ANALYSIS OF IMPACT OF RESIDENTIAL AIR CONDITIONERS ON DISTRIBUTION SYSTEMS

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***Abstract* – Air conditioners deserve special attention, because they represent a significant part of the power system load, mainly in high temperature regions. This work takes into account conventional and variable-speed types, as the latter one presents two possible arrangements i.e. with and without undervoltage protection. The modeling of equipments is analyzed for simulation purposes, as a novel representation of variable-speed units with undervoltage protection is introduced. The behavior of each air conditioner is verified in steady state operation considering typical power quality and voltage disturbances that occur in power systems such as voltage sags and interruptions. Furthermore, the influence of the aforementioned equipment on the power system is analyzed within the context of a distribution network.**

***Keywords* - air conditioning, dynamic response, load modeling, power system dynamic stability.**

I. INTRODUCTION

The impact of air conditioners on power systems has been intensively analyzed by engineers during many years for load modeling purposes and planning of utility distribution systems [1]. Such influence is not supposed to be neglected, once that they represent a significant part of the overall system load, mainly in high temperature regions.

Air conditioners can be classified in either conventional type or variable-speed type. Conventional air conditioners employ an asymmetrical two-phase motor with a starting capacitor. They operate with constant power independently of room temperature, because the compressor speed control is not present, as it is simply turned on/off by a thermostat. On the other hand, variable-speed devices are supplied by frequency converters that automatically increase or decrease the compressor speed according to the preset temperature. When the room temperature increases, the speed and consequently the electric energy consumption also do. Otherwise when the temperature goes down, the speed decreases, reducing the power demand from the system.

In some cases, manufacturers offer an energy saving of 13% yearly for variable-speed air conditioners in comparison with conventional ones of same capacity. This is because normally the power electronic device is started with only 30% of the rated capacity. The speed adjustment is a function of the room temperature, and is sometimes accomplished using fuzzy logic principles [2].

The main focus of this paper is to present the modeling of both types of air conditioner in order to propose case studies and evaluate their dynamic response in front of power system disturbances. Furthermore two arrangements for variable-speed air conditioners are analyzed. The first model only accomplishes the common function of a PWM frequency converter, and the second one has protection against undervoltage. The models described in this work are based on time domain, since the dynamic characteristics of mechanical and electrical parameters can be adequately represented, implying more reliable results for power quality studies [3]. In a second instance, the models are supposed to replace the typical representation involving impedance, current, and constant power.

II. AIR CONDITIONER MODELING

A. Compressor Caracteristics

The compressor corresponds to the major component of any air conditioner because it compresses the freezing gas responsible for heat exchanges. For the driving motor, such load has different behavior during the startup and steady state operation.

In the starting condition, the torque-speed characteristic is quadratic with an initial torque around 30%. However, when the equipment is running, torque becomes constant with speed due to the compression of the freezing gas. Design engineers believe that the mechanical torque will remain relatively constant during the stall situation [4].

Since the compressor presents low inertia and constant torque during steady state operation, air conditioners tend to demand more power from the system during disturbances. This mechanism may explain some of the voltage collapse incidents reported in [5] and [6], and the delayed recovery of the transmission voltage following normally cleared multi-phase faults as reported by Florida Power and Light Company [4] and Southern California Edison Company [7].

B. Conventional Air Conditioners

In a conventional air conditioner, the compressor is driven by an asymmetrical two-phase induction motor with a starting capacitor. The stator is composed by two windings, as shown in Fig. 1. A main winding is responsible for the running condition, with positive sequence voltage. An auxiliary winding is used for startup, with negative sequence voltage. Capacitor *C* has two functions, that is, to help the motor start and to correct power factor during steady state operation. Since it is designed for the motor operation at full speed, the starting torque is reduced.

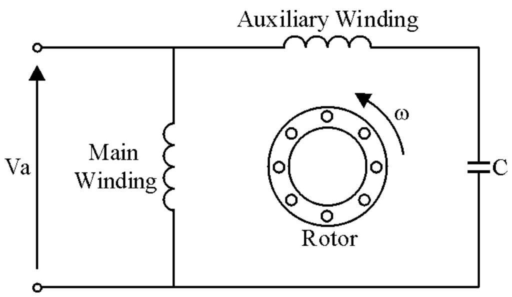

Fig. 1 Physical arrangement of the asymmetrical two-phase induction motor.

C. Variable-Speed Air Conditioners

Variable-speed air conditioners correspond to an improvement of the previous model, where a three-phase induction motor is used instead, supplied by a frequency converter with single-phase input, as energy consumption can be controlled according to the room temperature. A typical schematic is shown in Fig. 2.

It is believed that the employment of such equipment is supposed to increase significantly in the next few years since energy saving may become a priority for consumers. A research accomplished in 1999 reported that 86% of air conditioners in the Japanese power grid are of this type [8].

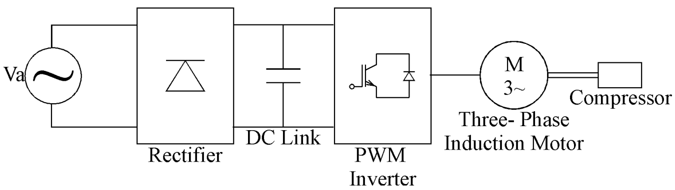

Fig. 2 Schematic representation of variable-speed air conditioners.

D. Variable-Speed Air Conditioners with Undervoltage Protection

This work analyzes two arrangements for the variable-speed air conditioner. The first one only accomplishes the common function of a frequency converter with PWM commutation. The second one was produced in Asia by Keling Electric [2], using a protection strategy against system undervoltage.

The PWM technique is intensively used in inverters, and the switching instant is determined by the comparison between a sinusoidal signal and a triangle wave. When the sinusoidal reference is higher than the triangle carrier, the comparator output turns the semiconductor device on, otherwise it is turned off.

It is important to mention that the sinusoidal wave frequency determines the fundamental frequency of the voltage across the inverter mains. Therefore the inverter output frequency must vary in order to control the induction motor speed. However, the voltage must change so that the proper volts/hertz ratio is maintained constant, implying constant air gap flux and electromagnetic torque [10].

In low frequencies, the stator current increases causing a larger voltage drop across stator resistance R_s. Then the motor input voltage must reach a given boost voltage V_o. Taking this into account, inverters may have two voltage versus frequency characteristics i.e. linear offset or nonlinear, according to Fig. 3. The linear characteristic can not be applied due to the boost voltage.

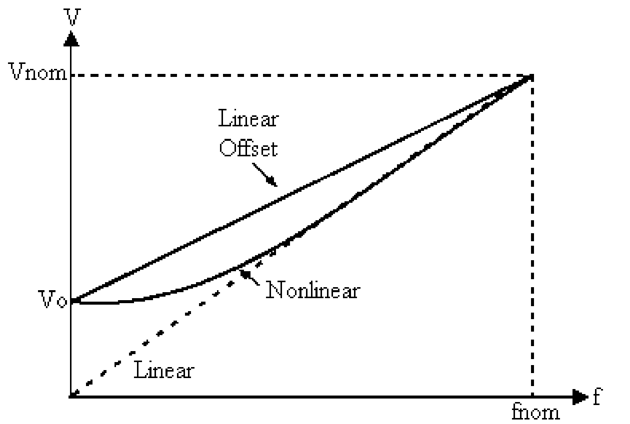

Fig. 3. Adjustment strategies for *V/f* characteristics to keep the air gap flux constant.

Protecting against undervoltage consists in decreasing the operation frequency when the dc link voltage is reduced, keeping the volts/hertz ratio constant and preserving the electromagnetic torque in the induction motor. When the frequency decreases, there is a reduction in the motor speed, causing the mechanical power to be reduced as well. When the voltage level is reduced and the system is threatened by the voltage collapse phenomenon, the reduction on the power demand of such equipment is a belief.

The modeling of air conditioners with undervoltage protection has not yet been developed and evaluated in studies that consider the power quality point of view. This is supposed to be the main contribution of this work and is discussed as follows.

E. On The Modeling of Variable-Speed Air Conditioners with Undervoltage Protection

When the disturbance occurs, the calculation of the new operation frequency is obtained using the acceleration ramp represented in Fig. 4, as the following expression is given:

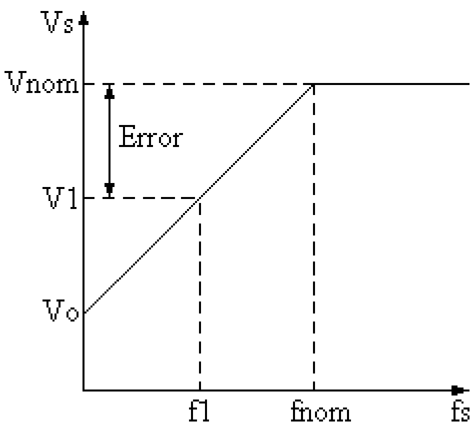

Fig. 4. Acceleration ramp.

$$V_{nom} = V_o + kf_{nom} \tag{1}$$

where:
V_{nom} – rated output voltage of the inverter [V];
V_o – boost voltage [V];
k – voltage gain per frequency unit [V/Hz];
f_{nom} – rated operation frequency [Hz].

The angular coefficient k is given by:

$$k = \frac{V_{nom} - V_0}{f_{nom}} \tag{2}$$

If the voltage decreases to V_1, the frequency becomes f_1, and expression (2) is written as:

$$k = \frac{V_{nom} - V_1}{f_{nom} - f_1} \tag{3}$$

From (3), the new operation frequency f_1 can be obtained as a function of k, which depends on the boost voltage according to (2), and also on the error between V_{nom} and V_1.

$$f_1 = f_{nom} - \frac{\text{error}}{k} \tag{4}$$

When the error is null, the operation frequency is f_{nom}. Since the angular speed ω_1 can be given as function of frequency f_1, the sinusoidal reference of the PWM control can be represented by (5).

$$v_r = \sqrt{2} V_r \sin(\omega_1 t) \tag{5}$$

where:
V_r – amplitude of the reference voltage [V];
ω_1 – updated angular speed [rad/s];
t – time [s].

Considering that v_r rotates anticlockwise around a horizontal reference axis with angular speed ω_1 describing an angle ϕ, expression (6) results.

$$\phi = \omega_1 t \tag{6}$$

Substituting (6) in (5) gives:

$$v_r = \sqrt{2} V_r \sin \phi \tag{7}$$

Since ω_1 changes when there is a voltage variation, one can rewrite (6) as:

$$d\phi = \omega_1 dt \tag{8}$$

Expression (8) can be rearranged as:

$$\phi = \int \omega_1 dt \tag{9}$$

The aforementioned expressions can be used to implement the block diagram shown in Fig. 5, where V_d and V_d' are the actual and desired voltages across the dc link, whose values are $\sqrt{2}V_{nom}$ and $\sqrt{2}V_1$, respectively.

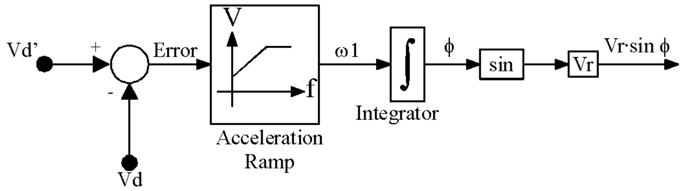

Fig. 5. Block diagram representing *V/f* control.

III. ANALYSIS OF AIR CONDITIONING LOAD AS PART OF A DISTRIBUTION NETWORK

The system shown in Fig. 6 is composed by a 69kV transmission line connected to the substation at bus 4, as the distribution network supplied by transformer T_2 derives. It contains four 50kVA transformers, whose loading is 50kVA at 0.9 lag. The load distribution is defined as in [11], where 25% is due to air conditioning, 5% is represented by refrigerators, and the rest is concerned with static loads related to lighting and heating.

For power system studies, utilities may consider the active power demand as 78% due to constant current-type loads and 22% due to constant impedance-type loads, and the whole reactive power demand is due to constant impedance-type loads. Furthermore, for a residential distribution network in a high temperature region where air conditioners are abundant, the transformer loading due to static loads is 70% [11]. To represent the power system under extreme situation, the transformers are assumed to operate at full load. Additionally, the saturation effects and the core nonlinearity are considered in the analysis.

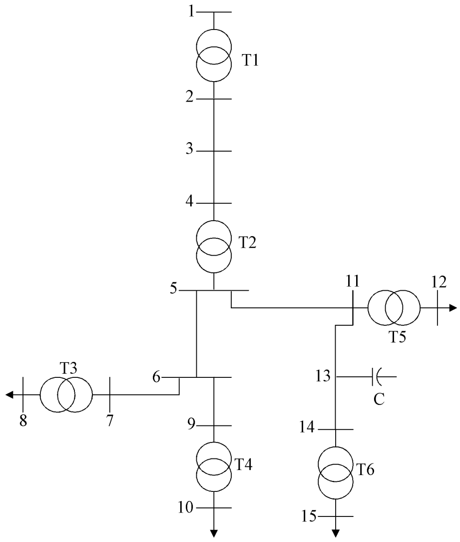

Fig. 6. Distribution power system.

A. Fault Occurrence

Considering that the air conditioning load is composed only by conventional units, the active power in steady state condition across the secondary side of transformer T_2 is 127kW, as shown in Fig. 7. When the fault occurs, the active power is reduced to 100kW, since less active power is demanded due to the static load when voltage drops to 0.81pu.

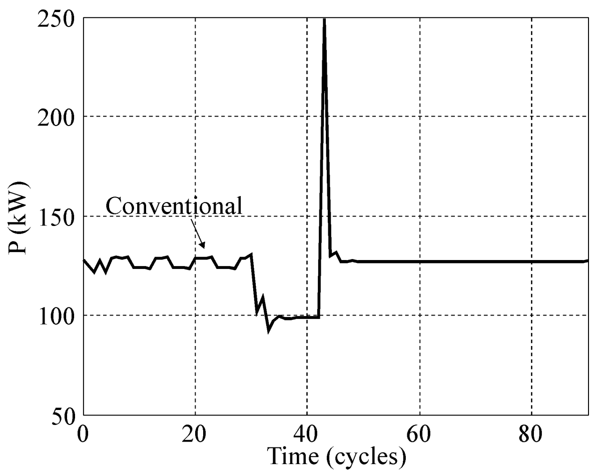

Fig. 7. Active power for conventional air conditioners

Similar analysis can be performed in Fig. 8 replacing conventional air conditioners by variable-speed equipment. If the normal-type arrangement is considered, the active power is reduced to 95kW. Otherwise, if adapted units represent the load, it drops to 64kW, which corresponds to the best performance during the fault.

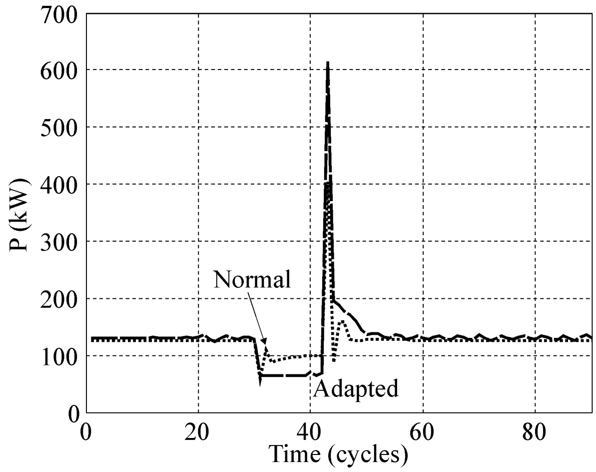

Fig. 8. Active power for variable-speed air conditioners.

For conventional air conditioners, the reactive power in steady state operation is 102kvar, which decreases to 92kvar for a short period during the fault.

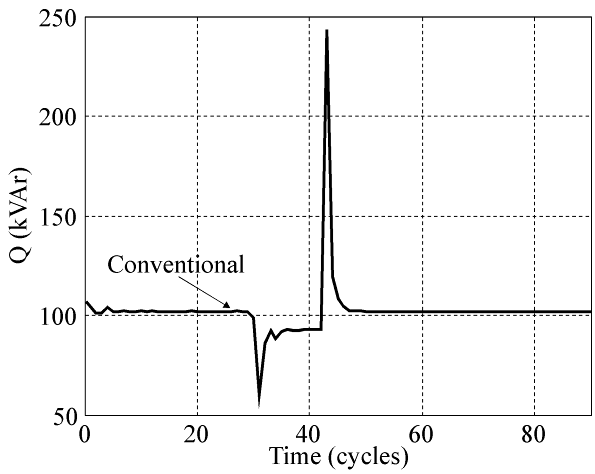

Fig. 9. Reactive power for conventional air conditioners.

For the normal and adapted arrangements of variable-speed air conditioner, reactive power is decreased to 70kvar and 50kvar, respectively.

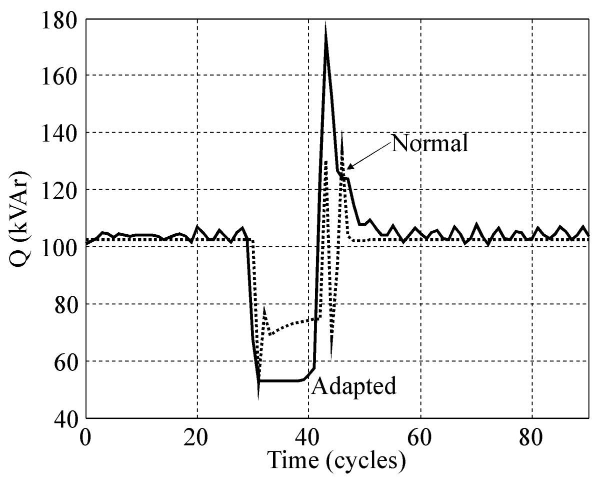

Fig. 10. Reactive power for variable-speed air conditioners.

In the aforementioned situations, there is a sudden increase in the active power at the end of the disturbance due to the compressor rotation speed, which is reduced when the fault occurs.

IV. CONCLUSION

Variable-speed air conditioners can be very attractive because temperature control is a desirable characteristic that makes the rational use of energy possible. The starting operation does not need to occur at full load, and there is also the adjustment of the necessary power in agreement with the environment temperature. However, such equipment offers two main disadvantages i.e. higher harmonic distortion and cost when compared to the conventional-type air conditioner.

Another advantage of such equipment over the conventional configuration is the behavior during voltage sags. The latter air conditioner absorbs high amount of active and reactive power, while the former one maintains the power flow stable until the utility voltage is normalized. However it demands high amount of active power to recharge the capacitor. Variable-speed air conditioners use a frequency converter with sinusoidal pulse width modulation, as two arrangements are possible. The first configuration does not present protection against undervoltage, and has been thoroughly studied in previous works. The second one accomplishes this function by adjusting the volts/hertz ratio for the motor, monitoring the dc link voltage to control the operation frequency and keep the developed torque constant.

The adapted arrangement has the advantage of minimizing the power transferred to the load when the dc link voltage is reduced. An air conditioner that employs this technique absorbs a larger amount of active and reactive power from the system when the voltage level is restored, as this situation is analogous to the motor startup. However, its application is still recommended because when the system voltage is low, the power demand is also lower than in normal condition.

The analysis of a distribution network with transformers at full load has shown that variable-speed units demand less active power when the utility voltage is reduced (for instance, due to fault occurrence), which may be desirable for generators under this condition.

ACKNOWLEDGEMENT

The authors would like to acknowledge CAPES for the financial support to this work.

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