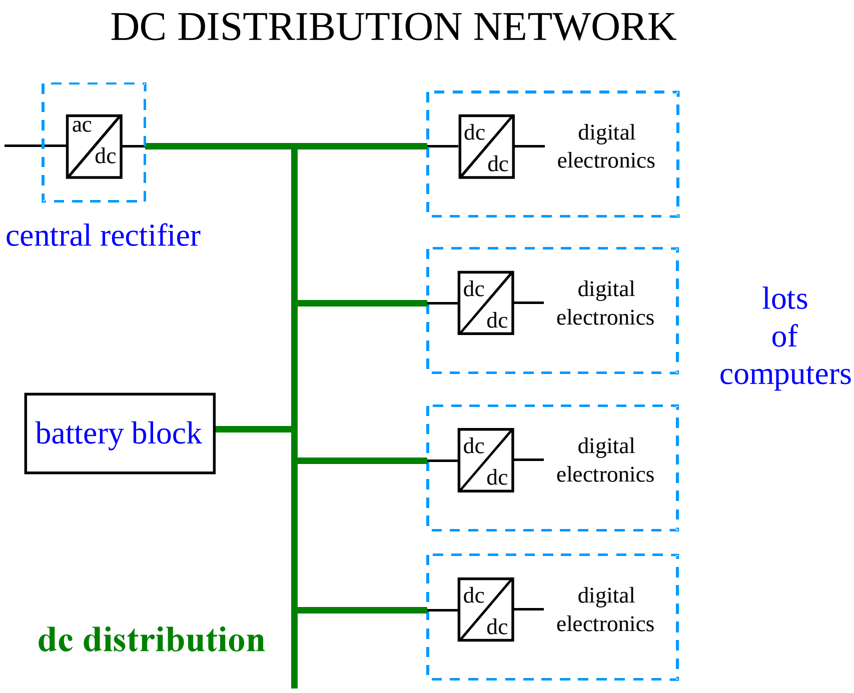

Fig.3 – Dc-supply to an office. Battery block ensures high reliability.

5.2 Battery sizing

5.2.1 Description of a battery system

A battery is composed of a certain number of equal cells in series, and a cell is made by a number of plates connected in parallel. Each cell has a voltage at its clamps, which is typical of the chemical reaction inside. Lead-acid cells, for instance, give the particular 2.0 V voltage [12, p.754]. The battery voltage is then given by the sum of the voltages of the cells in series.
The plates in parallel inside the cell determine the amperhour capacity because a single plate can give a limited amount of current (thus energy), while to deliver a higher current more plates are needed.
The capacity of a block constituted by many cells in series is equal to the capacity of one of them. If many cells are connected in parallel, instead, the total capacity is the sum of the single capacities.
On the market there are batteries of different voltages and capacity. To choose the most suitable one for each case, it is necessary to calculate the number of cells in series and parallel necessary to get the voltage and capacity required by the system, and then to match this result with the battery models present on the market.
In this project lead-acid batteries have been chosen, both because they are the most common (thus the cheapest if compared with other batteries of the same capacity) and because they are the most suitable for this use. They can stand quite big discharge currents, without damaging the plates inside.

5.2.2 System rated voltage and back-up time

The battery system has to be sized for the different voltage levels considered in this study:

- 326 V dc
- 230 V dc
- 120 V dc

The 48 V dc is not considered here because the results of Chapter 4 have demonstrated that it cannot be used in the existing system taken as example.
It is also necessary to decide for how long the batteries have to last in case of main supply unavailability and which loads are considered uninterruptible.

In the case study there are typical office loads as computer, printer, fax copy machine and lights. A kitchen is present with cooker, fridge, coffee machine, boiler and other similar loads.
In case of fault the only appliances for which an outage causes economical losses are computers and the others of the first group for a total power of 7920 W. All loads in the kitchen are neglected. As far as lights are concerned, only the desk lamps have been considered supplied by the back-up system (to allow people continuing their work) and 8 lamps, each of 36 W located at 10-m distance from each other, have been chosen in the corridor, for safety and emergency.

Concerning the supply interruption duration, four different back-up times have been chosen:

- 8 hours
- 4 hours
- 1 hour

For the entire duration specified, the battery system has to assure a minimum voltage level that allows the loads to work properly.

The first two values would cover cases of long-duration unavailability of the main supply, like environmental disasters or big maintenance. Anyway, these are very unlikely events, and the design of the back-up system for such long duration is justified only if its cost is lower than the money loss associated to the supply interruption.
The 8-hour back-up time would ensure coverage for a whole working day in case the supply interruption happens early in the morning and is not repaired during the whole day. The 4-hour duration is a medium value that takes into account the fact that the interruption is very unlikely to occur just before people start working. The last interval was chosen, instead, as a protection against voltage dips and short-duration interruptions. Typical back-up time for UPSs in use nowadays go from 10 up to 30 minutes.

5.2.3 Number of cells and batteries

To calculate the number of cells required for the battery pack, the following procedure suggested by [11] and [12] is applied:

- choose the maximum and minimum voltage allowed for proper operation of the load, with respect to the rated voltage;

- calculate the maximum and minimum voltage drop along the cables, considering for the maximum one the resistance calculated at 80°C and for the minimum at 25°C (as additional safety margin);

- the number of cells in series is then determined as:

$$n \leq \frac{U_{V\max} + \Delta U_{\min}}{U_{ZLE\max}} \tag{5.1}$$

where U_{Vmax} is the maximum permitted continuous demand voltage, ΔU_{min} is the minimum voltage drop between battery and load, U_{ZLEmax} is the maximum trickle-charge voltage per cell equal to U_{ZLE} (trickle-charge voltage per cell) + 1 %;

- calculate the minimum cell voltage (or cut-off voltage, i.e. the voltage at the end of discharge) as:

$$U_{Z\min} \geq \frac{U_{V\min} + \Delta U_{\max}}{n} \tag{5.2}$$

with U_{Vmin} the minimum permitted continuous demand voltage, ΔU_{max} the largest voltage drop between battery terminals and load and n the number of cells calculated above;

- calculate the total current required by the loads as:

$$I_{tot} = \frac{P_{tot}}{V} \tag{5.3}$$

where P_{tot} is the total power of the system and V the system rated voltage;

- choose a discharge time for the battery, which is the back-up time;
- once the current required by the appliances is known from Eq. (5.3), the battery type to be chosen is the one whose current (at the discharge time and-cut off voltage required) best matches the given system current (being equal or higher). Manufacturers usually provide diagrams for each kind of battery similar to the one shown in Fig.4 [11].

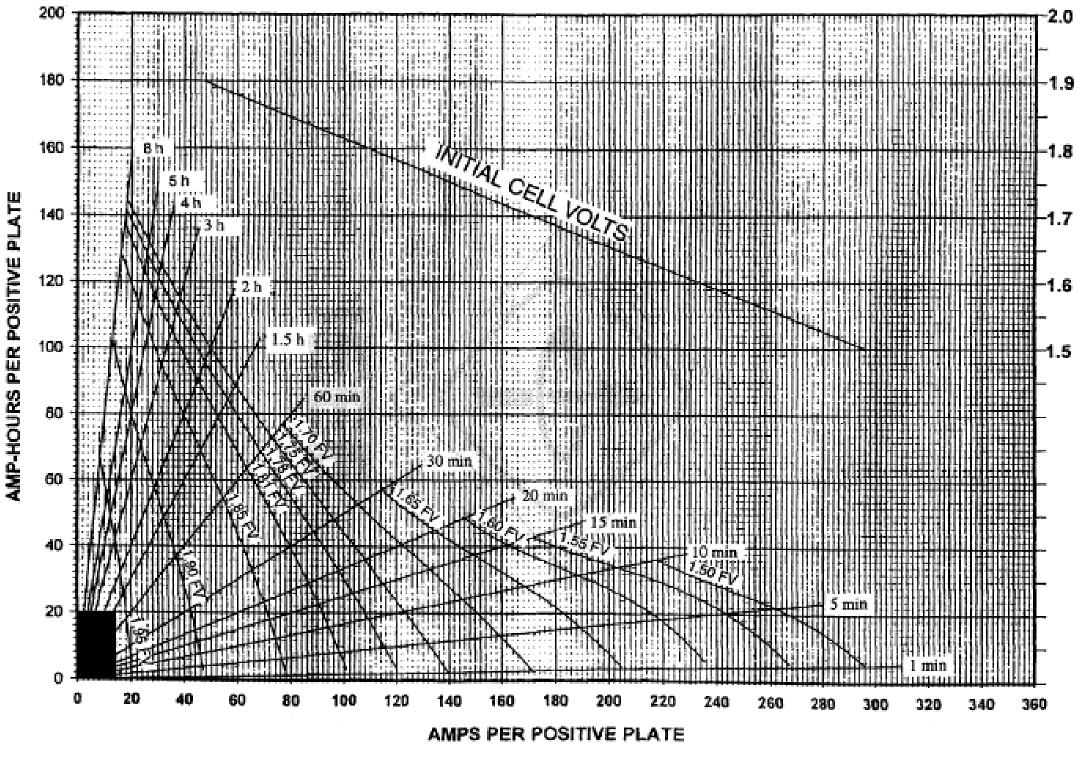

Fig.4 – Typical capacity vs. discharge current for lead-acid battery, from [11].

Alternatively, they provide tables where one can find the current supplied by the battery, known the discharge time and final cell voltage. If it is not possible to find such a battery on the market, a number of them will have to be connected in parallel according to the formula:

$$Nr\_parall \geq \frac{I_{tot}}{I_{cell}} \tag{5.4}$$

i.e. the number of cells or batteries to be put in parallel is the integer number immediately higher than the ratio of the system total current and the one supplied by the battery.
In the system considered, the voltage excursion allowed by the loads has been considered equal to + 10% and – 20%. The battery, chosen between those produced by Dynasty [13], is the UPS 12-100, which has a voltage of 12 V and a capacity for 20-hour duration at the temperature of 77 °F of 26 Ah.
Results of the procedure described above concerning the system analyzed are reported step by step from Tab.1 to Tab.4 for the discharge times and the voltage levels chosen at the beginning of the project. In Tab.1, the minimum and maximum voltage drops are reported, together with the corresponding feeder number (feeders considered here are nr. 8, 9, 11, 12, 13, 20, 21, 22, and a part of nr.7; for related loads see Tab.2 of Chapter 4), and the minimum and maximum voltage allowed for the load. The number of cells in series and the cut-off voltage calculated from Eqs. (5.1) and (5.2) are also reported.

TAB.1 – NUMBER OF CELLS IN SERIES AND MINIMUM VOLTAGE AT CELL TERMINALS

DC Voltage [V]	Max. voltage drop at 80 °C [V]	Nr. of feeder	Min. voltage drop at 20 °C [V]	Nr. of feeder	V load max	V load min	Nr. of cells in series	Min.Cell Voltage [V]
326 V	2.8	9	0.46	21	358.6	260.8	146	1.80
230 V	4.0	9	0.65	21	253	184	103	1.82
120 V	7.7	9	1.25	21	132	96	54	1.91

The necessary data from the manufacturer are reported in Tab.2, which gives the current corresponding to the cut-off voltages reported in the table for the different desired durations [13]. For each voltage level, the total current is calculated from Eq. (5.3) with P_{tot} =7920 W, and the number of batteries in parallel is calculated for the different durations desired, by using Eq. (5.4) and the data in Tab.2. Results are reported in Tab.3. Finally the total number of batteries required is reported in Tab.4, calculated as the product between number of batteries in series and in parallel. Note that the number of 12 V batteries in series is obtained by dividing the number of the cells in series from Tab.1 by the number of cells in a battery (in this case 6, for a 12-V battery).

TAB.2 – CONSTANT CURRENT DISCHARGE RATINGS AT DIFFERENT CELL CUT-OFF VOLTAGES

Final discharge voltage [V]	CURRENT [A] @ cut off voltage		
	8 hours	**4 hours**	**1 hour**
1.8	2.95	5.40	16.40
1.82	2.90	5.30	16.10
1.9	2.62	4.75	14.00

TAB.3 - NR. OF BATTERIES IN PARALLEL CORRESPONDING TO DIFFERENT DURATIONS AND VOLTAGES

Voltage [V]	8 hours	4 hours	1 hour	I tot [A]
326	8	4	1	24.3
230	12	6	2	34.4
120	25	14	5	66.0

TAB.4 – TOTAL NUMBER OF BATTERIES IN A PACK

Voltage [V]	8 hours	4 hours	1 hour
326	201	110	36
230	205	112	37
120	228	126	43

5.3 Price and weight

The price of one UPS 12-100 battery is 66.46 $ [13] and its weight is 9.6 kg. The total cost of the battery pack is equal to the product of the number of batteries of Tab.4 for the price of a single unit. Prices in U.S. Dollars are reported in Tab.5. To have an idea of the weight, consider that the maximum is 1095 kg in the case of 120 V (back-up time 8 hours) while the minimum is 182 kg (back–up time 1 hour, voltage 326 V).

TAB.5 – PRICES FOR THE BATTERY PACK IN U.S. DOLLARS

Voltage [V]	Price [$]		
	8 hours	**4 hours**	**1 hour**
326 V	13352.5	7294.4	2401.8
230 V	13600.2	7441.6	2449.7
120 V	15157.3	8360.4	2836.6

These cost figures may be compared with the current situation, in which reliability is ensured by many small UPSs as in Fig.2. In this example, a total power of 7920 W has to be fed by the back-up system. The load is assumed to be composed by PCs, with rated power of 180 W, resulting in a number of 44 UPSs, if one for each PC is considered. The lowest-price UPS found in our survey that has a rated power of 180 W and a back-up time of 10 minutes costs 87.5 $ [14]. This means that covering the total load for 10 minutes with small UPSs would cost 3850 $. By comparing with Tab.5, it is clear that even in the worst case (120 V) a battery pack with back-up time of 1 hour cost less than the UPS that has a back-up time of only 10 minutes.

5.4 Conclusions

In this Chapter, a back-up supply for the dc system example case has been designed for the durations of 1 hour, 4 hours and 8 hours. The battery block is supposed to supply only the uninterruptable loads during this time, for a total power of about 8 kW.
It has been demonstrated that to supply the same amount of load with small UPSs, as it is done in the current ac system, would cost more. In particular, the price of the battery block with back-up time of 1 hour is lower than the cost of the necessary UPS with back-up time of 10 minutes. Note that the battery chosen does not belong to a special type, but is a common battery used for UPS applications.
Moreover, substituting the small UPSs with a single battery block directly connected to the DC system leads to further savings due to reduced losses, since many small rectifiers and inverters are taken away. However, this aspect has not been considered in this Chapter.

6 Circuit Breakers for Dc Systems

6.1 Introduction

It is a general belief that interrupting dc short-circuit currents is impossible or at least extremely difficult or expensive. Knowledge about this subject is developed although not widespread. There are of course differences in interrupting fault currents in ac and dc systems, but interrupting a dc current in a low-voltage dc system does not pose big problems.
Aim of this chapter is to present the difference between ac and dc current interruption, to explain how to apply ac breakers to dc application and to demonstrate that proper dc ratings are available.

6.2 Basic concepts

6.2.1 Basic function of a circuit breaker

The breaker functions are:

- switching rated current at rated voltage;
- sensing overcurrent conditions and operate to open them automatically providing overcurrent protection.

To accomplish the first function, the typical breaker has a set of contacts that can be manually switched open and closed under an operating handle. In a multipole breaker, all poles are mechanically linked to open and close together.
For the second function, the circuit breaker also has a current sensing system, for each pole, which is mechanically linked to a latch. If an overcurrent condition is reached and sustained for the predetermined time delay, the sensing element will cause unlatching of the mechanism. The circuit breaker opens automatically by means of energy stored in springs, when the mechanism is unlatched, and since the poles of a multipole breaker are mechanically linked, all poles open.

6.2.2 Overcurrent sensing

Fig.1 illustrates a typical time-current tripping characteristic for a thermal-magnetic circuit breaker. It can be separated into three regions:

- the long-time delay region at the top;
- the transition region at the center;
- the instantaneous region at the bottom.

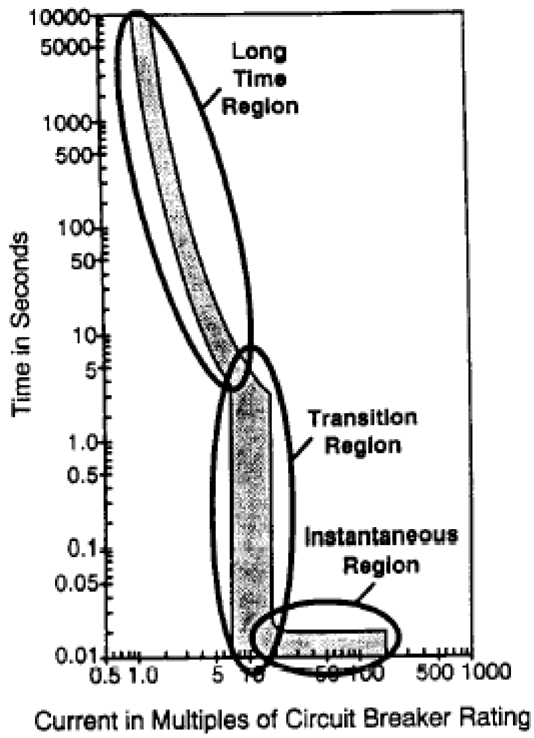

Fig.1 – Typical time-current curve for a Thermal-Magnetic Trip Unit, from [15].

The long time region generally includes currents from 100 % of the rated, which the breaker will carry indefinitely, to the level at which it will begin to trip instantaneously. In most cases this long time upper level is about 500 % of the rated current. The sensing element is a bimetal, which is heated by current flowing through the circuit breaker. Deflection is proportional to I^2 so that it is an ideal rms current sensor.

Trip times in the transition region are not precisely defined since it is here that the transition from thermal to magnetic tripping occurs. Depending on the level of current flowing, tripping can be thermal, with the built in delay shown on the thermal curve, or magnetic with no intentional delay. In the second case, the magnetic force is proportional to the square of the instantaneous value of current, rather than the rms value over some period.

The instantaneous region, tripping and clearing are instantaneous, with no intentional delay, accomplished by the electromagnet discussed for the transition region. Actual clearing time will vary on the design of the interruption system of the circuit breaker.

6.2.3 Circuit interruption

As the circuit breaker contacts open under overload or short-circuit conditions, an electric arc is formed between them due to the circuit self-inductance, always present in circuits, that expends the energy stored through it. The voltage-current characteristic of a stationary arc is shown in Fig.2.

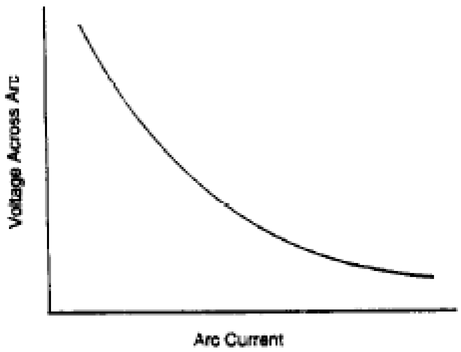

Fig.2 – Voltage and current characteristic of stationary arc [15].

It is called a negative differential resistance characteristic. To clear the arc and interrupt the circuit, it is necessary to increase the voltage to a point at which the arc is unstable, where the conductivity of the arc is low. The major contributor to conductivity that is influenced by interruption devices is temperature along the arc.
The metal plate arc stack is still the most common technology used in low-voltage circuit interruption. Using this concept, the arc is forced into the arc stack by means of Lorentz magnetic force or gas pressure. The stack separates the arc into a number of shorter arcs in series. Under appropriate conditions of separation and cooling, the arc becomes unstable and extinguishes. Then, as long as the contact separation is dielectrically sufficient and the degree of cooling is sufficient to deionize the chamber, the arc will not reignite and interruption is accomplished.

6.3 Differences in interrupting ac or dc [15]

To interrupt a dc circuit, ac breakers can be used but the differences have to be remarked for a proper choice of dc ratings. However, multipliers or similar tools are provided by manufacturers, together with the ac curve, for the application engineer to convert it for use with dc circuits.

Considering the overcurrent sensing, differences are not noticed in the long-time region, since deflection is due to the heating, which is caused by the rms value of the current, same in ac and in dc. So the time-current characteristic is the same for both ac and dc in long-time region.
For the instantaneous region, clearing time will vary depending on the breaker design and whether the circuit is ac or dc. However, the maximum total clearing time is generally expressed as a conservatively long duration on ac trip curves because of the large number of other variables as long as the current rise time constant is 10 ms or lower, so unless otherwise clarified by manufacturer, the ac maximum clearing time will also satisfy dc.
Different situation is found in the transition region. The electromagnet is activated by current flowing through the circuit breaker and the magnetic force, as mentioned before, is still proportional to the square of the instantaneous value of current. But the current on ac trip curves is expressed in terms of rms value, while in dc is expressed as instantaneous value. In this case, this difference in expressing current is an essen-

tial factor in adjusting ac curves to dc systems. Combining also other disparities between dc and ac characteristics in the transition region, some of them unique to each design, manufacturers will generally provide adjustments to the trip curves in the form of multipliers or redrawn ac trip curves. The effect of these adjustments is to slightly increase the stated ac magnetic tripping levels when the same circuit breaker is used in dc circuits, as indicated in Fig.3.

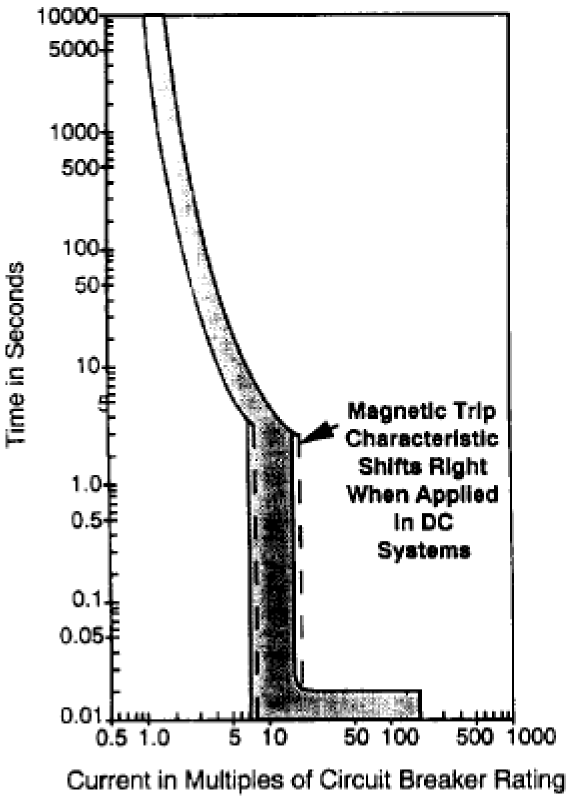

Fig.3 – Characteristic curve for a thermal-magnetic Molded-Case Circuit Breaker modified for DC application, from [15].

Several manufacturers express this difference in a multiplying factor of 1.1 to 1.4 times the tripping current, for dc applications. Sometimes, instead, e.g. when intended for protection of batteries against sustained overloads, circuit breakers are provided with special magnetic trip levels designed lower than standard.

Concerning arc extinguishing, performance of the same circuit breaker in an ac circuit should be expected to be very different than in a dc one even though circuit parameters seem to be the same. Forces operating in the circuit breaker to sense current level, separate contacts and direct the arc are generally all proportional to the square of the instantaneous current $i^2(t)$. These conditions will all happen sooner in the ac than in dc circuit, as well as the destructive forces that tend to damage insulators or displace elements of the circuit, so reacting times are completely different.

But the most important divergence between interruption of ac and dc circuits is the current passage through zero driven by a sinusoidal voltage, that in dc is missing. If the degree of ionization is sufficiently low as current normally reaches zero on a sine wave, the arc will not reignite and the overcurrent is cleared. In this sense, the ac circuit is somewhat supportive of interruption. Many designs, however, will force an early current zero such they do not wait for the normal sine wave period under short circuit conditions. For these interruptions it is immaterial whether the circuit is ac or dc, since interruption is initiated and carried through during the initial upswing of fault current.

6.4 Application of ac breakers to dc systems [15]

The circuit breakers must be rated expressly for dc applications, since a correlation between ac and dc ratings cannot normally be established. Often, trip curves drawn for ac applications are used for dc applications as well. But in this case manufacturers generally publish adjustment factors for instantaneous tripping current levels.
Thermal-magnetic moulded-case circuit breakers (MCCB) with direct acting trip units are available with ratings for these systems. Some of them, when used for dc circuit protection, have poles connected in series, especially above 250 V dc. Fig. 4 illustrates the most commonly specified connections.
By connecting poles in series, arc interruption is shared, permitting more effective elongation and segregation of the inductive arc. But attention have to be paid to requirements for such connections, marked on the circuit breaker and in instructions for its application, since a problem could be found when using them in systems with one polarity grounded. A single ground fault could cause a full voltage over-current condition across a single pole and the breaker has to be tested with full rated voltage across individual pole for this connection to be allowed. It is specified anyway if their use is for grounded or only ungrounded systems.

Important for application is that the dc time constant for which the circuit breaker is rated must be equal to or greater than that of the system in which it is used, since forces depending on instantaneous value are lower in dc due to absence of sinusoidal trend and a too big constant time risk not to get the sufficient force to open contacts.

Different matter is for UPS systems. Considering that battery systems will float to a voltage above nominal when load is minimal, tests are done at the maximum (float) voltage. Besides, it is not expected that these circuit breakers will be used for frequent switching applications, so the number of endurance and overload operations is reduced from that required for the general application devices.

If breakers marked with dc ratings are identified as “suitable only for use on UPS” both nominal and maximum voltages are marked on the circuit breaker. While if that label is not specified, it means that they are suitable for general application on dc as well UPS systems, and in this last case the marked voltage is taken as the maximum (float) voltage.

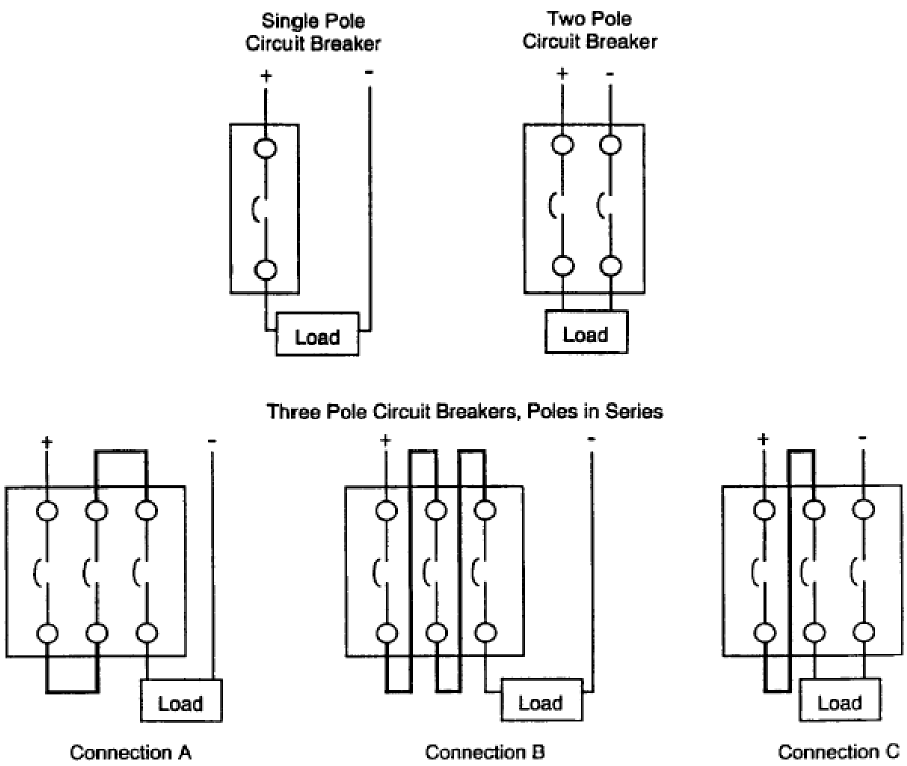

Fig. 4 – Common circuit breaker DC connections, from [15].

6.5 Circuit breakers for low voltage dc application

A survey has been done about breakers for dc application that exist on the market. To choose the breakers range, the short-circuit current in the case study is considered to get an idea of the voltage and current levels to be interrupted.
The system data found at the substation are:

- $S_{s.c.}$ = 156.4 MVA — short-circuit power of the medium-voltage network (10.5 kV);
- $I_{s.c.}$ = 8.6 kA — network short-circuit current;

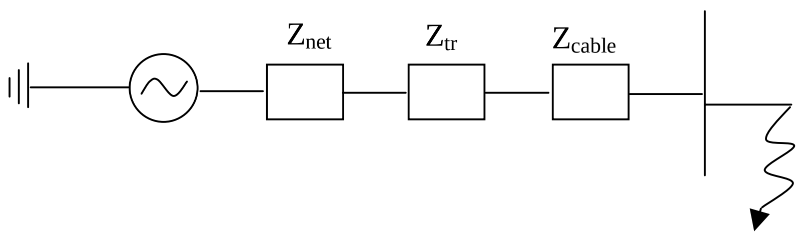

Fig.5 – Simple electric scheme from generation to switchgear.

For the transformer in the substation the following features are given:

- V_1 / V_2 = 10.5 / 0.420 kV;
- A = 800 kVA transformer power;
- $v_{s.c.}\%$ = 5.1 % short-circuit voltage percent value;
- P_{cc} = 9900 W short-circuit power losses.

The parameters of the cable connecting the substation and the switchgear are:

- $S = 70\ mm^2$ cross-section area;
- L = 20 m length;
- r = 0.443 Ω/km specific resistance at 20 °C;
- x = 0.07 Ω/km specific reactance;
- R = 0.0090 Ω actual resistance at 25 °C;
- X = 0.0014 Ω actual reactance.

Using these data, the one-line circuit of Fig.5 has been solved.

Network impedance has been calculated according to the following equation:

$$Z_{net} = \frac{V_{rat}^2}{S_{s.c.}} \tag{6.1}$$

where V_{rat} is the rated voltage (11.0 kV in this case) and $S_{s.c.}$ the network short-circuit power.

The transformer impedance is given by:

$$Z_{tr} = \frac{Z_{s.c.}\%}{100} \cdot \frac{V_1^2}{A} \tag{6.2}$$

with $Z_{s.c.}\%$ the percent value of transformer impedance, which is equal to $v_{s.c.}\%$, V_1 the nominal primary voltage and A the transformer rated power.

The impedance of the cable is:

$$Z_{cable} = \sqrt{R^2 + X^2} \tag{6.3}$$

where R and X values, respectively resistance and reactance, have been reported before.

Results of these calculations are (all reported to the secondary side of the transformer):

- Z_{net} = 9.269 e-5 + j 9.269 e-4 Ω
- Z_{tr} = 2.47 + j 9.89 mΩ
- Z_{cable} = 0.0090 + j 0.0014 mΩ

The short circuit current, if a fault occurs at the switchgear, is then equal to:

$$I_{s.c.} = \frac{V_2}{Z_{tot}} = 13.673\,\text{kA} \tag{6.4}$$

where V_2 is the secondary voltage level, and Z_{tot} is the sum of the impedances calculated before, i.e. the network, the transformer and the cable impedances.

A survey of existing breakers for dc applications has been done and some tables taken from manufacturer catalogues are reported. Both voltages and currents have been found to match the order of magnitude of values used in this project. For example, the table reported in Fig.6 presents breakers with rated current from 160 A up to 2500 A by Siemens [16]. For dc application, the voltage levels go from 250 V dc up to 750 V dc, depending on the number of paths in series, and the rated short-circuit breaking capacity goes up to 20 kA.

3VF3 to 3VF8 Circuit-Breakers
3- and 4-pole, up to 2500 A

Technical data								
Type		3VF3	3VF4	3VF5	3VF6	3VF7	3VF8	
Max. rated current I_n depending on version	A	160/205; 225	200/250	315/400	500/630/800	800/1250	1600/2000	2500
Rated insulation voltage U_i acc. IEC 60 947-2								
Main circuits	V AC	750	750	750	750	750	750	
Control circuits	V AC	690	690	690	690	690	690	
Rated impulse withstand voltage U_{imp}								
Main circuits	kV	8						
Auxiliary circuits	kV	4						
Rated operational voltage U_e								
IEC	V AC	690¹)	690	690	690	690	690	
NEMA	V AC	600¹)	600	600	600	600	600	
Permissible ambient temperature	°C	–20 to + 70				–5 to + 60		
Permissible load for various ambient temperatures close to the circuit-breaker, related to the rated current of the circuit-breaker		(1) (2)	(1) (2)	(1) (2) (3)	(1) (2) (3)	(3)	(3)	(3)
– Circuit-breakers for plant protection at 40 °C	%	100 100	100 100	100 100 100	100 100 100	100	100	100
50 °C	%	96 92	96 94	96 92 100	96 91 100	91	100	100
55 °C	%	93 87	94 90	93 87 100	93 86 100	85	100	96
60 °C	%	91 83	92 87	90 84 100	90 82 100	81	100	92
70 °C	%	86 73	88 80	85 75 85	84 70 84	–	–	–
– Circuit-breakers for motor protection at 40 °C	%	100/100	–	100	100	–	–	
50 °C	%	100/96	–	100	100	–	–	
55 °C	%	100/90	–	100	100	–	–	
60 °C	%	100/86	–	100	100	–	–	
70 °C	%	100/77	–	87	90	–	–	
– Circuit-breakers for starter combinations and non-automatic circuit-breakers at 40 °C	%	100	100	100	100	100	100	100
50 °C	%	100	100	100	100	91	100	100
55 °C	%	96	96	95	95	85	100	96
60 °C	%	91	92	90	90	81	100	92
70 °C	%	86	88	85	84	–	–	–
Rated short-circuit breaking capacity (DC) not for 3VF circuit-breakers for motor protection; Time constant τ = 10 ms; 1 conducting path / 2 conducting paths in series / 3 conducting paths in series / 4 conducting paths in series; for 3VF3 to 3VF6: up to 250 V DC / 440 V DC / 600 V DC / 750 V DC	kA	20/10⁸)	20	20	20	–²)	–²)	
NEMA; Time constant τ = 8 ms; 1 conducting path / 2 conducting paths in series: 250 V DC / –	kA	10	10	10	10	–²)	–²)	
– / 250 V DC	kA	22/10⁸)	22	22	22	–²)	–²)	
Main switch – characteristics (IEC 60 947-2) with lockable rotary drives		yes	yes	yes	yes	yes	yes	
EMERGENCY-STOP switch characteristics (DIN VDE 0113)		yes	yes	yes	yes	yes	yes	
Rated short-circuit breaking capacity acc. IEC 60 947-2 (AC 50/60 Hz)⁷)		Rated short-circuit breaking capacity, see 3 pages further.						
Endurance	operating cycles	10 000	10 000	8000	8000	3000	3000	
Max. operating frequency	1/h	300	240	240	240	60	20	

1) With circuit-breakers with rated currents ≤ 40 A: U_e maximum 415 V.
2) Not suitable for DC switching.
3) Busbar connection pieces (see Accessories).
4) 800 A: 3 × 40 × 5
5) Max. cross-section only once, cross-section smaller: up to sum of max. cross-sections
6) 2 conductor connections.
7) Can also be used in 400 Hz networks. Technical data available on request.
8) 10 kA for 3VF.. ..–0....–....
(1) Thermal overload release set to upper value, i.e. thermal overload release with fixed setting.
(2) Thermal overload release set to lower value.
(3) Electronic release.

Fig.6 – Circuit breakers by Siemens, rated for both ac and dc applications [16].

In ABB catalogue molded-case breakers have been found, with rated ultimate short-circuit breaking capacity given for both ac and dc use [17]. Rated currents go from 125 to 250 A; rated service voltage for dc application goes from 250 to 750 V, as shown in Fig. 7. Note that the smallest one, S1, can only be used for 250 V dc by putting two poles in series, and short-circuit breaking capacity is 16 kA / 25 kA (depending on the type). This will satisfy all voltage levels considered in this project but 326 V. In the latter case, bigger breakers will have to be used (for example with three poles in series).

SACE Isomax S moulded case circuit-breakers

Technical and electrical overview

			S1		S2			S3		
Rated uninterrupted current, Iu		[A]	125		160			160 - 250		
Poles		No.	3-4		3-4			3-4		
Rated service voltage, Ue	(a.c.) 50-60 Hz	[V~]	500		690			690		
	(d.c.)	[V–]	250		500			750		
Rated impulse withstand voltage, Uimp	[kV]		6		6			8		
Rated insulation voltage, Ui		[V]	500		690			800		
Test voltage at industrial frequency for 1 min.		[V]	3000		3000			3000		
Rated ultimate short-circuit breaking capacity, Icu			B	N	B	N	S	N	H	L
(a.c.) 50-60 Hz	220/230 V~	[kA]	25	40	25	50	65	65	100	170
(a.c.) 50-60 Hz	380/415 V~	[kA]	16	25	16	35 (1)	50	35 (1)	65	85
(a.c.) 50-60 Hz	440 V~	[kA]	10	16	10	20	25	30	50	65
(a.c.)	50-60 Hz 500 V~	[kA]	8	12	8	12	15	25	40	50
(a.c.)	50-60 Hz 690 V~	[kA]	—	—	6	8	10	14	18	20 (5)
(d.c.)	250 V– (2 poles in series)	[kA]	16	25	16	35	50	35	65	85
(d.c.)	500 V– (2 poles in series)	[kA]	—	—	—	—	—	35	50	65
(d.c.)	500 V– (3 poles in series)	[kA]	—	—	16	35	50	—	—	—
(d.c.)	750 V– (3 poles in series)	[kA]	—	—	—	—	—	20	35	50
Rated duty short-circuit breaking capacity, Ics (2)		[%Icu]	50%	50%	100%	75%	75%	100%	75%	75%
Rated short-circuit making capacity (415 V~), Icm		[kA]	32	52.5	32	74	105	74	143	187
Opening time (415 V~)		[ms]	8	6	8	7	6	8	7	6
Rated short-time withstand current for 1 s, Icw		[kA]								

Fig. 7 - Circuit breakers by ABB, rated for both ac and dc applications [17].

6.6 Conclusions

In this Chapter it has been tried to give an answer to one typical reason of hesitation in apply dc to the distribution systems: protection, i.e. interrupting the fault current. It has been assessed that the problem has been treated in the literature and it has been concluded by examining the available literature that existing ac-low voltage breakers can be used for DC applications, but the correct ratings must be explicitly given for interruption of a DC current.

Moreover, it has been demonstrated through a survey of catalogues of low-voltage breakers that several manufacturers actually give the rated service voltage and interrupting capacity for DC applications. Some examples by well-known manufacturers have been reported.

7 Economic Evaluation

7.1 Cost Analysis

The following assumptions have been made when evaluating the costs of the dc system:

- a scenario has been imagined in which dc is widespread and components for dc applications are present on the market and not tailored to specific applications. Therefore, the additional costs of designing and producing customized components have been neglected.
- The dc voltage levels considered here do not include 48 V because, according to the results presented in Chapter 4, it gives unbearable voltage drops and power losses with the cross-sections of cables normally used for residential applications. Therefore, the voltage of 120 V dc, 230 V dc and 326 V dc are considered.
- To obtain the particular voltage levels considered here, a three-phase diode rectifier is used. This because it is the cheapest solution. Alternatively a PWM-controlled IGBT-converter may be used to have higher current quality on the ac network, but the cost will be higher.
  In this case, a dedicated transformer is required since the three-phase diode bridge rectifier gives as output a dc voltage equal to [10]:

$$V_{dc} = 1.35 \cdot V_{LL} \tag{7.1}$$

where V_{LL} is the line-to-line voltage of the three-phase ac system. Fig.1 shows the required transformer secondary voltage for the chosen voltage levels.

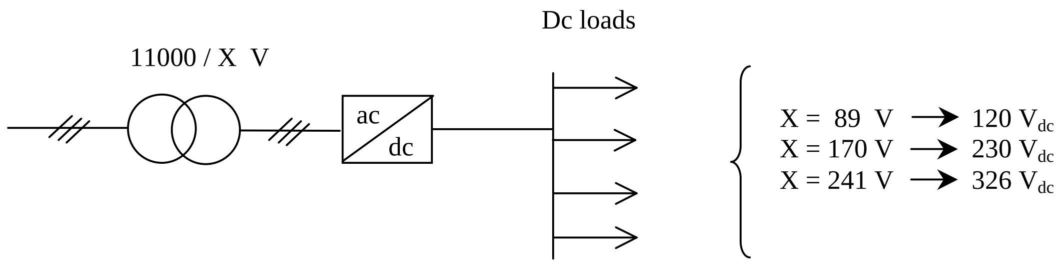

Fig.1 – A dedicated transformer and a diode rectifier are used to obtain the desired voltage level.

- To simplify the analysis, the only load considered here is the PC, with a power consumption of 180 W. As demonstrated by the measurements in Chapter 3, this is in fact representative of most of the loads present in an office.
- It has been assumed that the only modification necessary to adapt the PC to a dc supply is removing the single-phase input rectifier. In other words, the dc-dc converter already present in the PC directly after the rectifier will become the input stage with no modifications, or at least no modifications that lead to additional costs. In fact, the current drawn by the PC, which is around 1 A in the 230 V ac system, will range from 1.5 A with 120 V dc to 0.5 A with 326 V dc. This allows assuming to have the same type of chopper (no relevant difference in power losses and installation costs).
- Costs associated with the circuit breakers have not been considered.

On the basis of these assumptions, the comparison of the cost of the dc system with the existing ac system will be based on a comparison of initial (or installation) costs and operational (or running) costs.

7.2 Installation Costs

7.2.1 Cost of the rectifier

A big difference between the ac system and the proposed dc system is that the low-power rectifiers present in each PC are substituted with one bigger rectifier for the whole system.
In Elfa catalogue [18] the bridge rectifiers reported in Tab.1 have been found.

TAB.1 – FEATURES AND PRICE OF DIFFERENT BRIDGE RECTIFIERS

BRIDGE RECTIFIER					
TYPE	**Stock number**	**V_{RRM}**	**I_{AV}**	**PRICE [$]**	**CLASS**
1KAB100E/IR	70-074-38	600	1.2	0.43	**1-PHASE 1.5 A**
26MT120/IR	70-074-03	1200	25	9.34	**3-PHASE 25-35 A**
36MT120/IR	70-034-37	1200	35	10.5	
60MT120KB/IR	70-035-36	1200	60	49.9	**3-PHASE 60 A**

In the table V_{RRM} is the maximum repetitive peak reverse voltage and I_{AV} the maximum average forward current.
The price have been chosen considering for the single-phase one the price of each device in a 100-piece stock, which is assumed here to be equal to the cost for the manufacturer. For the three-phase, the price of each device in a 25-piece stock is considered. Calculations have been made for each of the dc voltage levels considered (326 V, 230 V, 120 V) and the existing 230 V ac system.
First of all the power delivered by the three-phase rectifier has been calculated, chosen the voltage V and given the current I that is the maximum allowed by the device (given in Tab.1):

$$P_{tot} = V \cdot I_{max} \quad (7.1)$$

Then the number of computers that can be fed by the rectifier has been found as:

$$N = P_{tot} / 180 \quad (7.2)$$

where 180 W is the power consumption of the PC.

Once found the number of PCs that can be fed by that rectifier, one can calculate the cost of the other solution, i.e. feeding each PC with a small single-phase rectifier, by multiplying the number of PCs, N from (7.2), for the price of the single phase rectifier given in Tab.1.

Results are reported in Tab.2 for the bridge whose maximum current is 25 A, in Tab.3 for the 35-A bridge, in Tab.4 for the 60-A rectifier. In column 4 the price of the three-phase rectifier is shown, in column 5 the cost of the number of single-phase rectifiers that give the same output power.

TAB.2 – COMPARISON OF INSTALLATION COSTS FOR 25-A 3-PHASE RECTIFIER

Dc Voltage [V]	Nr. of PCs supplied	Output power [W]	Single converter price [$]	Several converters price [$]
326 V	45	8,150	9.34	19.47
230 V	32	5,750	9.34	13.74
120 V	17	3,000	9.34	7.17

TAB.3 - COMPARISON OF INSTALLATION COSTS FOR 35-A 3-PHASE RECTIFIER

Dc Voltage [V]	Nr. of PCs supplied	Output power [W]	Single converter price [$]	Several converters price [$]
326 V	63	11,410	10.5	27.26
230 V	45	8,050	10.5	19.23
120 V	23	4,200	10.5	10.03

TAB.4 - COMPARISON OF INSTALLATION COSTS FOR 60-A 3-PHASE RECTIFIER

Dc Voltage [V]	Nr. of PCs supplied	Output power [W]	Single converter price [$]	Several converters price [$]
326 V	109	19,560	49.9	46.73
230 V	77	13,800	49.9	32.97
120 V	40	7,200	49.9	17.2

In Tab.2 and Tab.3 note that for the voltage of 120 V dc the solution with only one rectifier is more expensive, while for 230 V dc and 326 V dc it is cheaper than having a number of small rectifiers. Moreover, for 326 V dc the savings are higher than for 230 V dc. This is due to the fact that the limit for the diodes in the bridge is on the

current, so using a higher voltage allows drawing more power at the output, i.e. better use of the same rectifier. The cost of the other solution, instead, increases linearly with power. In Tab.4 instead, the solution with one 60-A three-phase rectifier appears to be always the most expensive, independently on the voltage level. This probably due to the fact that diodes of a different (more expensive) type have to be used to carry this higher current, and therefore the price goes up.
If the required output power is high, it could be better to put two or more bridges in parallel of the lower-current category instead of buying a bigger one. For example, supplying 13.8 kW, corresponding to 77 PCs, at 230 V dc, would cost 21 $ if two 35-A rectifiers are used. This is equal to two thirds of the price at the "several converters" solution (33 $) and less than half the price of one 60-A rectifier (50 $).

7.2.2 Cost of cables

The minimum size of the cables for low-voltage distribution on the market is 1.5 mm^2 and, as demonstrated in Chapter 4, this section can be used in principle with all voltage levels considered here, although special care must be taken not to overpass the voltage drop limit with 120 V dc. So it can be concluded that there is no difference in the initial costs of the cables.

7.2.3 Cost of the back-up system

It has already been demonstrated in Chapter 5 that the use of a big battery block for back-up power in the proposed dc systems leads to consistent savings, if compared with the current solution in ac systems, which consists in a number of small UPSs.
In the case study analyzed, for instance, 44 PCs were considered supplied by the back-up system, for a total power of 7920 W. The cheapest UPS system found on the market (which can supply 180 W for 10 minutes) has been compared with a battery pack sized for one-hour duration. The corresponding costs, considering a 230 V system in both ac and dc cases, are:

- 3850 $ for the UPS;
- 2447.9 $ for the battery pack.

The total savings are about 1,400 $ and, moreover, the back-up time is longer for the batteries (1 hour vs. 10 minutes). In case a different voltage level is desired for dc, the comparison between the existing UPSs (for 230 V ac) and the designed battery block for that case gives anyway money savings in dc. For example, in the 120 V dc and 326 V dc cases, the total expense for the battery is of 2836.6 $ and 2401.8 $ respectively, thus lower than existing UPSs in both cases.

7.3 Operational Costs

7.3.1 Rectifier efficiency

The efficiency of the rectifier is an important term in the evaluation of the costs associated with the proposed solution.
In this section, the power losses of the rectifier at the system entrance will be compared with the total power losses in the AC/DC conversions in the traditional ac system. The same three rectifiers analyzed in 7.2.1 will be considered here.

In the data sheets of the components reported in Tab.1, the maximum total power losses have been found and reported in Tab. 5. In Tab. 6 the efficiency has been calculated by diving the power losses by the maximum output power of the rectifiers given in Tab.2, Tab.3 and Tab.4, for the three voltage levels and the four diode bridges.

TAB. 5 – POWER LOSSES FOR THE RECTIFIERS

TYPE	Stock number	CLASS	Absolute power losses [W]
1KAB100E/IR	70-074-38	**1-PHASE 1.5 A**	2
26MT120/IR	70-074-03	**3-PHASE 25 A**	55
36MT120/IR	70-034-37	**3-PHASE 35 A**	75
60MT120KB/IR	70-035-36	**3-PHASE 60 A**	160

TAB. 6 – POWER LOSSES FOR THE RECTIFIERS IN %

DC Voltage [V]	1.9 A*	25 A	35 A	60 A
326 V	---	0.675	0.657	0.818
230 V	1.111	0.957	0.932	1.159
120 V	---	1.833	1.786	2.222

* only 230 Vac since it is the actual case

Results obtained demonstrate that percent power losses are of the same order of magnitude for all rectifiers considered. However, when using 326 V dc, power losses are lower in the dc solution with only one rectifier for all three types considered. When using 120 V dc, power losses are always higher than with the traditional ac solution. Finally, when using 230 V dc, percent power losses are lower for the two smaller rectifiers of the same category (rating 25 A and 35 A) as compared with the single-phase rectifier, while they are higher for the bigger rectifier rating 60 A.

7.3.2 Cable losses

In this section, a comparison will be made between cable losses at 230 V ac and at the different dc voltage levels considered. Losses along the cables are proportional to the square of the current, considered in absolute value. In dc systems there is no reactive current but this does not make a big difference at low voltage anyway, since reactances are low. More important appears, instead, to consider the effect of the voltage on the power losses: at lower voltage the current is higher and losses too.

For simplifying the analysis, let us consider a system with a total power of 30 kW, as in the case study of this thesis, but with the following features:

- number of feeders = 30;
- feeder length = 25 m;
- load power = 1 kW (each feeder);
- cross-section = 1.5 mm^2.

The total power losses are calculated with voltage varying between 120 V and 1000 V and compared with the losses at 230 V.
In Fig.2 the savings expressed in power losses (percent value) are reported, i. e. the difference between the power losses at that voltage and the losses at 230 V have been considered (this is why it gives zero in correspondence of that voltage), divided by the system total power. One can notice very quickly that by using for example 120 V, power losses will be 1.65% higher that for 230 V. On the other hand, after 500 V the “saved power” becomes very small as the voltage increases further.

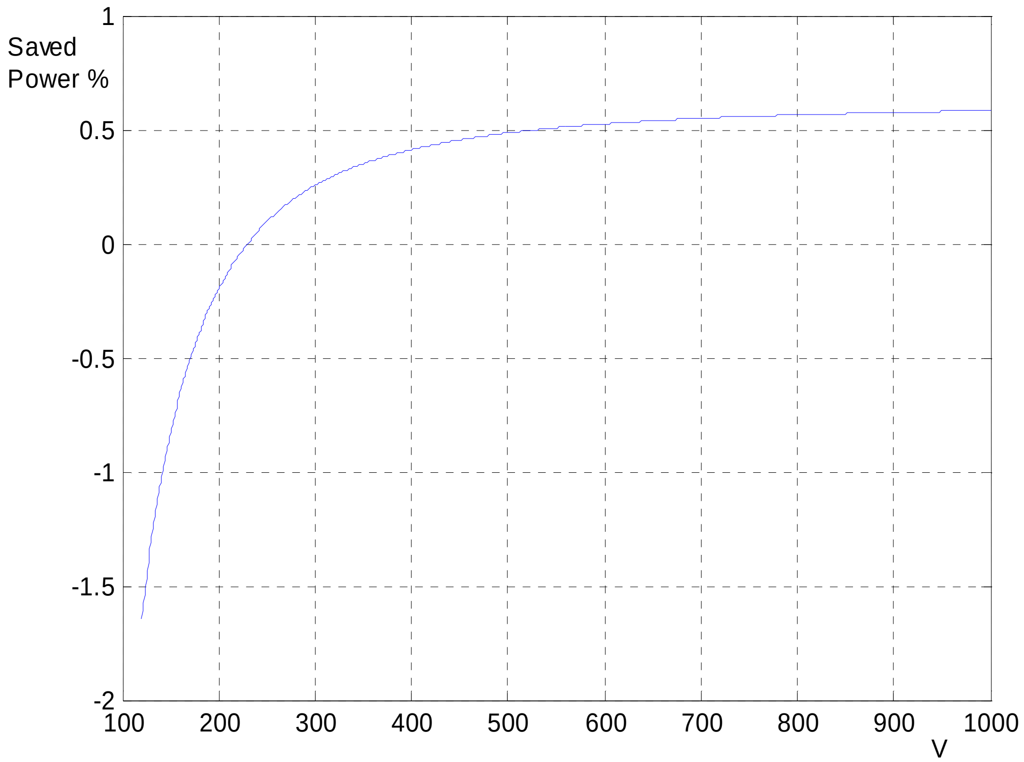

Fig.2 – Saved power when the voltage varies from 120 V to 1000 V (power losses at 230 V are taken as reference).

Of course, this aspect can play a different role depending on the price of the electrical energy in the different countries. For example, it has already been observed that the price of electrical energy is very low in Sweden and very high in Italy. If we take again these two countries as example, we obtain the following cost for the energy:

- kWh cost = 0.55 SEK (for Sweden)
- kWh cost = 350 £ (for Italy)

From the diagram in Fig.2 it is possible to quantify the savings in money each year. Energy consumption has been calculated by considering a working year composed by:

- 8 hours each day;
- 5 days each week;
- 50 weeks in one year

which gives a total of 2000 working hours per year. By multiplying this number for the power losses, the yearly energy consumption is calculated. Expenses for energy have been found multiplying the year energy consumption for the cost of the kWh. Results are expressed in Fig.3 in the Italian currency and in Fig.4 in the Swedish one.

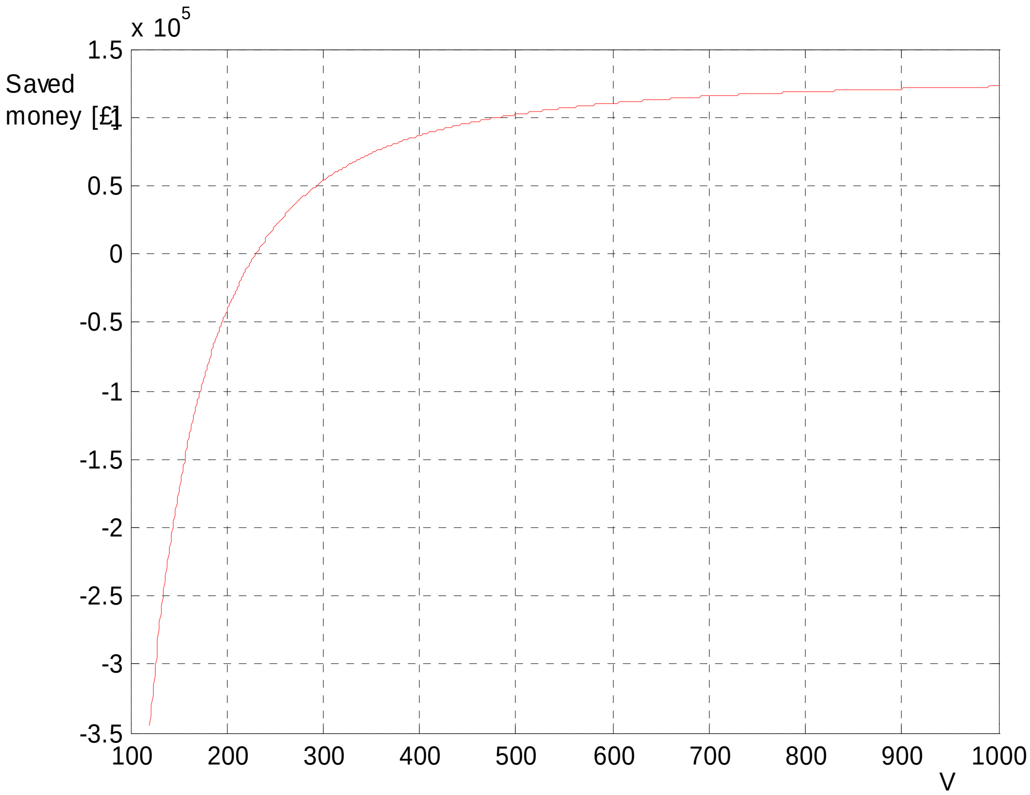

Fig.3 – Saved money for energy consumption during one year (Italian Lira).

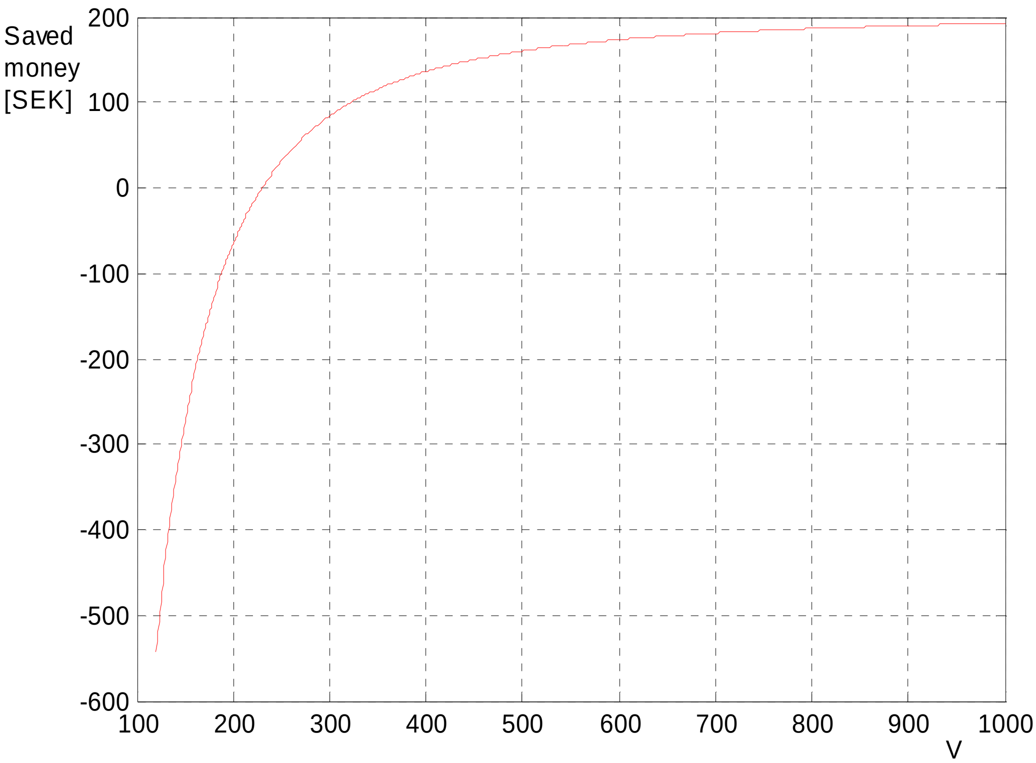

Fig.4 – Saved money for energy consumption during one year (Swedish Kr.).

7.4 Conclusions

In this Chapter, a comparison has been made between the costs involved in the traditional 230 V ac system and the proposed dc system, for the three voltage level analysed in Chapter 4 and 5 (326 V, 230 V, 120V). The voltage level of 48 V has been excluded from this exam since the results from Chapter 4 have clearly shown the impossibility of its application. The load considered is composed by only PCs, since its features include the typical electronic load characteristics.
The cost evaluation has been structured in two main groups (initial and operating costs). Within these two groups, three terms of costs have been considered:

- rectifier;
- back-up system;
- cables.

As far as initial costs are concerned, it has been found that substituting many small rectifiers with one bigger for the whole system does not automatically lead to savings. Savings on the cost of the rectifier are possible as far as higher voltages (230 V and 326 V) and medium current rectifiers (25÷35 A) are involved. When the high output current requires the use of a high-current bridge (with bigger diodes, in this case allowing 60-A current) the several-bridges solution is definitely cheaper. However, high output power can be achieved with consistent savings by paralleling two or more of the smaller three-phase bridges.

The back-up system, as better explained in Chapter 5, is always cheaper than a number of small UPSs: it leads to savings at all the proposed voltage levels and allows higher endurance for lower price.
Finally, there are no differences in installation cost of the cables because their size remains the same.

As far as running costs are concerned, it has been shown that the efficiency increases for the dc solution with a single rectifier when a voltage of 326 and 230 V dc is used and the rectifier is properly sized. When using 120 V dc, power losses are always higher than with the traditional ac solution.
A comparison of the running costs of the back-up system (many UPSs vs. one big battery block) has not been done, since in this case it is obvious that the dc solution is more efficient, because two conversions for each load are saved.
Power losses in the cables do not differ very much between ac and dc, because the reactive current is anyway very low in low-voltage distribution. However, by analysing the losses when the voltage varies from 120 V to 1000 V, it has been shown that there is a certain difference (about 1.65 %) between 120 V and 230 V, while when increasing the voltage further the decrease in power losses gets lower and lower. After 500 V power losses do not change much anymore.

8 Conclusions

Aim of this thesis was to investigate the possibility of substituting the existing ac supply in residential distribution systems with a dc one. A first conclusion that can be drawn from the analysis carried out is that the answer depends very much on the type of application considered, i.e. the function of the building and the type of loads present in it play a big role. From the survey conducted, offices appear to include mostly low-power electronic loads, while in private houses a big amount of loads is still constituted by resistive loads (for heating and sanitary applications) or motors. This is especially true in Sweden, where the cooker is driven by electricity and, together with the washing machine and the dryer, makes up for a big part of the consumption of a house.

For office applications, it can be concluded that a dc supply can lead to big advantages if a proper voltage level is chosen. From both the technical and the economical point of view, the most suitable dc voltage level seems to be 326 V.
The choice of a dc system with this voltage level in an office leads to a simplification of the distribution system, due to the substitution of a number of small diode rectifiers (input stage for electronic appliances) with a single one at the entrance of the system. It is readily applicable to existing systems, as this voltage level is higher than the ac voltage currently in use, which makes it possible to use the existing cables without trespassing the limits on the maximum allowed current and voltage drop on the feeders. Moreover, it has been shown that this choice leads to savings in installation costs, assuming the price of the equipment for the consumer to be reduced of the value corresponding to the price of a small diode rectifier in a 100-piece stock. With proper choice of the three-phase diode rectifier, operational costs have also been shown to be lower in the proposed dc system due to the higher efficiency of one device vs. many.

Another important factor is the high reliability required by an office. The choice of dc makes it possible to achieve high reliability in an easier way, with respect to the present solutions. It has been demonstrated that a battery block, dimensioned for 326 V, will allow big money savings with respect to the currently used UPS systems, for both installation and running costs (because of the higher efficiency, due to the fact that two conversion stages are missing). Moreover, the battery block chosen in this study gives a better protection from supply interruption, because it can be sized for a longer duration than the UPS, still at a lower cost.

When considering private houses, reliability is not as important as in offices but safety is a big concern. A better choice could thus be a very low voltage like, for example, 48 V. The reason for considering exactly this value is the availability of system components for that voltage, because it is the voltage currently used for telecommunication equipment (which uses dc). Unfortunately, it is clear from the voltage drop analysis carried out for the case study considered that this voltage cannot be used, at least not in existing systems with the same cables, because the resulting voltage drops would be too high.

A possible choice could be the voltage of 120 V, which at least does not require protection against indirect contacts and would lead to currents not as high as with 48 V. However, special care has to be taken because, according to the analysis shown, for some combinations of feeder length and load power the voltage drop limits or the cable maximum current can be trespassed.
This could be a viable option for example in Italy, because the power consumption of an apartment is not higher than 3 kW (feeder length is anyway normally not very high in apartments), but it does not seem to be realistic for the power consumption of apartments in Sweden. It would require the replacement of all cables with bigger one, with high associated costs. Moreover, the use of either 48 V or 120 V would require modifications in the appliances to adapt them to this lower voltage, thus raising the cost of the appliance itself.

It seems reasonable to conclude that the use of dc in offices can be strongly advised, since it has been demonstrated to lead to a simplified system and to big savings. On the other hand, there are no reasons that would justify technically and economically the adoption of a dc system in private houses. However, future developments could occur that will urge reconsidering this choice. In this case, the voltage level of 230 V dc should be chosen for houses, because most loads in private houses are resistive and no changes would thus be required for them (the rms value of voltage is the same for ac and dc). Moreover, the use of this voltage level will not require replacement of the cables.
One such development that can be expected to have a big impact on this topic is local generation, like solar cells, fuel cells and micro-turbines. By using dc, it will be possible to connect these sources to the system in an easier way, by eliminating the AC/DC conversion stages necessary for connection to the ac system. This should lead to savings because of the higher efficiency achieved.
Another possible scenario that can be imagined is one in which dc is widely used for supplying offices, data centers and telecommunication facilities, leaving a smaller and smaller part of the distribution system to be supplied by ac. In this case, choosing dc also for residential systems (instead of having both ac and dc systems present at the same time) would thus make the system less complex. Again, the voltage level of 230 V dc should be chosen for houses.

In fact, this study has focused on the present situation, as far as loads, generation and structure of the system are considered. The analysis of the same topic in a scenario in which the structure of the distribution system has been changed by the introduction of dispersed generation could give somewhat different results and will be an interesting development of this study. Another interesting aspect that has not been considered here and would be interesting for future study is the possibility of actively controlling the interface between the dc system under consideration and the rest of the network. By adopting a PWM-controlled rectifier with IGBTs at the entrance of the system, a number of control functions could be implemented, including for example controlling the voltage for preventing overload situations. Finally, an aspect that needs to be analysed deeper in detail is the protection and grounding of the system.

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Appendix A
Programs for Voltage Drop Calculations

In this Appendix, the programs and the data used for the voltage drop calculations shown in Chapter 4 are reported. These include:

- the program "voltage_drop.m" written in Matlab that calculates the voltage drop;
- a subroutine "previous.m" called by the main program, that puts data in the correct format for the main program;
- matrix with the load data to be used in calculations for the ac system;
- matrix with the load data to be used in calculations for the dc system.

A.1 Main Program

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% This function calculates voltage drop and power losses (in percent value) for any number of feeders starting from a common switchgear,
% with any number of loads derived along the feeders at a whatever distance between them.
% The switchgear is connected to the substation by a cable whose parameters are specified at the beginning.
% The loads are derived along the feeder from a node. Each node has a progressive number from the switchgear to the end of the feeder,
% and the distance between two subsequent nodes is used by the program (parameter called "length").
% In a node more than one load can be present, and in the data matrix it is not important to put the node numbers in order.
% The subroutine "accorpa" will do it.
%
%
%                 Node#1      Node#2           Node#3            Node#4
% Feeder #1---------+-----------+----------------+------------------+
%                   |           |                |                  |
%                   |           |                |                  |
%                   +--+--+     +--+--+          +--+--+            +--+
%                      |  |        |  |             |  |               |
%                      |  |        |  |             |  |               |
%                      V  V        V  V             V  V               V
%                     P1  P2      P3  P4           P5  P6              P7
%
%
%                        L2                               L4
%                   |<--------->|                   |<---------------->|
%
%                L1                      L3
%          |<--------->|        |<---------------->|
%
%
%
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% matrix Load2=[feeder index, node index, load power [kW], length [m] (distance between two nodes),
% cross-section [sq.mm], angle between voltage and current (phi), type (1:single phase OR 3:three phase)]
% E is the rms voltage line-to-ground in AC system or the DC voltage, T the cable temperature in °C (i.e. 80 degrees for thermal overload)
% "swtch" is 1 for DC or 3 for AC supply (factor to calculate voltage drop on the connection cable between substation and switchgear in the
% 2 different cases)
```

```
function [drop_table]=voltage_drop(load2,E,T,swtch)

load=previous(load2);                    % calculates P, phi (phase angle) of a load equivalent to a group of loads connected to the same node
load(:,3)=load(:,3)*1000;               % transforms load power from [kW] to [W]
T0=20;                                  % °C (Celsius)
rho0=0.0178;                            % [Ohm * sq.mm / m] specific resistance at 20 °C
alfa=0.00323;                           % thermal coefficient for copper conductors
rho=rho0*(1+alfa*(T-T0));               % [Ohm * sq.mm / m] specific resistance at the given temperature
f=50;                                   % [Hz] AC frequency
x=0.1;                                  % [Ohm/km] specific reactance of the feeders (valid for both 1.5 sq.mm and 2.5 sq.mm cross sections)


% cable connecting (in our study case) the transformer to the switchgear features:
% cross section S=70 sq.mm, lenght l=20 m , r=0.443 Ohm/km at 20 °C, x=0.07 Ohm/km


rhocavo=0.443*(1+alfa*(T-T0));          % [Ohm * sq.mm / m] cable specific resistance at the given temperature
R=rhocavo*20*1.0e-3                    % connecting cable resistance
X=0.07*20*1.0e-3                       % connecting cable reactance

result=[];                              % initializes results table
Resistance=[];                          % initializes wire resistance table (values in Ohm)
Iquad=[];                               % initializes segment squared current vector
Itota0=[];                              % initializes active current vector
Itotr0=[];                              % initializes reactive current vector
type=[];                                % initializes matix of the factors to account for three phase or single phase loads

[num_load data_load]=size(load);

for i=1:num_load
    indexF=load(i,1);                   % feeder index
    indexL=load(i,2) ;                  % node index
    P=load(i,3);                        % power [W]
    l=load(i,4);                        % distance between nodes on the same feeder [m]
    S=load(i,5);                        % wire cross-section [mmq]
    fi=load(i,6) ;                      % angle between voltage and current in each node [rad]
    type1=load(i,7);                    % load type (1:single phase, 3:three phase)

    if type1==1                         % factor selection to account for load type
        kc=1;                           % single phase
    else
        kc=3;                           % three phase
    end
    load(i,8)=P/kc/E;                            % active current for each node
    load(i,9)=P/kc/E*sin(fi)/cos(fi) ;           % reactive current for each node
```

```
    type=[type;type1];                          % load type vector

        if type1==1                             % if the load is a single phase one
            Itota1=load(i,8);                   % active current ACTUALLY exiting from a node
            Itotr1=load(i,9);                   % reactive current ACTUALLY exiting from a node
        else                                    % else it is a three phase load
            Itota1=load(i,8)*3;                 % active current ACTUALLY exiting from a node
            Itotr1=load(i,9)*3;                 % reactive current ACTUALLY exiting from a node
        end

        Itota0=[Itota0;Itota1];                 % put real active currents in a vector
        Itotr0=[Itotr0;Itotr1];                 % put real reactive currents in a vector
end

% calculations for connecting substation to switchgear cable

        if swtch==1                        % factor to account for DC distribution system
            Itota=sum(Itota0)              % total active current that joins the switchgear (currents sum of ALL the feeders)
            Itotr=sum(Itotr0)              % total reactive current that joins the switchgear (sum of the currents along ALL the feeders)

        else                               % factor to account for AC distribution system
            Itota=sum(Itota0)/3;           % total active current that joins the switchgear (divided by 3 because the cable is 3-phase
                                           %% and only one wire is considered in the modelling
            Itotr=sum(Itotr0)/3;           % total reactive current " "
        end


Itot=(Itota^2+Itotr^2);                        % total current, SQUARED
PTOT=sum(load(:,3));                           % system total power

   if swtch==3                                 % selectcs ac case
        deltaVcavo=sqrt(3)*(R*Itota+X*Itotr) ;  % voltage drop along the cable
        deltaPcavo=3*R*(Itot);                 % power loss along the cable

   else                                        % select dc case
        deltaVcavo=2*(R*Itota+X*Itotr);        % voltage drop along the cable
        deltaPcavo=2*R*Itot;                   % power loss along the cable
   end


for i=1:num_load
    z=i;
    itra=load(i,8);
    itrr=load(i,9);
```

```
    while ((z<num_load) & (load(z+1,1)==load(z,1)))
        itra=itra+load(z+1,8);
        itrr=itrr+load(z+1,9);
        z=z+1;
    end

    load(i,10)=itra ;                          % active current on a feeder segment (between 2 nodes)
    load(i,11)=itrr ;                          % reactive current on a feeder segment (between 2 nodes)
end

for k=1:num_load                               % calculates each segment squared current

 Iquad1=(load(k,10)^2+load(k,11)^2);
 Iquad=[Iquad;Iquad1];                         % puts  each segment squared currents in a vector, to be used later

end

 z=1;
while z<=num_load
    if type(z)==1                             % accounts for single phase (or DC)
         kv=2;                                % factor for voltage drop (s.ph/dc)
         kp=2;                                % factor for power losses (s.ph/dc)
         kr=kv;                               % factor for resistances  (s.ph/dc)
    else                                      % accounts for three phase
         kv=sqrt(3);                          % factor for voltage drop (thr.ph)
         kp=3;                                % factor for power losses (thr.ph)
         kr=1;                                % factor for resistances  (thr.ph)
    end

    deltaV=kv*(rho/load(z,5)*load(z,4)*load(z,10)+x*load(z,4)*1.0e-3*load(z,11));   % calculates each segment voltage drop
                                                                                    %% "x*load(z,4)*1.0e-3" is the reactance for single wire
                                                                                    %%%  segment
    deltaP=kp*(rho/load(z,5)*load(z,4)*Iquad(z));                                   % calculates first segment power loss
    Ptot=load(z,3);                                                                 % first node active power
    IfeederMAX=sqrt(Iquad(z));                                                      % first segment current which is equal to the
                                                                                    %% maximum current crossing the ENTIRE feeder
    Res=kr*(rho/load(z,5)*load(z,4));                                               % first segment resistance

 % the Wire Resistances table contains: Feeder Index, Segment Index, Wire Segment Resistance (Ohm), Load Power (kW)

    Resistance=[Resistance;load(z,1) load(z,2) Res load(z,3)/1e3];                  % first segment [resistance] results


    while  z<num_load & load(z+1,1)==load(z,1)
    Ptot=Ptot+load(z+1,3);                                                                         %  adds next node active power
```

```
    deltaV=deltaV+kv*(rho/load(z+1,5)*load(z+1,4)*load(z+1,10)+x*load(z+1,4)*1.0e-3*load(z+1,11)); %  adds next segment voltage drop
                                                                                                   %% to the previous on the same feeder
    deltaP=deltaP+kp*(rho/load(z+1,5)*load(z+1,4)*Iquad(z+1));                                     %  adds next segment power loss
                                                                                                   %% to the previous on the same feeder
    Res=kr*(rho/load(z+1,5)*load(z+1,4));                                                          %  calculates next segment resistance
                                                                                                   %% WITHOUT adding it to the previous
    Resistance=[Resistance;load(z+1,1) load(z+1,2) Res load(z+1,3)/1e3];                           %  updates resistance matrix
                                                                                                   %%%of calculation
    z=z+1;
    end

    if type(z)==1                        % coefficient to account for single phase
        ke=1;
    else                                 % coefficient to account for three phase
        ke=sqrt(3);
    end

    deltaVPC=deltaV/ke/E*100;            % voltage drop percent along the feeder
    deltaPPC=deltaP/Ptot*100;            % power loss percent along the feeder

% distinguishes ac case from dc case in referring to line-to-ground or line-to-line
% voltage in connecting cable voltage drop percent value

    if swtch==3                                        % ac case
        Kcavo=sqrt(3);
    else                                               % dc case
        Kcavo=1;
    end

    deltaVTOTPC=deltaVPC+deltaVcavo/(Kcavo*E)*100;         % total percent voltage drop
    deltaPTOTPC=deltaPPC+deltaPcavo/PTOT*100;              % total percent power loss

% returns: feeder index, single phase/three phase type [1/3], Power [kW], feeder percent drop voltage
% (referred to line-to-ground voltage for single phase/DC and to line-to-line voltage for threephase), feeder percent power losses,
% feeder percent drop voltage plus main cable voltage drop,
% feeder percent power losses referred to single feeder power plus main cable p.l.referred to total system power,
% feeder current, feeder absolute voltage drop value (for later use in other programmes)


    result=[result;load(z,1) type(z) Ptot/1000 deltaVPC deltaPPC deltaVTOTPC deltaPTOTPC IfeederMAX deltaV];

    save Resistance Resistance;                       % Saves the wire resistances table in a file called ´Resistance.mat´ for later use
                                                      % Resistance is a matrix containing : feeder index, load index, segment resistance,
                                                      % power[kW]
```

```
    deltaV=0;
    deltaP=0;
    z=z+1;

end
save Itota Itota;    % saves system total active current to be used in subsequent calculations

disp 'feeder# index# Ptot[kW] deltaVPC deltaPPC deltaVTOTPC deltaPTOTPC IfeederMAX  deltaV'  % displays the written sentence
drop_table=result;

    totalPower=PTOT
    Icable=sqrt(Itot)
    deltaVcablepercent=deltaVcavo/Kcavo/E*100
    deltaPcablepercent=deltaPcavo/PTOT*100
```

A.2 Subroutine "previous.m"

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% This subroutine groups loads with the same node number (on the same feeder) in one
% load with corresponding active and reactive power. Returns the active power and
% the angle between voltage and current each node.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% matrix load=[feeder index, node index, load power [kW], length [m]
%(distance between two nodes),cross-section [sq.mm],angle between voltage and
% current(phi), type (1:single phase OR 3:three phase)]

function [risult]=previous(load)
    feeders=[];                         % initializes "feeders" matrix
    newload=[];                         % initializes "newload" matrix

    [maxrighe maxcolonne]=size(load);
    flag(1:maxrighe)=0;                 % creates a boolean array
    i=1;
    while i<=maxrighe                   % find feeder first and last element
        first=i;
        while i<maxrighe & load(i,1)==load(i+1,1)
            i=i+1;
        end
        last=i;
        feeders=[feeders; load(i,1) first last];    % saves results in "feeders"
                                                    %% matrix
        i=i+1;
    end

    [maxrighe maxcolonne]=size(feeders);
    conta=1;
    for i=1:maxrighe                     % for each feeder repeats calculations
                                         %% from first to last node
        first=feeders(i,2);
        last=feeders(i,3);
        if last>first
            for j=first:last             % find all the loads corresponding in the
                                         %% same node
                if flag(j)==0;
                    P=0;                 % calculates active power and phase angle
                                         %% for the first load
                    Q=0;
                    for k=j:last
                        if load(k,2)==load(j,2) & flag(k)==0 % calculates power and
                                                             %% angle for the others
                            P=P+load(k,3);
                            Q=Q+load(k,3)*tan(load(k,6));
                            flag(k)=1;
                        end
                    end
                    fi=atan(Q/P);
                    newload=[newload; load(j,:)];
                    newload(conta,3)=P;
                    newload(conta,6)=fi;
                    conta=conta+1;
                 end
            end
        else
            newload=[newload; load(first,:)];
            conta=conta+1;
            flag(first)=1;
        end
    end

    risult=newload;
```

A.3 Matrix "Load ac"

This matrix includes load data to be used for ac calculations: it has to be input to the main program as "load2".

Feeder index	Node number along the feeder	Power [kW]	Distance between subseq. nodes [m]	Wire cross section [mm^2]	Angle between voltage and current [rad]	Distrib. System type
2	1	1.3	15	2.5	0	1
3	1	4.5	19	2.5	0	3
4	1	4.7	22	2.5	0	3
5	1	1.3	15	2.5	0	1
6	1	2.0	15	2.5	0	1
7	1	0.072	5	1.5	-0.2181	1
7	2	0.072	5	1.5	-0.2181	1
7	3	0.072	5	1.5	-0.2181	1
7	4	0.072	5	1.5	-0.2181	1
7	5	0.072	5	1.5	-0.2181	1
7	6	0.072	5	1.5	-0.2181	1
7	7	0.072	5	1.5	-0.2181	1
7	8	0.072	5	1.5	-0.2181	1
7	9	0.072	5	1.5	-0.2181	1
7	10	0.052	5	1.5	-0.1745	1
7	11	0.052	5	1.5	-0.1745	1
7	12	0.052	5	1.5	-0.1745	1
7	13	0.052	5	1.5	-0.1745	1
7	14	0.052	5	1.5	-0.1745	1
7	15	0.052	5	1.5	-0.1745	1
7	16	0.052	5	1.5	-0.1745	1
8	1	0.18	10	1.5	0	1
8	2	0.18	5	1.5	0	1
8	3	0.18	2	1.5	0	1
8	4	0.18	1	1.5	0	1
8	5	0.18	4	1.5	0	1
8	1	0.03	10	1.5	0.8976	1
8	2	0.03	5	1.5	0.8976	1
8	3	0.03	2	1.5	0.8976	1
8	4	0.03	1	1.5	0.8976	1
8	5	0.03	4	1.5	0.8976	1
9	1	0.18	20	1.5	0	1
9	2	0.18	8	1.5	0	1
9	3	0.18	2	1.5	0	1
9	4	0.18	8	1.5	0	1
9	5	0.18	2	1.5	0	1
9	1	0.03	20	1.5	0.8976	1
9	2	0.03	8	1.5	0.8976	1
9	3	0.03	2	1.5	0.8976	1
9	4	0.03	8	1.5	0.8976	1
9	5	0.03	2	1.5	0.8976	1
11	1	0.18	16	1.5	0	1
11	2	0.18	4	1.5	0	1
11	1	0.03	16	1.5	0.8976	1
11	2	0.03	4	1.5	0.8976	1
12	1	0.18	5	1.5	0	1
12	2	0.18	3	1.5	0	1

12	3	0.18	2	1.5	0	1
12	4	0.18	2	1.5	0	1
12	1	0.03	5	1.5	0.8976	1
12	2	0.03	3	1.5	0.8976	1
12	3	0.03	2	1.5	0.8976	1
12	4	0.03	2	1.5	0.8976	1
13	1	0.18	20	1.5	0	1
13	2	0.18	3	1.5	0	1
13	3	0.18	3	1.5	0	1
13	4	0.18	1	1.5	0	1
13	5	0.18	3	1.5	0	1
13	1	0.03	20	1.5	0.8976	1
13	2	0.03	3	1.5	0.8976	1
13	3	0.03	3	1.5	0.8976	1
13	4	0.03	1	1.5	0.8976	1
13	5	0.03	3	1.5	0.8976	1
19	1	2.0	21	2.5	0.6435	1
20	1	0.9	14	1.5	0.1745	1
21	1	0.45	14	1.5	0.1745	1
22	1	1.8	14	1.5	0.1745	1
26	1	0.9	20	1.5	0.1745	1
27	1	0.1	20	1.5	0.6435	1
28	1	0.15	20	1.5	0.6435	1
29	1	0.15	20	1.5	0.6435	1
31	1	0.144	20	1.5	-0.2181	1
31	2	0.144	5	1.5	-0.2181	1
31	3	0.144	5	1.5	-0.2181	1
31	4	0.144	5	1.5	-0.2181	1
31	5	0.144	5	1.5	-0.2181	1
32	1	0.144	20	1.5	-0.2181	1
32	2	0.144	5	1.5	-0.2181	1
32	3	0.144	5	1.5	-0.2181	1
32	4	0.144	5	1.5	-0.2181	1
32	5	0.144	5	1.5	-0.2181	1
33	1	0.144	2.5	1.5	-0.2181	1
33	2	0.144	2.5	1.5	-0.2181	1
33	3	0.144	2.5	1.5	-0.2181	1
33	4	0.144	2.5	1.5	-0.2181	1
33	5	0.144	2.5	1.5	-0.2181	1
33	6	0.144	2.5	1.5	-0.2181	1
34	1	0.144	15	1.5	-0.2181	1
34	2	0.144	2.5	1.5	-0.2181	1
34	3	0.144	2.5	1.5	-0.2181	1
34	4	0.144	2.5	1.5	-0.2181	1
34	5	0.144	2.5	1.5	-0.2181	1
34	6	0.144	2.5	1.5	-0.2181	1
34	7	0.144	2.5	1.5	-0.2181	1
35	1	0.072	18	1.5	-0.2181	1
35	2	0.104	2	1.5	-0.1745	1
35	3	0.104	2	1.5	-0.1745	1
35	4	0.104	2	1.5	-0.1745	1
35	5	0.052	1	1.5	-0.1745	1
35	6	0.052	1	1.5	-0.1745	1
35	7	0.104	1	1.5	-0.1745	1
35	8	0.104	1	1.5	-0.1745	1
35	9	0.104	1	1.5	-0.1745	1
35	10	0.104	1	1.5	-0.1745	1

A.4 Matrix "Load dc"

This matrix includes load data to be used for dc calculations: it has to be input to the main program as "load2".

Feeder index	Node number along the feeder	Power [kW]	Distance between subseq. nodes [m]	Wire cross section [mm^2]	Angle between voltage and current [rad]	Distrib. System type
2	1	1.3	15	2.5	0	1
3	1	4.5	19	2.5	0	1
4	1	4.7	22	2.5	0	1
5	1	1.3	15	2.5	0	1
6	1	2.0	15	2.5	0	1
7	1	0.072	5	1.5	0	1
7	2	0.072	5	1.5	0	1
7	3	0.072	5	1.5	0	1
7	4	0.072	5	1.5	0	1
7	5	0.072	5	1.5	0	1
7	6	0.072	5	1.5	0	1
7	7	0.072	5	1.5	0	1
7	8	0.072	5	1.5	0	1
7	9	0.072	5	1.5	0	1
7	10	0.052	5	1.5	0	1
7	11	0.052	5	1.5	0	1
7	12	0.052	5	1.5	0	1
7	13	0.052	5	1.5	0	1
7	14	0.052	5	1.5	0	1
7	15	0.052	5	1.5	0	1
7	16	0.052	5	1.5	0	1
8	1	0.18	10	1.5	0	1
8	2	0.18	5	1.5	0	1
8	3	0.18	2	1.5	0	1
8	4	0.18	1	1.5	0	1
8	5	0.18	4	1.5	0	1
8	1	0.03	10	1.5	0	1
8	2	0.03	5	1.5	0	1
8	3	0.03	2	1.5	0	1
8	4	0.03	1	1.5	0	1
8	5	0.03	4	1.5	0	1
9	1	0.18	20	1.5	0	1
9	2	0.18	8	1.5	0	1
9	3	0.18	2	1.5	0	1
9	4	0.18	8	1.5	0	1
9	5	0.18	2	1.5	0	1
9	1	0.03	20	1.5	0	1
9	2	0.03	8	1.5	0	1
9	3	0.03	2	1.5	0	1
9	4	0.03	8	1.5	0	1
9	5	0.03	2	1.5	0	1
11	1	0.18	16	1.5	0	1
11	2	0.18	4	1.5	0	1
11	1	0.03	16	1.5	0	1
11	2	0.03	4	1.5	0	1
12	1	0.18	5	1.5	0	1
12	2	0.18	3	1.5	0	1

12	3	0.18	2	1.5	0	1
12	4	0.18	2	1.5	0	1
12	1	0.03	5	1.5	0	1
12	2	0.03	3	1.5	0	1
12	3	0.03	2	1.5	0	1
12	4	0.03	2	1.5	0	1
13	1	0.18	20	1.5	0	1
13	2	0.18	3	1.5	0	1
13	3	0.18	3	1.5	0	1
13	4	0.18	1	1.5	0	1
13	5	0.18	3	1.5	0	1
13	1	0.03	20	1.5	0	1
13	2	0.03	3	1.5	0	1
13	3	0.03	3	1.5	0	1
13	4	0.03	1	1.5	0	1
13	5	0.03	3	1.5	0	1
19	1	2.0	21	2.5	0	1
20	1	0.9	14	1.5	0	1
21	1	0.45	14	1.5	0	1
22	1	1.8	14	1.5	0	1
26	1	0.9	20	1.5	0	1
27	1	0.1	20	1.5	0	1
28	1	0.15	20	1.5	0	1
29	1	0.15	20	1.5	0	1
31	1	0.144	20	1.5	0	1
31	2	0.144	5	1.5	0	1
31	3	0.144	5	1.5	0	1
31	4	0.144	5	1.5	0	1
31	5	0.144	5	1.5	0	1
32	1	0.144	20	1.5	0	1
32	2	0.144	5	1.5	0	1
32	3	0.144	5	1.5	0	1
32	4	0.144	5	1.5	0	1
32	5	0.144	5	1.5	0	1
33	1	0.144	2.5	1.5	0	1
33	2	0.144	2.5	1.5	0	1
33	3	0.144	2.5	1.5	0	1
33	4	0.144	2.5	1.5	0	1
33	5	0.144	2.5	1.5	0	1
33	6	0.144	2.5	1.5	0	1
34	1	0.144	15	1.5	0	1
34	2	0.144	2.5	1.5	0	1
34	3	0.144	2.5	1.5	0	1
34	4	0.144	2.5	1.5	0	1
34	5	0.144	2.5	1.5	0	1
34	6	0.144	2.5	1.5	0	1
34	7	0.144	2.5	1.5	0	1
35	1	0.072	18	1.5	0	1
35	2	0.104	2	1.5	0	1
35	3	0.104	2	1.5	0	1
35	4	0.104	2	1.5	0	1
35	5	0.052	1	1.5	0	1
35	6	0.052	1	1.5	0	1
35	7	0.104	1	1.5	0	1
35	8	0.104	1	1.5	0	1
35	9	0.104	1	1.5	0	1
35	10	0.104	1	1.5	0	1