A technical procedure for assessment of energy saving by means of Variable Speed Drive in compressed air facilities. Contribution to evaluation and monitoring for the Italian energy saving decrees

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Abstract

The proposed EU Directive on energy services finds in Italy a first-for-the-country application through the Decrees on energy efficiency, recently revised in July 2004. In this second edition the scheduling has also been updated, aiming to achieve a 5.8 Mtoe saving on primary energy by 2009 (electricity and natural gas). Although, energy intensive industries and the energy sector, subjected to other Directives, are excluded, small and medium enterprises (SMEs) as well as the civil sector form an interesting target of the new Directive. For the implementation of these obligations in the Italian legislation, various technical procedures have already been approved since 2001 by the Regulatory Authority for electricity and gas. But several others are on their way to be studied, discussed, submitted and eventually accepted. These procedures state how to evaluate and monitor the outcomes of the measures and actions on energy efficiency. In this paper the authors describe a methodology and subsequent procedure to assess savings in compressed air systems with variable speed drives motors. Possibilities and restrictions regarding evaluation and monitoring will be discussed.

Introduction

In July 2004 the Italian Government revised the so-called energy efficiency decrees [1][2] and set up new deadlines for energy distributors. The new Decrees specify less ambitious energy saving targets than the previous, also moving deadlines ahead and covering a time span from year 2005 through 2009. In Table 1 the annual and cumulative commitment for electricity dealers is presented, expressed in terms of primary energy saving.

In the period 2005-2009 an overall amount of 3.1 Mtoe must be saved. In accordance with this target Italian regions and autonomous provinces shall determine their own targets. They must set up a program such as the Energy master plan which can also be more binding, rather than just deliver their exact share in the national target. So far, the approved plans have mainly focused on the public and residential sector, where substantial savings are expected to come. Less attention seems to be paid to t the industrial non energy-intensive sectors [3].

Article 3 of the decree on the electricity savings states that, at least, 50% of the actions taken shall imply a direct reduction in the electricity demand. By year 2010 almost 7 TWh, which account for 1.9% of the reference scenario consumption, have to be saved over the MATT's (Ministry for the Environment and Territory) projection of 364 TWh final electricity demand. This assessment is based on a 2% annual growth rate (2000-2010), which resembles the 1992-

Table 1. Italian commitment for electricity dealers 2005-2009.

within …	MTOE/y	MTOE (cumulative)
2005	0.10	0.10
2006	0.20	0.30
2007	0.40	0.70
2008	0.80	1.50
2009	1.60	3.10

2002 trend. Besides, from the national plan for GHGs reduction it turns out that industry is planned to increase its electricity consumption at a rate of 2.6% per year, both in the "reference" and in the "trend" scenario. This is based on the opinion that the progress on efficiency is doomed to slow down and that the possibilities for action decrease because of measures taken in the past [3].

Despite general consensus on this statement at a Ministry level, the authors believe that there is an unexploited potential to improve efficiency in industrial processes. The proposal, described in this paper, aims to give a broader view on the opportunities to realize efficiency.

This work deals with savings in the commodity "electricity" only. However, the types of machines described in the following, even the ones with no adjustable speed drives, can be subjected to additional energy saving operations, for instance the thermal recovery.

Why is compressed air consumption so important for industry?

A recent study from the European Union on compressed air in European industry shows that the potential energy savings can be close to 2 TWh/y, while the overall consumption for such facilities is roughly 11 TWh/y, representing 10% of the total industrial electricity use [4].

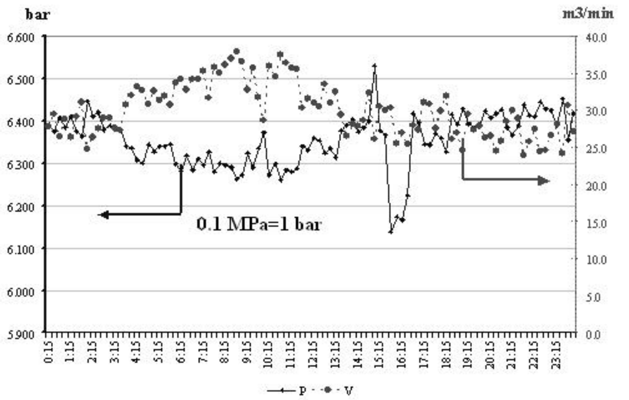


Figure 1. An example of pressure (left axe) and air rate (right axe) survey over 24 hours in a food firm.

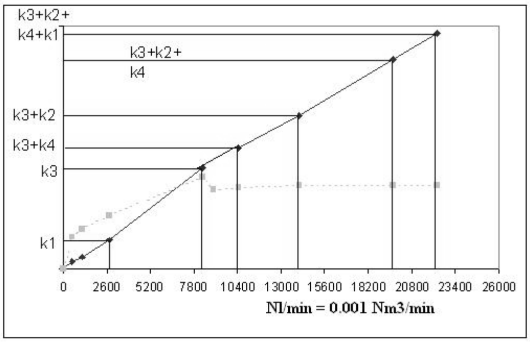


Figure 2. An example of the insertion sequence for 4 different compressors (k1, k2 lobe compressors, k3, k4 screw compressors) depending on the deliverable air to the network (x-axe).

Compressing air is a very energy intensive operation whose efficiency hardly reaches 15%. According to 1998 data from the Italian association of compressor retailers, the Italian market ranks second in number of sold units, after the US and at the same level as Germany, accounting for 17 000 systems per year. This feature is mainly due to the industrial structure in Italy that is predominantly made up of SMEs. Thus, the compressors, ranging from a few kWs to several hundred kWs, are very common in every company. The compressors deliver a rated air flow at a preset pressure value (typical values are 0.7 – 0.8 MPa) to account for pressure losses and leakages in the air distribution network. Final air use regards for example a molding machine or one or more actuators. Unfortunately the optimal application of air compressor systems is neglected and, as production increases, the number of compressors does as well. But feasibility studies which should accompany the development of more efficient compressed air networks are rarely undertaken [5].

A BRIEF EXPLANATION OF SYSTEMS CONFIGURATIONS

In the following we will present a procedure to assess and monitor the achievable energy savings by means of the installation of electronic devices which change the frequency in the motors driving the air compressor systems.

By changing the speed of the motor, the amount of compressed air changes as well, better fitting to the end users' demand. This continuous modulation avoids to frequently switch the compressor from load to no load operating conditions, which are characterized by a generalized waste of energy: during the no load status the compressor does not work, but its drive keeps on being connected to the grid, consuming energy.

In conformity with other procedures already approved for other applications, this procedure has to be applied to a stand-alone system and must satisfy two paramount demands: (i) minimize the amount of data to be given by the proponent, (ii) use the so-called analytical or engineering procedure, where a model shall be defined, by means of its measurable and not measurable parameters, possibly with no resort to any corrective unexplained factor, according to the M&V (measurement and verification) methods defined in [8].

Although the two demands mentioned above entail approximations in the assumptions, the positive feature is that they answer to the need of using very simple procedures in the elaboration, validation and control stage, with no chance of overestimating the potential saving. Nevertheless the matter can be doomed to be deepened.

Before focusing on the procedure, first the operating conditions of the compressed air system have to be known. This will allow to build the load profile for the requested compressed air over a typical working day, or more typical working days if relevant, and to match it with the power consumption from the grid. In figure 1 and 2 two graphs, derived from this preliminary monitoring activity, are presented. Figure 1 shows the results of measurements in the field for a system made up of more than one compressor. One curve shows the load-no load operation, which are recorded by a pressure meter, the other curve shows production (or lack of production) of compressed air. The presence of the pressure meter only, without a flux meter, is a very important prerequisite because the measurement process should rely on a non invasive action done without need for expensive and sensitive interventions on the piping. Of course, if there is a chance to also monitor the real air production, it has to be exploited.

The second important issue relates to the size of the back-up air tank, downstream the compressor(s), which is neglected if compared to the amount of the daily deliverable air. This means that we are not considering the delay introduced by the tank between what is requested by the network and what is supplied by the compressor to the tank. Another issue regards the operating sequence: if more than one compressor is used (see Figure 2) based on customized software for the surveillance and management of the facility [7]. It allows to identify the operating sequences of each machine, depending on the network air requirements.

Along with the air demand from the network, the assessment needs to gather information on the type of the compressors and the efficiency of the compressors at different load factors (usually at the rated and at the so-called no load condition). Data regarding the working hours and operating activities are also useful to build up the time-dependant demand.

For the alternative VSD configuration (compressor with variable speed drive), replacing the on/off compressors, additional information is needed, such as the range of loads and the performance at different load levels. Due to variable air demand over the day, a regulation and control system is highly recommended.

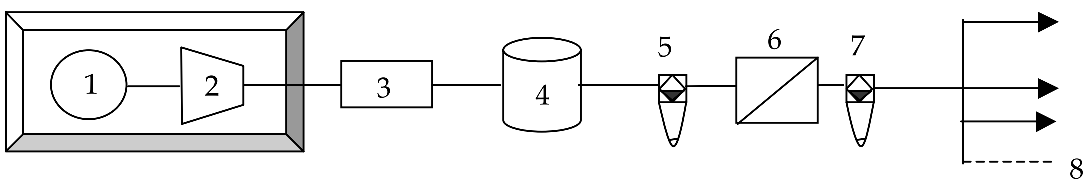
Baseline and VSD schemes

The evaluation methodology on energy savings examines the energy consumption of the two alternative configurations (reported in figure 3 and 4) to regulate the air flow rate according to the compressed air requirement. Figure 3 represents the standard system configuration (with one compressor), while figure 4 represents the VSD alternative system. The tank is considered in both cases, according to the assumption explained in the section above.

Figure 3 shows the baseline scheme for compressed air production, made up of 7 different main parts: the drive and the compressor, the pressure monitoring system, a back-up tank (useful to trim peaks of the downstream air demand), the filters and dryer and the pipeline to air using applications. The variability in the delivery is achieved by a load/no-load (on/off) control on the compressor. "Load operation" means that the drive works at the rated speed while delivering the rated air flow. "No-load operation" means that the compressor is decoupled from the drive, but the drive keeps on rotating , thus still energy is consumed from the grid. The pressure level in the tank between the compressor and the applications masters the compressor's operations: when the value goes below a set minimum pressure threshold, then the compressor starts. On the contrary, when the value reaches the maximum set threshold, the compressor is put on halt.

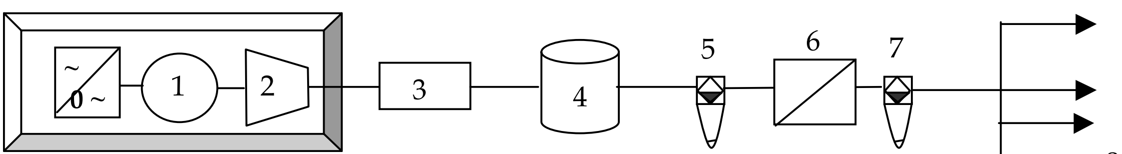
As a matter of fact the baseline configuration is already an optimized configuration, because the use of a storage tank allows to downsize the compressor capacity with respect to size of the demand. The compressor runs at its rated conditions when it is feeding the tank, while for the rest of the time it is idling. The energy, then consumed, can be a significant share of the overall consumption, though. The energetic advantage of the VSD configuration lies mainly in the optimization of consumption in this time span.

Figure 4 reports the alternative system, where the additional item "0", representing the inverter, is placed upstream the motor. The inverter is a device, controlling the speed of the motor through continuous frequency-voltage regulation. Thus, the load fluctuation, due to variable air needs, is satisfied by smoothly changing the motor-compressor's speed. Lower speeds are applied for less delivered air, but the compressor always works at its best performances and the overall efficiency is far better than the one in the on/off run.



Nomenclature: 1 drive, 2 compressor, 3 measurement system, 4 tank, 5-7 filters, 6 dryer, 8 users

Figure 3. *Baseline compressed air system configuration with on/off control.*



Nomenclature: 0 inverter, 1 drive, 2 compressor, 3 measurement system, 4 tank, 5-7 filters, 6 dryer, 8 users

Figure 4. *Alternative compressed air system configuration with VSD control.*

THE ANALYTICAL PROCEDURE TO ASSESS AND MONITOR THE ENERGY SAVING

The authors believe that the procedure could also have a broader field of application, meaning bigger sized compressors than just the proposed range below, thus further tests are underway. So far, the reasons for such an exclusion are based on the evidence that the savings, directly measured on the field for bigger sized compressors as part of the ongoing work, would be too underestimated. Therefore, the following procedure is meant to be applied to compressors from 30 kW through 100 kW, where all the data come from information directly taken on the machine itself. The engineering procedure will be the bases of the technical document that the authors are going to submit for comments and approval to AEEG (Italian Regulatory Authority for the electricity and gas). This technical document, once approved, will officially certify how to evaluate and monitor the benefits arising from such a measure.

In order to account for the air requirements from the compressed air system, two important recorded data are used in the analysis. In the baseline configuration, the so-called "hours in the load-mode" account for the working hours when the compressor run at its rated conditions and the so-called "hours in the no load-mode" account for the time the compressor has been decoupled from the drive, but not switched off. This measurement is easy to do because every compressor is equipped with a counter, recording such data over the sample period (one day, one week, the shift-time,…). The following variables are defined:

Hours in the on-state = Hours in the load-state (associated with P_1 power from the grid)+ Hours in the no load-state (associated with P_2 power from the grid) =
$A_1 + A_2 = n_f$

(Equation1)

Hours in the off-state (associated with P_3 power from the grid) = Sample period – Hours in the on-state =
$S_p - n_f = A_3$ *(Equation 2)*

$$\% L = \frac{A_1}{S_p}$$

(Equation 3)

$$\% NL = \frac{A_2}{S_p}$$

(Equation 4)

$$\% O = \frac{A_3}{S_p}$$

(Equation 5)

$$P_m = \frac{\int_{A_1} P_1 dt + \int_{A_2} P_2 dt}{n_f}$$

(Equation 6)

$$P_4 = \frac{P_m}{\eta_m}$$

(Equation 7)

$$\int_{A_4} q_4 \cdot dt = q_1 \cdot A_1$$

(Equation 8)

ES_{year} = ES*(number of typical working week/year)
(Equation 9)

where

"q_4" is the instantaneous flow rate, supplied by the VSD machine over its A_4 working hours in order to deliver over time the same amount of air as in the reference configuration. "q_1" is the rated (fixed) compressed air flow. Parameter η_m is the efficiency of the inverter. The values A_4 and P_4 represent the discriminant elements of the effectiveness of the alternative configuration, i.e. to get $E_2 < E_1$.

Let us consider the following case: 30 kW compressor (rated power), 80% drive efficiency (therefore 37.5 kW needed from the grid, quantity P_1) and no load power (measurable or from compressor technical data sheet, quantity P_2). Measurable data are far better than what is assumed in the official data sheet because in practice values could depart from conditions in a lab, which are somehow optimal. This difference is due to some factors, just to cite the most important: the inlet air temperature is often higher than what reported on the datasheet, implying greater consumption during its compression. Thus at the most, the procedure underestimates the potential saving. In Table 2 the calculation of the energy saving through replacement by a VSD compressor is presented over one typical working week (S_p = 168 hours). A_4, A_6 and P_4 are the data of the alternative configuration.

For the case study, where P_1 = 37.5 kW, P_2 = 6 kW and η_m = 93%, the results in Table 3 show that over 42 working

Table 2. Calculation scheme of weekly energy savings for a VSD compressor vs. reference configuration.

		Reference configuration(Fig.1)				VSD Configuration (Fig.2)			
		Load	No load	offline	Total 1	Load	No load	offline	Total 2
hours	(A)	A1	A2	A3	168	A4	A5=0	A6	168
power from the grid	(P)	P1	P2	P3=0	Pm	P4	0	0	(**)
Energy consumption	(E)	A1*P1	A2*P2	A3*P3	E1=ΣAi*Pi	A4*P4	0	0	E2=A4*P4
Energy Saving (Toe/week)	ES=(E1-E2)*0.22*10^{-3}								

(**) not significant

Table 3. Calculated results for a case with a VSD compressor (40 kW rated power, working at an average load of 50%).

		Reference configuration(Fig.1)				VSD Configuration (Fig.2)				
		Load	No load	offline	Total 1	Load	No load (**)	offline	Total 2	number of the typical working weeks
hours	(A)	35	55	78	168	71		97	168	
power from the grid	(P)	37.5	6	0	18.25	19.62		0	(**)	
Energy consumption	(E)	1,313	330	-	1,643	1,396		0	1,396	
Energy Saving (Toe/week)		0.05							15.00%	
Energy Saving (Toe/y)		2.28								42

(**) not significant

weeks the achievable primary energy saving equals 15% of the original consumption. The reference system runs for 90 hours/week and is offline for the remaining 78 hours, while the VSD configuration works at an average load of 50% for 71 hours/week. The electricity consumption in the reference case is 1 643 kWh/week versus 1 396 kWh/week of the VSD configuration. Under the reported assumptions the replacement of such a small machine can make an ESCO achieve an interesting 2.3 Toe/y. Besides, such a replacement can help to meet a future increase in the demand. In the monitoring stage P_m becomes a measurable data as well as A_4.

SOME REMARKS ON THE METHODOLOGY AND THE ROLE OF ESCOS

Until February 2005 no proposal on the technical procedure for calculating energy savings has been addressed to AEEG because several tests are still missing to realise broader applications. Broader applications could mean that the final procedure shall be sound, not only for bigger sized machines, but also for other alternative configurations: for instance with no back-up tank between the VSD machine and the compressed air network. Besides, further studies could be needed for a comprehensive procedure applying to systems with more than one machine, all working in parallel. However, the procedure seems suitable for further extensions. A further asset is that it could be used both in the planning stage (ex-ante evaluation) and in the monitoring stage (ex-post evaluation), annually updated. According to some studies carried out in the food and kindred and expanded polystyrene sectors [5] [7], some manufacturing processes need compressed air not only in the automation of the process (to operate valves and actuators) but also as part of the process itself (for instance in the moulding or in the materials handling). This is the case where the savings are the most significant and diversified: compressors are bigger in size and no-load conditions occur more often, meaning that there is room to act on the optimization of the commodity not only on its production but also on its distribution and delivery. The trade industry associations, which have access to valuable information on the production process as well as compressors dealers, can play an outstanding role in uncovering this hidden potential. They could even get the benefit from it, by setting up "tailored" ESCOs for each specific industrial sector. It seems that a coordinated cooperative effort between these two entities, also with qualified engineers, designing and/or maintaining the facilities, can unveil and minimize most of the wasted energy. As it is detailed in [4], [5] and [7] payback times are often less than 24 months. Also third party financing or project financing could be a good starting point to get things moving but so far, only large projects have been able to access this money. Small projects, even if highly potential and huge in number, have been left aside. The energy efficiency certificates scheme and the binding national obligations are now expected to do the trick and get the market started, by giving the right credit to all kind of energy efficiency actions.

Conclusions

The proposed evaluation methodology for a single compressor allows (i) to minimize the needed amount of data from the proponent and (ii) to use a simple procedure with no need of correction factors. A reliable set of equations are the main features in the planning stage, while no measured data are available, yet. In the monitoring stage the measurements can replace assumed technical data. SMEs could become an ideal target for ESCOs, focusing on compressed air savings. Besides, where compressed air is not only used in automation (pneumatic circuits, actuators) but also in the process itself (for instance in the molding of the plastic transformation divisions), savings are even more significant, due to more air needed. The bigger the compressors, the more the power that can be saved, because of the elimination of the expensive no-load conditions, that in the latter case can occur more often.

References

[1] Decree 2004/07/20, "Nuova individuazione degli obiettivi quantitativi per l'incremento dell'efficienza energetica negli usi finali di energia, ai sensi dell'art. 9, comma 1, del decreto legislativo 16 marzo 1999". Gazzetta Ufficiale N. 205, September 2004.

[2] Decree 2004/07/20, "Nuova individuazione degli obiettivi quantitativi nazionali di risparmio energetico e sviluppo delle fonti rinnovabili, di cui all'art. 16, comma 4, del decreto legislativo 23 maggio 2000". Gazzetta Ufficiale N. 205, September 2004.

[3] MATT, "Il piano nazionale per la riduzione delle emissioni di gas serra: l'ambiente come opportunità". Milan, 2003

[4] Radgen P. et al, 2001, "Compressed air systems in the European Union: energy, emissions, savings potential and policy actions", LOG_X Verlag GmbH, Stuttgart, ISBN 3-932298-16-0

[5] Anglani N., Mariani D., Petrecca G., 2002, "Opportunities and barriers to energy efficiency implementation in the Italian industrial sector: an open matter", Policy Modelling for Industrial Energy Use, LBNL Report number 52698, Seoul, Korea.

[6] AEEG, "Scheda tecnica n. 14 Installazione di sistemi elettronici di regolazione di frequenza in motori elettrici", 2004

[7] Anglani N., 2002, "Risparmio energetico, modalità di utilizzo e gestione dell'aria compressa nell'industria", Quaderni dell'Aria Compressa, Vol. 3/7, pg. 32-36.

[8] Pavan M., 2005, "Italian Energy Efficiency Obligations and White Certificates: Measurement and Evaluation". Workshop: Bottom-up measurement and verification of energy efficiency improvements: national & regional examples. Brussels. March 3rd.