Supply Voltage Effects on the Operation of Residential Air Conditioning Appliances: Experimental Analysis

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Abstract. The deregulation of the electric energy market and the difficulties related to distribution network such as the congestion, the increasing growth of the installed power density in urban zones, the growth of the delivery-provided energy and the spectacular increase that the peak power experiences are new problems to be faced by the utility engineers. So, the knowledge of the load behaviour is becoming more and more important in the planning and operation of the electric energy distribution network.

In this paper, the influence of domestic air conditioning equipment, one of the most energy consuming domestic loads in Spain, in the electrical energy distribution network is addressed. The research is focused on the analysis of the voltage supply effects on the operation of home air conditioning appliances from an experimental point of view.

Key words

Voltage regulation, Air conditioning equipment, Load modelling, Distribution network.

1. Introduction

The massive installation of residential air conditioning units in Spain and especially Andalusia has motivated the interest of local utilities to characterize the behaviour of this type of electrical load. The use of this electrical appliance has been growing within the residential sector during the last years due to its cost reduction. This change in the composition of classical residential loads can produce a change of the consumption pattern, obviously affecting both the planning and operation of the power system. In this sense, one of the important tasks to be solved is to characterize the behaviour of the residential air conditioning units versus voltage variations.

Two types of air conditioning technologies are usually installed in the residential sector. The first one is based on a hysteresis control of the temperature, performed by switching on/off the motor driving the compressor of the air conditioning unit. On the other hand, the inverter based applications are also used; in this type of appliance, the motor driving the compressor is fed through an inverter that adjusts the frequency in order to precisely match the requirements of the thermodynamic process. In spite of the energy savings that can be achieved with the latter technology, the former type of air conditioning units is more widespread installed due to its reduced initial cost.

This work is the continuation of the paper [1] which analyzes from a theoretical point of view the two type of air conditioning technologies usually installed in the residential sector. The paper content is as follows. First, a description of the laboratory tests is included. Then, the electrical equipment used in the experimental validation of the theoretical studies is described. Finally, the results for the two types of air conditioning technologies, the main conclusions and some suggestions for future work are presented.

2. Description of Laboratory Tests

The objective of the laboratory tests is to determine the influence of steady-state voltage variations in the operation of residential air conditioning appliances. The tests are focused on the voltage dependence of four main magnitudes:

- Demanded load current.
- Power factor.
- Active power demand.

Fig. 1 shows the diagram of the laboratory benchmark system. The air conditioning appliance is supplied through an autotransformer with a variable relation of turns (variac), so that it is possible to control the secondary voltage. Although other means to obtain a variable supply voltage for the air conditioning appliance, such as electronic based power supplies, it has been considered that a transformer is more suitable. The autotransformer not only reproduces better the real conditions of the appliance supply (almost sinusoidal voltage waveform and linear network impedance) but

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also does not introduce undesired effects such as high frequency voltage harmonics.

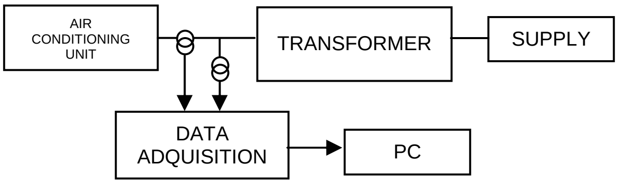

Fig. 1. Diagram of the laboratory test bench.

Two different types of air conditioning appliances have been studied in the electrical power laboratory:

- Conventional appliances. In this case, the inner temperature is controlled using a hysteresis band around the reference temperature adjusted by the final user. As a consequence, the compressor of the heat pump is switched on/off depending on the values of the inner and reference temperatures. The main disadvantage of this application is the continuous switching operations of the compressor when the reference temperature has been set up. This operation mode leads to an increment of electrical power losses, mechanical stress of the compressor, etc. On the other hand, the economic cost of this type of home air conditioning unit is quite low compared to the inverter based types.

- Inverter based appliances. The temperature is controlled in this case by adapting continuously the compressor operation to the heat pump requirements. For this purpose, the electrical motor driving the compressor is fed up through an inverter that changes the frequency in the proper manner. The main advantage of this type appliance is that is more efficient that the conventional units. However, this type of units is not as popular as conventional ones because of their higher initial cost.

It is interesting to note that the magnitudes to be measured not only are dependant on the voltage variations but also to both the inner and outer temperatures. However, neither measurement nor control of these parameters during the performed tests exist. Only the reference temperature, set by the final user, is a control variable during the tests. In this sense, further developments should include measurement or control of the actual inner and outer temperatures.

In order to establish adequate comparisons between the obtained data from the tests in absence of inner and outer temperature measurements, the tests have been performed starting from similar electrical conditions. So, the rated voltage has been always used to starting the operation of the equipment, and once the rated current of operation has been established, the voltage is modified to the desired value controlling the autotransformer.

3. Description of test equipment

Two commercial air conditioning appliances based on heat pump thermodynamic cycle, with a capacity of 3.5 kW (refrigeration) - 4 kW (heating) and 1 kW of electrical rated power have been tested in the electric power laboratory. Table 1 summarizes the main characteristics of both conventional and inverter based appliances.

Table 1. Technical characteristics of the conventional and inverter based air conditioning appliances.

Function		Cool	Heat
Supply		~/N, 230 V, 50 Hz	
Capacity (kW)		3.5	3.9
Input (kW)		1.09	1.08
Weight	Inside (kg)	10	
	Outside (kg)	40	
IP Code	Inside	IP 20	
	Outside	IP 24	

It is interesting to note that the units have the same rated characteristics. However, the technology applied in each unit is quite different. The unit based on a hysteresis control of the temperature is composed by a single-phase induction motor with a starting capacitor. The technical documentation of this air conditioning unit reveals that this capacitor is not only devoted to the starting operation but also to the reactive power compensation task during normal operation. The motor front end is connected to the power supply through a contactor dedicated to switch it on/off depending on the hysteresis control of the temperature as shown in Fig. 2.

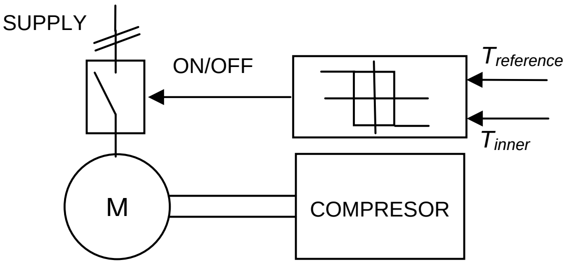

Figure 2. Hysteresis control of an air conditioning compressor.

On the other hand, the unit based on inverter technology is composed by a three-phase induction motor. This motor is fed through a voltage source inverter (VSI) connected to the power supply through a single-phase full-wave rectifier with a capacitive DC-link as shown in Fig. 3.

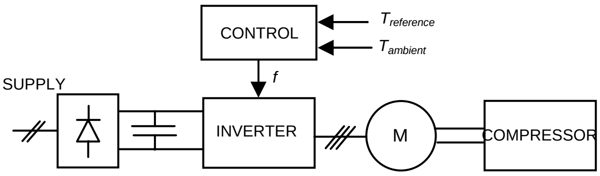

Figure 3. Inverter control of an air conditioning compressor.

Fig. 4 shows the laboratory arrangement used for the tests of these electrical loads. In this photo, both the internal and external units of the air conditioning appliances, the autotransformer used to feed up these loads, and the measurement equipment based on a power quality analyzer can be seen. The autotransformer data are shown in Table 2.

Figure 4. Laboratory arrangement.

Table 2. Autotransformer electrical data.

Rated power (kVA)	1.5
Frequency (Hz)	50
Input voltage (V)	250
Output voltage (V)	0 – 250
IP Code	IP 00

4. Experimental results

This section presents the results of the proposed experimental validation of the theoretical results.

A. Conventional Air Condition Appliances

Figures 5 to 7 show the dependence of the demanded current, active power and power factor with respect to the voltage supply. Note that, as stated in a previous section, the experiments have been performed with different reference temperatures, being no control of the inner or outer temperature. The reference temperatures should be within the interval from 21ºC to 24ºC. However, a wider temperature interval ranging from 22ºC to 28ºC has been studied in order to better asses the equipment behaviour.

The following conclusions can be derived analyzing the previous figures:

- The current demanded by the conventional unit in case of voltage reduction is higher than the rated current. However, the active and reactive power consumptions are reduced compared to their respective rated values.

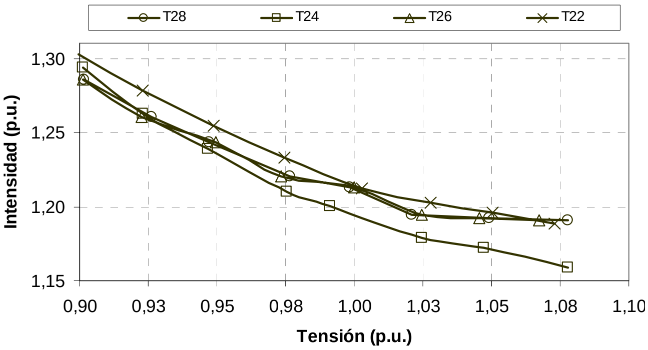

Figure 5. Conventional unit: Demanded current as a function of the supplied voltage [0.9-1.1] p.u. and the reference temperature.

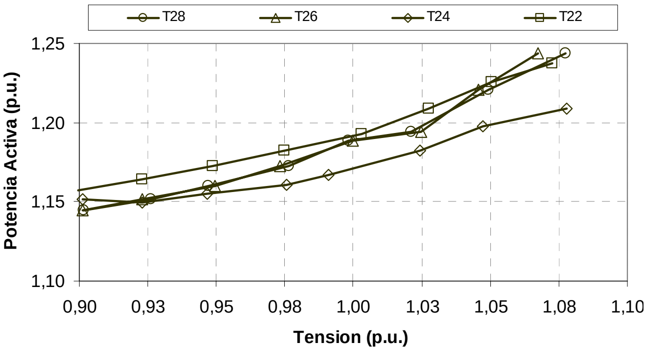

Figure 6. Conventional unit: Active power as a function of the supplied voltage [0.9-1.1] p.u. and the reference temperature.

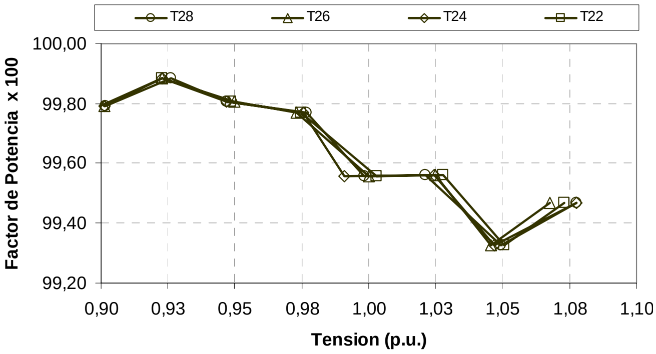

Figure 7. Conventional unit: Power factor as a function of the supplied voltage [0.9-1.1] p.u. and the reference temperature.

- The power factor of the unit is almost constant for the voltage interval used in these experiments. In this sense, the capacitor design is quite accurate.

It is interesting to note that these experimental results are perfectly correlated to the theoretical ones presented in the companion paper [1].

The previous results correspond to voltage variations within ±10% of the rated voltage. In fact, this is the permitted limit of the voltage variations in public distribution networks imposed by the European Normative EN50160 [2]. However, to asses the unit behaviour in case of lower voltages and their contribution to the voltage collapse phenomenon [3,4] should be interesting to further reduce the lower voltage limit. In this sense, figures 8 to 10 present the results in case of a voltage range varying from 0.75 p.u to 1.1 p.u. of the rated voltage.

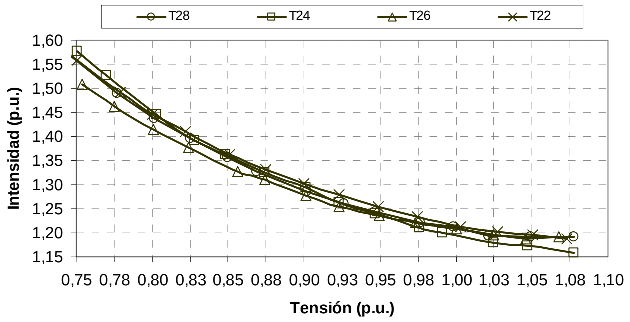

Figure 8. Conventional unit: Demanded current as a function of the supplied voltage [0.75-1.1] p.u. and the reference temperature.

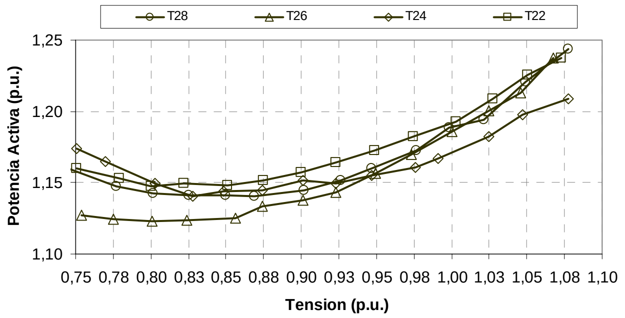

Figure 9. Conventional unit: Active power as a function of the supplied voltage [0.75-1.1] p.u. and the reference temperature.

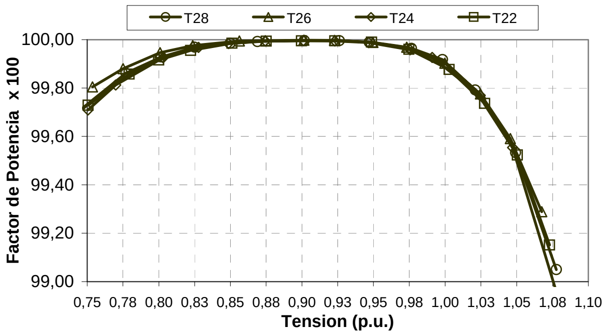

Figure 10. Conventional unit: Power factor as a function of the supplied voltage [0.75-1.1] p.u. and the reference temperature.

In case of analyzing this wider range of voltage variations, the following comments can be pointed out:

- The demanded current presents the same behaviour that in the previously analyzed voltage variations range. However, Fig. 8 reveals that in case of low voltages, the demanded current increases considerably.
- The active power demanded by the conventional units in case of low voltages, i.e. below 0.9 p.u., does not follow the behaviour previously described. Fig. 9 shows that the active power increases in these cases. Assuming that the power factor is almost constant, as seen in Fig. 10, the active power equals the apparent power. Thus, the increase of active power is produced because the voltage decrease is compensated by an increase in the demanded current.
- Using the experimental data obtained in the laboratory, the computation of the mathematical expressions correlating current versus voltage can be derived. This expression is critical to obtain an adequate load model representation that can be used in planning or operating tasks. The apparent power can be formulated as [5]:

$$S = Y_S U^2 + I_S U + S_S \tag{1}$$

Thus, the load is represented by a combination of simple loads of constant admittance-impedance (Y_S -Z_S), constant source current (I_S) and constant apparent power (S_S). In the same way, it is possible to obtain a expression of the demanded current as:

$$I = \frac{S}{U} = Y_S U \; + I_S + \frac{S_S}{U} \tag{2}$$

Table 3 shows the value of these parameters that better fits the obtained experimental data.

Table 3.Conventional unit: obtained parameters from experimental data.

Parameters		Temperature			
		28 ºC	26ºC	24ºC	22ºC
Current	Y_S	2.65	2.42	2.44	2.17
	I_S	-4.55	-4.10	-4.35	-3.70
	S_S	3.11	2.89	3.10	2.74

B. Inverter Based Air Condition Appliances

Figures 11 to 13 show the dependence of the demanded current, active power and power factor with respect to the supply voltage. These curves have been represented versus the supplied voltage considering the reference temperature as a parameter.

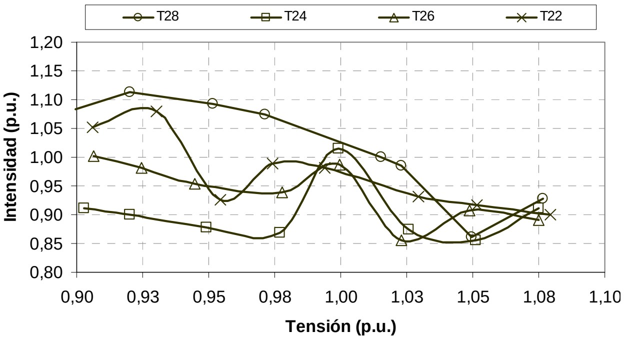

Figure 11. Inverter based unit: Demanded current as a function of the supplied voltage [0.9-1.1] p.u. and the reference temperature.

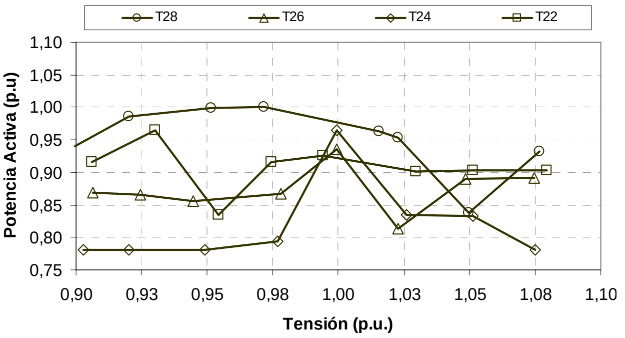

Figure 12. Inverter based unit: Active power as a function of the supplied voltage [0.9-1.1] p.u. and the reference temperature.

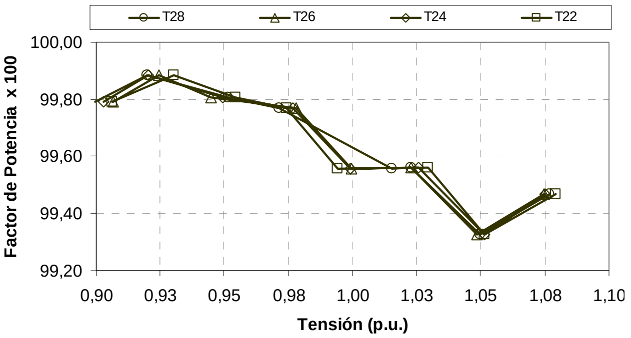

Figure 13. Inverter based unit: Power factor as a function of the supplied voltage [0.9-1.1] p.u. and the reference temperature.

The following comments can be pointed out from the obtained experimental data:

- The demanded current and active power does not follow a clear behaviour with respect to the voltage variations. In this sense, a lot of points out of the trend curve determined by the major part of the experimental data are advised. This fact can be motivated by the action of the control system that continuously regulates the frequency of the motor driving the compressor unit.

- The power factor of this type of units is again almost one. However, in this case a small amount of reactive power is injected to the power system. This fact is motivated by the capacitor installed in the DC-link between the unit mains and the inverter.

Table 4 shows the parameters used in the correlation between the demanded current and the voltage. Note that the parameters are in this case quite scattered with respect to the temperature due to the behaviour of the curves shown in Fig. 11.

Table 4. Inverter based unit: obtained parameters from experimental data.

Parameters		Temperature			
		28 ºC	26ºC	24ºC	22ºC
Current	Y_S	-5.62	1.28	3.95	-0.50
	I_S	11.06	-2.19	-7.01	1.10
	S_S	-4.41	1.83	3.93	0.36

5. Conclusions

The main conclusions derived from this experimental approach focused on the effects of the voltage variations on the operation of home air conditioning appliances are summarized as follows:

- Conventional appliance
    - The air conditioning load can be successfully modelled as a combination of three simple constant loads (*Z*, *I* and *S*).
    - A moderate voltage reduction ($\Delta U \leq 10\%$) increases the current load and reduces the power demand. This behaviour has been theoretically fully explained and validated in an experimental study.
    - Higher voltage reductions increase the reactive power demand as the capacitor drastically reduces the reactive power compensation.
- Inverter appliance
    - From an energy efficiency point of view, this type of equipment is more suitable than the conventional one, because the compressor always work in the optimal operating point required by the thermodynamic process. Nevertheless, this type of devices is a non-linear load, generating harmonic currents leading to a number of well-know problems.
    - A greater dispersion in the experimental results exists, justified by the actuation of the control system of the equipment that continuously varies of the frequency of the motor driving the compressor.
    - An increase of the demanded current exists when voltage variations occurs as in the case of conventional units.
    - This type of loads can be modelled as constant power loads in case of voltage variations lower than 10% of the rated voltage. In spite of this fact has not been clearly appreciated in the developed experimental study, the theoretical analysis confirms this assumption. In case of deeper voltage variations, this equipment usually is disconnected automatically by the undervoltage relay associated to the DC-link. In this sense, the inverter based air conditioning units are not as critical as the conventional ones in case of major voltage variations.

It is important to note that the experiments have been performed without any measurement or control of the inner and outer temperatures. In this sense, a line of future research will be to include in the modelization of the air conditioning loads the influence of these two new variables.

Acknowledgement

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