INTERNATIONAL SCIENTIFIC CONFERENCE CIBV 2014
7-8 November 2014, Braşov

ON ELECTRICAL ENERGY EFFICIENCY IN BUILDINGS

M. BUZDUGAN[1] **H. BĂLAN**[2]

Abstract: *The paper deals with electrical energy efficiency in buildings. In the introductory section the main aspects of auditing electrical energy systems in buildings is addressed. In the second section the main sources of power losses in induction motors along with some features of the modern efficient inductor motors are briefly presented. The third one is devoted to the main topologies of variable speed electrical drives in buildings equipment (i.e. square wave and phase width modulation inverters). The final section deals with power quality issues determined by the variable speed drives in buildings (especially in air handling units, pumping and lighting). Concluding it can be noticed that even if variable speed electric drives contribute to improve energy efficiency, the power quality issues lower energy efficiency and consequently these problems must be cancelled or at least mitigated.*

Key words: *voltage source inverters, square wave inverters, phase width modulation inverters, harmonic content.*

1. Introduction

Due to economic and environmental reasons, humanity is constantly under pressure to reduce energy consumption.

One of the main issues relating to energy consumption is the emission of carbon dioxide, a "greenhouse gas" determining global warming.

Another concern is the ever-increasing demand for fossil fuels, nonrenewable energy sources, to support economic development.

Reduction in energy consumption can be achieved in several ways, but also through energy efficiency programs, involving a systematic approach in promoting an efficient use of energy containing objectives and priorities. More often it is not only the management team of the companies concern, but of the national and international organizations that are held to draw energy policies.

2. Efficient Motors in Electric Drives

Pumps, fans, compressors, are mostly powered by induction motors, widely used in these applications and therefore being essential to the operation of most modern buildings. At the same time, they are quite often costly items.

All induction motors have inherent inefficiencies, energy losses including:

- iron losses, associated with the magnetic field created by the motor (voltage related

---

[1] Faculty of Building Engineering, Technical University of Cluj-Napoca.
[2] Faculty of Electrical Engineering, Technical University of Cluj-Napoca.

and therefore constant for any given motor and independent of load).

- copper losses (or I^2R losses), determined by the resistance of the copper wires in the motor; the greater the resistance of the coil, the more heat is generated and the greater the power loss.
- friction losses, constant for a given speed and independent of load.

Iron losses predominate and since they result from the consumption of reactive current, the power factor is correspondingly low, even at full load (typically around 0.8).

Correct sizing of electric motors is critical to their efficient operation, since oversized motors tend to exhibit poor power factors and lower efficiencies. Depending on size and speed, a typical standard motor may have full load efficiency between 55% and 95%.

Generally, the lower the speed, the lower the efficiency and the lower the power factor are.

Typically motors exhibit efficiencies which are reasonably constant down to approximately 75% full load. Thereafter they may lose approximately 5% down to 50% of full load, after which the efficiency falls rapidly (see Fig. 2) [1].

At the same time the power factor tends to fall off more rapidly than the efficiency under part load conditions.

Consequently, if motors are oversized, the need for power factor correction becomes greater.

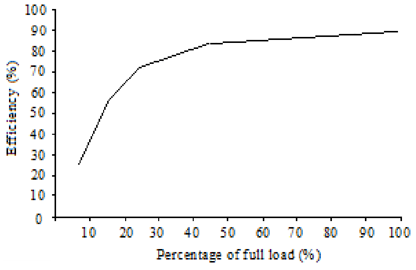


Fig. 1. *Induction motor efficiency*

Oversizing of motors also increases the capital cost of the switchgear and wiring which serves the motor.

In addition to these standard motors, some motor manufacturers also produce premium efficiency motors, which operate at efficiencies about 3 to 7 percent higher than the standard designs. In these energy efficient motors, losses are reduced by [2]:

- use of wire with lower resistance
- improved design of the rotor electric circuit
- higher permeability in the magnetic circuits of the stator and rotor
- use of thinner steel laminations in the magnetic circuits
- improved shape of the steel stator core and rotor magnetic circuits
- smaller gap between stator and rotor
- internal fan, cooling fins, and cooling air passages designed to reduce the cooling power requirement
- use of bearings with lower friction

Apart from these, a very effective way to increase energy efficiency consists in the use of variable speed drives.

3. Variable Speed Drives in Buildings Equipment

Most induction motors used in buildings are fitted to fans or pumps. The traditional approach to pipework and ductwork systems has been to oversize pumps and fans at the design stage, and then to use commissioning valves and dampers to control the flow rate by increasing the system resistance. While mechanical constrictions are able to control the flow rate delivered by fans and pumps, the constriction itself increases the system resistance and results in increased energy loss. This situation is highly undesirable and is one of the main reasons why the energy consumption associated with fans and pumps is fairly high in so many buildings [3].

An alternative approach to the use of valves and dampers is to control the flow rate by reducing the speed of the fan or pump motor, strategy which results in considerable energy savings.

Variable speed drives are nowadays used in conjunction with supply and return fans, centrifugal chillers, as well as with virtually any type of centrifugal pump. Speed control is considered primarily for its energy savings benefits.

The main advantage of the adjustable frequency drive is that the standard AC motors may be used.

Basically, induction motors are constant -speed devices, their speed depending on the number of poles provided in the stator, when the voltage and frequency of the supply remain constant.

One of the traditional methods of varying induction motor's speed is to connect the stator to change the number of poles. This method is still in use (e.g. for the driving motor of the ventilo converters). The main drawback of this method, beyond the higher manufacturing cost, is that speed change is not continuous, but a discreet one, having a certain number of steps (usually three, tripling the base speed).

The slip (and accordingly the speed) can be modified for a given load by varying the line voltage. The shaft torque is proportional to the square of the voltage, so reducing the line voltage rapidly reduces the available torque. Consequently only very limited speed control is possible by this method.

An excellent way to vary the speed of a squirrel-cage induction motor is to vary the frequency of the applied voltage. To maintain a constant torque, the ratio of voltage to frequency must be kept constant, so the voltage must be varied simultaneously with the frequency. Adjustable frequency controls perform this function [4].

At constant torque, the horsepower output increases directly as the speed increases.

For a 50-Hz motor, increasing the supply frequency above 50 Hz will cause the motor to be loaded in excess of its rating, which must be done only for brief periods.

For a supply frequency of less than 50 Hz, the speed will be less than the rated speed of the motor. As the frequency is reduced, the voltage should also be reduced, to maintain a constant torque.

Sometimes it is desirable to have a constant output horsepower over a given speed range. These and other modifications can be obtained by varying the ratio of voltage to frequency as required. Some controllers are designed to provide constant torque up to 50 Hz and constant horsepower above 50 Hz, to permit higher speeds without overloading the motor.

The speed of an AC induction motor can be changed over a very wide range from 10% to 20% of 50-Hz-rated speed up to several times rated speed. At higher speeds, care must be taken to not exceed the horsepower rating of the motor.

At low speeds, roughly 20% of rated speed or less, care must be taken to not exceed the permitted motor's temperature rise. If speed gets too low, the motor may "cog"— the rotor jumping from one position to the next, instead of rotating smoothly — or it may stall completely.

Variable frequency drives (VFD), acting as an interface between the AC power supply and the induction motor, must perform the following requirements:

- Ability to adjust the frequency according to the desired output speed.
- Ability to adjust the output voltage so as to maintain a constant air-gap flux in the constant torque region.
- Ability to supply a rated current on a continuous basis at any frequency.

Fig. 2 illustrates general principle of variable (adjustable) speed drives. The block schematics of the conversion consists in converting the AC power input into DC by means of either a controlled or an uncontrolled rectifier.

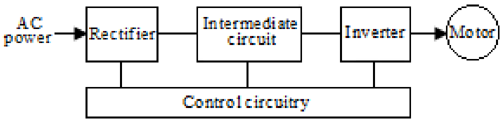


Fig. 2. *Block schematics of a VSD*

The intermediate circuit (the DC link) filters the ripple at the output of the rectifier, and the combination of the controlled rectifier and filter provides a variable DC voltage to the inverter.

The filter of the intermediate circuit is a passive one consisting in a bulky capacitor, a mH inductance or a combination of these elements of circuitry.

The inverter converts DC to variable frequency AC. An inverter belongs to the voltage source. Similarly, an inverter which behaves as a current source at its terminal is called a current source inverter.

Because of the low internal impedance, the terminal voltage of a voltage source inverter remains substantially constant with variations in load.

The control circuit of the variable speed drive (VSD) enables exchanges of data between VSD and peripherals, gathers and reports fault messages and carries out protective functions of the VSD.

The inverter of the VSD (Fig. 3) operates in a square-wave mode, which results in phase to neutral voltage as shown in Fig. 4.

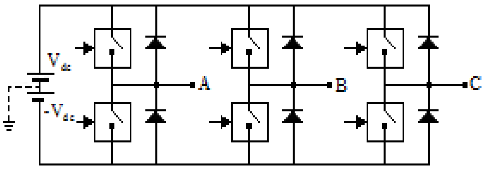


Fig. 3. *Square-wave mode inverter*

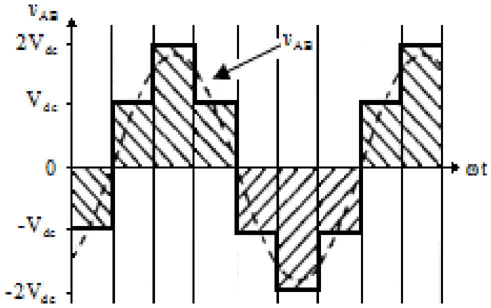


Fig. 4. *Waveforms at the output of the inverter*

In a square-wave inverter, each input is connected alternatively to the positive and negative power-supply outputs to give a square-wave approximation to an AC waveform at a frequency that is determined by the gating of the switches [5].

The voltage in each output line is phase shifted by 120° to provide a three-phase source.

The switches produce a stair-step voltage for each motor phase. At frequencies below the rated frequency of the motor, the applied voltage must be reduced. Otherwise, the current to the motor will be excessive and cause magnetic saturation.

A decreasing voltage level to keep the peak flux constant can be done with the square-wave inverter decreasing the DC voltage as motor speed is reduced below rated speed. This can be done by a controlled rectifier, but this produces problems with harmonics in the power system supplying the controller.

Theoretically, voltage harmonics magnitude in the inverter output decreases with the harmonic order with respect to the fundamental frequency phase-to-neutral voltage. Because of substantial magnitudes of low-order harmonics, these currents result in large torque ripple, which can produce troublesome speed ripple at low operating speeds.

The standard three-phase VSI topology of a pulse-width-modulated PWM drive is shown in Fig. 5.

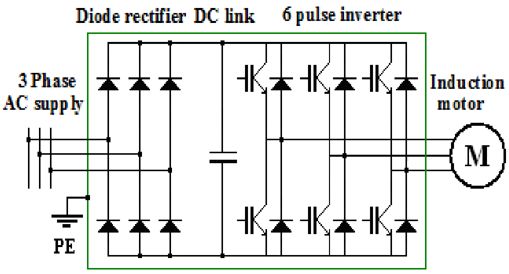


Fig. 5. *Standard PWM of voltage source inverter*

Assuming a three-phase utility input, a PWM inverter controls both the frequency and the magnitude of the voltage output. Therefore, at the input, an uncontrolled diode bridge rectifier is generally used.

In a PWM inverter, the harmonics in the output voltage appear as sidebands of the switching frequency and its multiples.

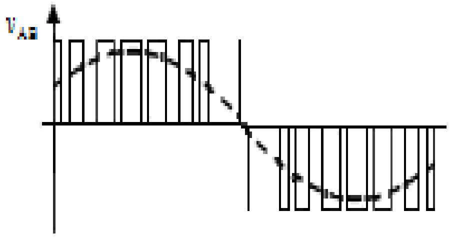


Fig. 6. *Waveform of the output voltage of PWMVSI*

Therefore, a high switching frequency results in an essentially sinusoidal current in the motor (Fig. 6).

Since the ripple current through the DC-bus capacitor is at the switching frequency, the “input DC source” impedance seen by the inverter would be smaller at higher switching frequencies. Therefore, a small value of capacitance suffices in PWM inverters, but this capacitor must be able to carry the ripple current.

A small capacitance across the diode rectifier also results in a better input current waveform drawn from the utility source. However, care should be taken to avoid letting the voltage ripple in the dc-bus voltage become too large, which would cause additional harmonics in the voltage applied to the motor.

Figure 4 shows the ideal waveforms of three-phase VSI SPWM. All phase voltages are identical, but 120° out-of-phase without even harmonics; moreover, harmonics at frequencies, a multiple of 3, are identical in amplitude and phase in all phases [5].

4. Power Quality in Building Equipments

Power electronics circuits used in motor controls can be susceptible to power quality related problems, as transient overvoltages, voltage sags and harmonic distortion. These problems may determine control anomalies, nuisance tripping and in some cases circuitry damage [6].

Capacitors, used in the electrical system to provide power factor correction and voltage stability during periods of heavy loading determine transient overvoltages when they are energized.

Circuits may be also sensitive to temporary reductions in voltage (sags), usually caused by faults on either the customer’s or the utilities electrical system.

Lighting systems and other electric devices can also cause distortion in the electrical current, affecting power quality.

Fluorescent, HID and low-voltage systems, which use ballasts or transformers, can have distorted current waveforms.

Devices with heavily distorted current waveforms use current in short bursts, instead of following the voltage waveform and affecting in their turn the voltage waveform. The load current waveform will be out of phase with the voltage waveform creating a phase displacement that reduces the efficiency because of the reactive power drawn from the system. It is well known that reactive power places an extra load on the distribution system. This extra virtual load represents a supplementary burden for utilities.

Highly distorted waveforms have a high harmonic content. Even harmonics (second-order on up) tend to cancel each other effects, but odd harmonics tend to add in a way that increases the distortion because the peaks and troughs of their waveforms are coincident.

The value indicating the harmonic content is the total harmonic distortion of the current THDi and of the voltage THDv.

In literature, power quality associated with variable speed drives means mainly voltage dips, supply interruptions and harmonic distortion that have negative effects on almost all the components of the electrical system, by causing new dielectric, thermal and mechanical stresses.

Harmonics in the square-wave inverter have two sources. At the input, the controlled rectifier generates harmonics that produce electrical noise in the power system. These can be filtered, but this reduces efficiency and the power factor, which is already low in a controlled rectifier.

The output waveforms also produce serious harmonics. The stairstep output waveforms have only odd harmonics. The third and ninth harmonics cause no problems, since they are in phase and cancel at the input of the wye-connected motor. Higher harmonics, mainly the fifth and seventh, cause currents that increase losses in the motor but produce no torque. These harmonics are filtered some by the inductance of the motor.

Power electronics circuits used in motor controls can be susceptible to power quality related problems, as transient overvoltages, voltages sags and harmonic distortion. These problems may determine control anomalies, nuisance tripping and in some cases circuitry damage.

Capacitors, used in the electrical system to provide power factor correction and voltage stability during periods of heavy loading determine transient overvoltages when they are energized.

Circuits may be also sensitive to temporary reductions in voltage (sags), usually caused by faults on either the customer’s or the utilities electrical system.

Lighting systems and other electric devices can cause distortion in the electrical current, which can affect power quality. Fluorescent, HID and low-voltage systems, which use ballasts or transformers, can have distorted current waveforms.

Devices with heavily distorted current waveforms use current in short bursts, instead of following the voltage waveform and affecting in their turn the voltage waveform. The load current waveform will be out of phase with the voltage waveform creating a phase displacement that reduces the efficiency because of the reactive power drawn from the system. Reactive power places an extra load on the distribution system.

Highly distorted waveforms have a high harmonic content.

Even harmonics (second-order on up) tend to cancel each other effects, but odd harmonics tend to add in a way that increases the distortion because the peaks and troughs of their waveforms coincide.

The value which indicates the harmonic content is the total harmonic distortion of the current THDi and of the voltage THDv.

In literature, power quality associated with variable speed drives means mainly voltage dips, supply interruptions and harmonic distortion that have negative effects on almost all the components of the electrical system, by causing new dielectric, thermal and mechanical stresses.

Harmonics in the square-wave inverter have two sources. At the input, the controlled rectifier generates harmonics that produce electrical noise in the power system. These can be filtered, but this reduces efficiency and the power factor, which is already low in a controlled rectifier.

The output waveforms also produce serious harmonics. The stair-step output waveforms have only odd harmonics. The third and ninth harmonics cause no problems, since they are in phase and cancel at the input of the wye-connected motor. Higher harmonics, mainly the fifth and seventh, cause currents that increase losses in the motor but produce no torque. These harmonics are filtered some by the inductance of the motor.

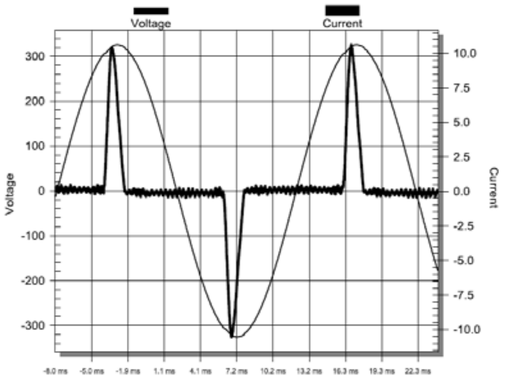


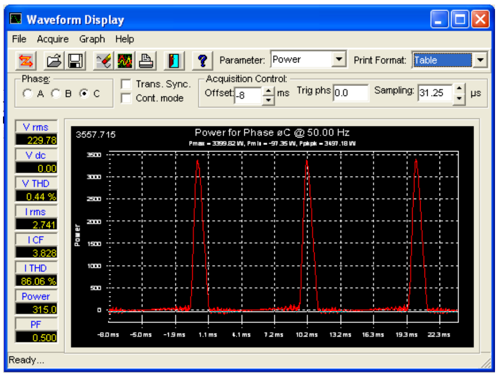
Fig. 7. *Supply voltage and current drawn by a rectifier*

Fig. 7 depicts the waveforms of the supply voltage and of the current drawn by a mono-phase rectifier. A highly distorted waveform of the current is revealed.

Measurements were carried out using a programmable power source (i.e. a clean power source).

In Fig. 8 the real power drawn by a PWMVSI is depicted. The waveform is discontinuous tracking somehow the current waveform.

At the same time, total power factor recorded in Fig. 8 is dramatically low, having a value of only 0.5, since the European regulations indicate for the neutral power factor a value of 0.93.



Parameter: Power
Print Format: Table
Phase: ○ A ○ B ● C
☐ Trans. Sync.
☐ Cont. mode
Acquisition Control: Offset: -8 ms Trig phs 0.0 Sampling: 31.25 µs
V rms 229.78
V dc 0.00
V THD 0.44 %
I rms 2.741
I CF 3.828
I THD 86.06 %
Power 315.0
PF 0.500
Ready...

Fig. 8. *Real power drawn by the AHU*

The harmonic content is shown in Fig. 9. One can see from the FFT (Fast Fourier Transform) chart that only odd harmonics are present and their amplitude is decreasing in hyperbolic way. However, the fifth, seventh and ninth order harmonic components are quite significant, which leads to a reduced energy efficiency, considering that these harmonic components have no useful effects.

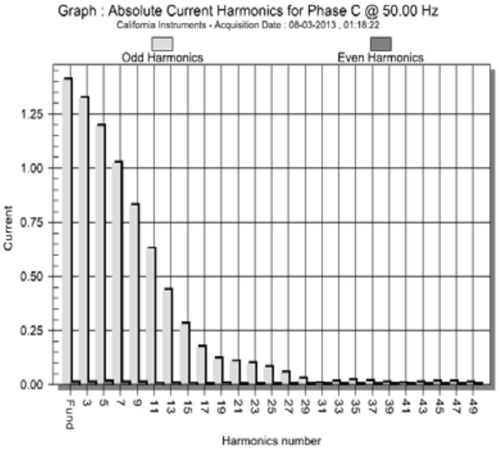


Fig. 9. *FFT chart of the harmonic limits of the AHU*

It can be noted in the left side of the chart from Fig. 8 that the THD of the input voltage is quite insignificant, the system being supplied by a clean power source (manufactured by California Instruments), while the THD of the current drawn by the rectifier is rather high, having a magnitude of 86%, revealing a very significant harmonic content.

5. Conclusions and further work

Power electronics embedded in modern buildings equipment, like fans, pumps, air handling units or chillers have plenty of advantages, but at the same time several drawbacks which have to be cancelled or at least mitigated.

The power factor issue an along with the undesired harmonic content are very serious matters in lowering the overall energy efficiency.

It is compulsory to deal with these drawbacks in terms of modern total power factor correction (the classical method of inserting capacities in order to compensate the displacement factor, the old cosφ, being more satisfactory) and of filtering the harmonic content retrofitting harmonic, active filters and/or EMI filters.

It should be noted that total power factor TPF and displacement power factor DPF differ in any circuit with nonlinear electrical loads because these types of load generate harmonics.

Several harmonic computer programs have been developed to perform a steady-state analysis of the facility's electrical system for each frequency at which a harmonic source is present. The programs will calculate the harmonic voltages and currents in the system. In these harmonic simulations, TPF corrections can be provided to check for system operation and possible undesired resonances.

As an overall conclusion, it can be said that the boom of the power electronics devices should be treated with utmost care since they may lead to significant power quality issues, greatly affecting the electrical energy efficiency.

References

1. Thumann, A., Franz H.: *Efficient electrical systems design handbook.* Taylor & Francis Ltd., 2009.
2. Buzdugan, M. I., Bălan H.: *Power Quality versus Electromagnetic Compatibility in Adjustable Speed Drives*. In: Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ'13), Bilbao (Spain), 2013.
3. Jayamaha, L.: *Energy-Efficient Building Systems - Green Strategies for Operation and Maintenance*, The McGraw-Hill Companies, Inc., 2007.
4. Beggs, C.: *Energy-Management, supply and conservation*. Butterworth-Heinemann, 2002, Taylor & Francis, 2012.
5. Rashid, M.H.: *Power Electronics Handbook - Devices, Circuits and Applications*. Elsevier Inc., 2007.
6. Hordeski, M.F.: *New technologies for energy efficiency*. Marcel Dekker, Inc., 2003.