METHODOLOGY FOR THE ANALYSIS OF ENERGY EFFICIENCY IN PNEUMATICS SYSTEMS

Abstract— The present article presents a methodology about the improvement of the energy efficiency in pneumatic systems through the restoring of air. In this way, 3 techniques of expansion of a cylinder are identified: expansion using the air of the compressor (conventional), restoring the air (efficient) and combining the air of the compressor and the restored air (hybrid). The methodology starts with the development of the GRAFCET of the system so that it can be decided whether to expand the cylinder in a conventional, efficient or hybrid way. The methodology can be applied to any case. Finally, graphs of comparison between the 3 methods of expansion with certain cylinder strokes and workloads are presented, to facilitate the subsequent selection of one system or another.

Keywords— Pneumatic system, efficiency, energetic, methodology, GRAFCET.

1 Introduction

To increase the energy efficiency is one the main aims of every industry in the world, this because its lack impacts directly their productive capacity and their annual costs as well as it compromises the environment. The use of pneumatics is fundamental for the industry and the fact that there are only few factories where compressed air is not used is a proof of that statement. Pneumatic components are used to execute movements and are indispensable for industrial automation (Hesse, 2002).

In this sense, pneumatic systems are largely used due to the advantages they offer such as high reliability, easy transportation, high operational safety and high response speed (De Negri, 2001). Therefore, the development of the present research is imperative. It focuses on developing a methodology to perform the energy efficiency analysis of a system model according to GRAFCET to establish one of the 3 techniques for the expansion of a cylinder: expansion using a new mass of compressed air (conventional), expansion reusing the stored air in the cylinder (efficient) and expansion using a combination of stored air and air from compressor (hybrid). After modeling the system and according to the characteristics of each cylinder, such as piston diameter, stroke and the moving mass, the best efficiency method is chosen from a weighing between consumption and expansion speed, according to the needs defined by the user.

2 Modeling of the pneumatic system

In 1977, the Association Française pour la Cybernétique Economique et Technique (AFCET) defines GRAFCET (Figure 1) as a functional step-transition graph. Subsequently, with the conception of new standards such as IEC 60848 (last edition in 2002) GRAFCET is defined as a language that allows to model discreetly the behavior of an automated system.

In pneumatic applications, it is known as the step-by-step method. The method starts with the use of a functional diagram according to the aforementioned standard. Then, with the determined functions, a logic diagram must be defined to finally implement it to a pneumatic circuit, electropneumatic with relays or electropneumatic using a Programmable Logic Controller (Gonzáles, 2004).

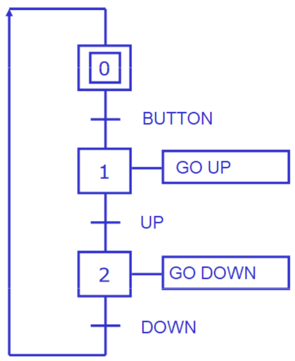

Fig. 1. Step by step method with GRAFCET. Source: Extracted from (Gonzáles, 2004).

3 Air reuse technique

In conventional circuits involving double acting actuators, 5/2 or 4/2 valves are used to control the expansion and retraction of the cylinders with compressed air for both cases (Figure 2-a)

However, this article proposes that the drive of a double-acting cylinder needs the addition of a 3/2 valve and the reconnection of the channels in such a way that the stored air of the cylinder can be reused in the retracted state as shown in Figure 2-b. There are other air reuse techniques proposed in (Blagojevic *et al.*, 2013) and (Blagojevic and Jankovic, 2016), but this work follows the guidelines of (Blagojevic and Stojiljković, 2008).

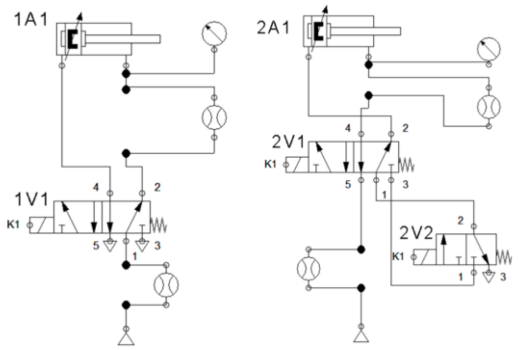

Fig. 2. (a) Left, Cylinder with conventional connection. (b) Right, Cylinder with reuse connection. Source: Own elaboration.

Figure 3 shows that for the cylinder with efficient connection there is only air demand for half a cycle (retract), while for the cylinder connected

conventionally there is demand for both retraction and expansion. This way, it is possible to confirm that the compressed air demand is lower, therefore, the energy consumption is also smaller.

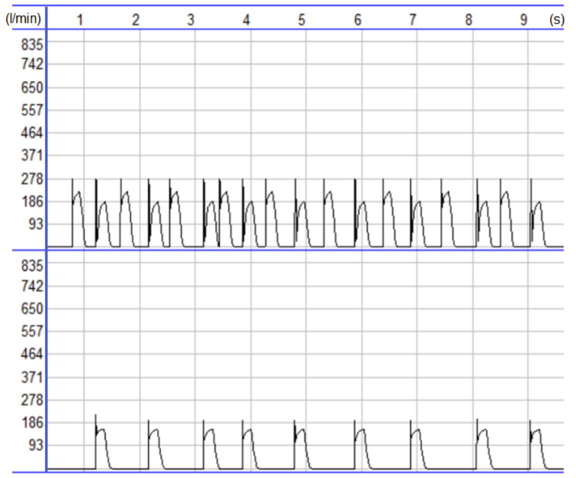

Fig. 3. Graphical flow (l/min) of compressed air in the cylinder with conventional graphic (top) of flow (l/min) of compressed air in the cylinder with efficient connection (below). Source: Own elaboration.

4 Methodology

Next, the steps of the methodology will be detailed to obtain the modified pneumatic or electropneumatic circuit to increase energy efficiency. In the presented circuits, the expansion technique that will be used is the one explained in the previous chapter.

4.1 Modeling considerations

The sequence must be previously defined in a GRAFCET model. In each state where expansion occurs, three states must be placed in parallel. In addition, a transition is placed before each block (efficiency variable) that indicates the decision whether the expansion is efficient, hybrid or conventional. Table 1 shows the combinations for each type of expansion, while Figure 4 shows an example for a cylinder "A", where the efficiency variables are AV1 and AV2

Table I
LOGIC OF EFFICIENCY VARIABLES

AV1	AV2	1A1
0	0	No movement
0	1	Conventional expansion (with compressor air)
1	0	Efficient expansion (with air reuse)
1	1	Hybrid expansion (with compressor air and air reuse)

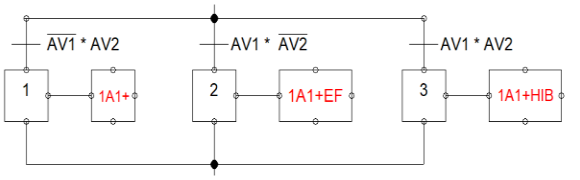

Fig. 4. GRAFCET indicating two branches in parallel for efficiency. Source: Own elaboration.

4.2 Logic diagram

Perform the logic diagram for each state of the GRAFCET model. This allows the GRAFCET diagram to be converted to a logical level that can be implemented in ladder language.

For example, Figure 5 shows a logic diagram for a state that has 2 start buttons 1S0 and 2S0, also has 2 previous states M15 and M16. Additionally, we have the 2 efficiency variables AV1 and AV2. As AV1 is denied and AV2 is positive, according to Table 1 it refers to a conventional expansion. The variables 1S1 and 2S1 are end-of-stroke sensors and M4, M5 and M6 are the states after M1. Finally, you can always restart the system with the reset button 'R'.

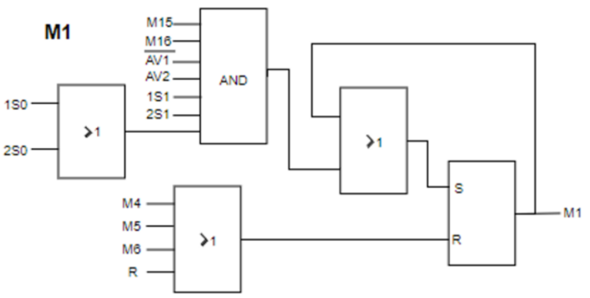

Fig. 5. Logic diagram for state M1. Source: Own elaboration.

4.3 Pneumatic conditioning

The conditioning is carried out in the same pneumatic circuit for the 3 types of expansion. The valve 1V1 / 14 must be activated first for all cases of expansion of the cylinder. The pneumatic circuit for each cylinder must be conditioned as in figure 6.

To use the air reuse method, the 1V2 valve is activated by the 1V2 / 12 solenoid, the air accumulated in the cylinder 1A1 is transported for its expansion. The accumulated air flows through ports 4-1 in valve 1V1 and through ports 2-1 in valve 1V2. Then the air flows through 3-2 in the 1V1 valve making the cylinder expand. It is important to note that there was no air purge at any time during the expansion. By not entering the compressor air, the previously used air is reused, thus generating an energy saving due to the compressor working time being reduced.

To use the conventional expansion method, valve 1V3 / 12 is activated, air flows from the compressor to ports 1-2 of valve 1V3 to enter valve 1V1 through ports 3-2 and thus expand the cylinder. It must be taken into account that air does not flow in ports 1-2 of the 1V2 valve because it is not driven for this type of expansion. The air purge was carried out through ports 4-1 on valve 1V1 and 2-3 on valve 1V2. In this case compressor air is used, as is conventionally done.

Finally, to use the hybrid method, both valves are activated (1V2 and 1V3). The accumulated air flows through ports 4-1 in valve 1V1 and through ports 2-1 in valve 1V2 until it reaches valve 1V2 via track 2-1. This air flow accumulates in the air of the compressor entering by 1-2 in the 1V3 valve. The accumulated air enters through ports 3-2 in valve 1V1, expanding the cylinder. In this type of expansion, the air purge was not performed either. As in this case the 2 types of expansion are combined, in addition to reusing the air compressor air is needed, but to a lesser extent.

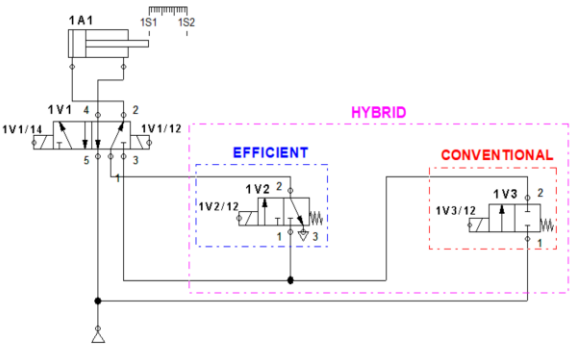

Fig. 6. Pneumatic conditioning circuit for conventional, efficient or hybrid expansion. Source: Own elaboration.

4.4 Electric conditioning

In addition to pneumatic conditioning, an electrical conditioning must also be performed (Figure 7) for the states 1 (M1), 2 (M2) and 3 (M3) which are presented in the Grafcet diagram (Figure 5). This conditioning must act as the driver for the solenoids 1V2/12, 1V3/12 and 1V1/14 presented in Figure 6. Since the solenoids cannot be repeated in a ladder program, this arrangement of contacts and solenoids is obligatory; therefore, the aim is to develop a combination of the states that can fulfill this purpose.

In state 1, AV1 is denied and AV2 is high and according to table 1 this combination refers to a conventional expansion (without efficiency). Solenoids 1V3 / 12 and 1V1 / 14 are activated.

For state 2, AV1 is positive and AV2 is denied, which refers to an expansion with efficiency. Solenoids 1V2 / 12 and 1V1 / 14 are activated.

Finally, for state 3, AV1 and AV2 are positive, a hybrid expansion is performed. Solenoids 1V3 / 12, 1V2 / 12 and 1V1 / 14 are activated.

As it is observed, the electrical conditioning has a direct relation with the pneumatic conditioning, since the solenoid 1V1 / 14 must be activated to switch the state of the valve 1V1 and proceed with the expansion phase.

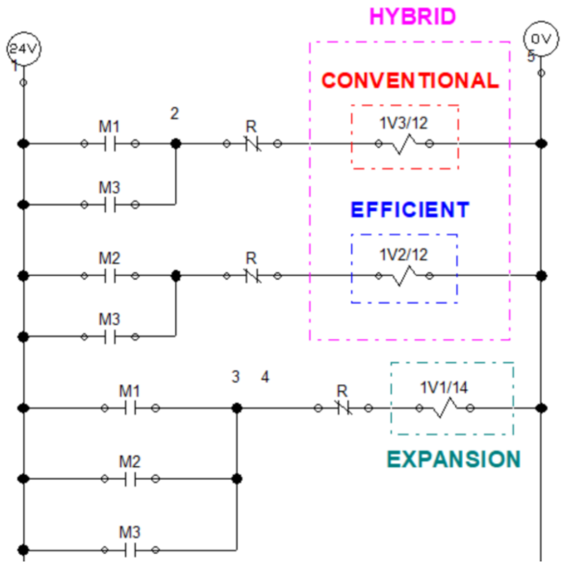

Fig. 7. Electric conditioning circuit for air reuse. Source: Own elaboration.

5 Case studies

The case studies were selected considering relevance of the process in the industry and the impact of air consumption.

The first case study is a circuit for the labeling of pieces, usually used in automobile industry, assembling industry, food industry and others related. The sequence for this circuit starts with the expansion of A cylinder, then the expansion of B cylinder, finally occurs the retraction of both cylinders, starting with B. (A+B+B-A-).

The second case consists of a bending of glasses frames system. The sequence here is more complex than the shown in the previous case. Now, four cylinders are used and the air consumption is higher. The sequence is A+C+C-B+D+D-(A-B-) (FESTO DIDACTIC, 1992).

5.1 Labeling of pieces (A+B+B-A-)

When the proposed methodology is applied to analyze this case, a GRAFCET (Figure 8) with 8 states is obtained. Six of them due to the expansion of each of the two cylinders and the remaining two for the conventional compression of the pneumatic cylinders.

The choose of the expansion method is made by manipulating the efficiency variables. The efficiency variables are AV1 - AV2 for cylinder A and BV1 - BV2 for cylinder B and the decision logic follows the combinations shown in Table 1.

In addition, there are four sensors for the monitoring the state of each cylinder. The variables 1S0 and 2S0 are for the single and continuous cycle respectively. Sensors are listed in table II.

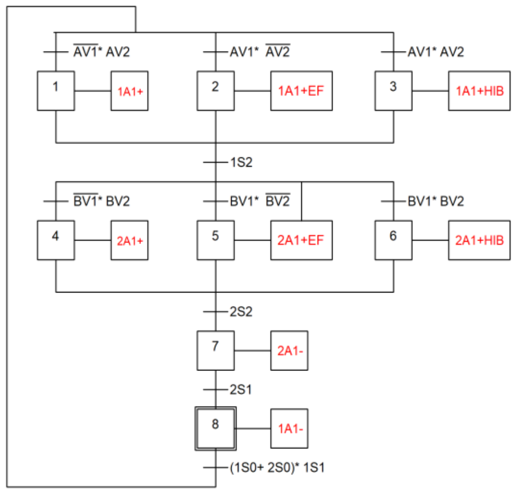

Fig. 8. GRAFCET for sequence of labeling of pieces using the proposed methodology. Source: Own elaboration.

Table II
SENSORS – LABELING OF PIECES

Names	State of cylinders
1S1	Start of stroke of cylinder A
1S2	End of stroke of cylinder A
2S1	Start of stroke of cylinder B
2S2	End of stroke of cylinder B

In the Fig 9. the final pneumatic circuit is presented.

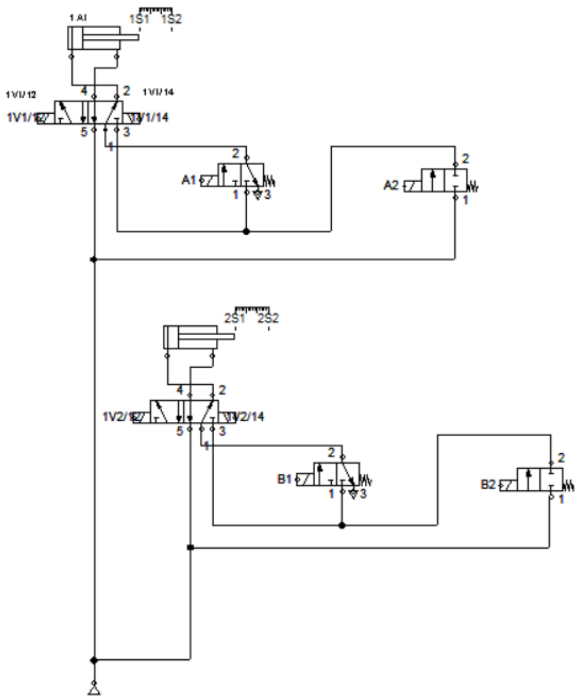

Fig. 9. Pneumatic circuit for case 1. Source: Own elaboration.

5.2 *Bending of glasses frames [A+C+C-B+D+A-(A-B-)]*

When the proposed methodology is applied to analyze the second case, a GRAFCET (Figure 10) with 16 states is obtained. Twelve of them due to the expansion of each of the four cylinders and the remaining three for the conventional compression of the pneumatic cylinders.

In this case, the choose of the expansion method is not made by manipulating the efficiency variables shown in Table 1. Instead, to expand a cylinder in a conventional, efficient or hybrid manner, the efficiency variables AV1-AV1 for cylinder A, BV1-BV2 for cylinder B, CV1-CV2 for cylinder C and DV1-DV2 for cylinder D must be manipulated.

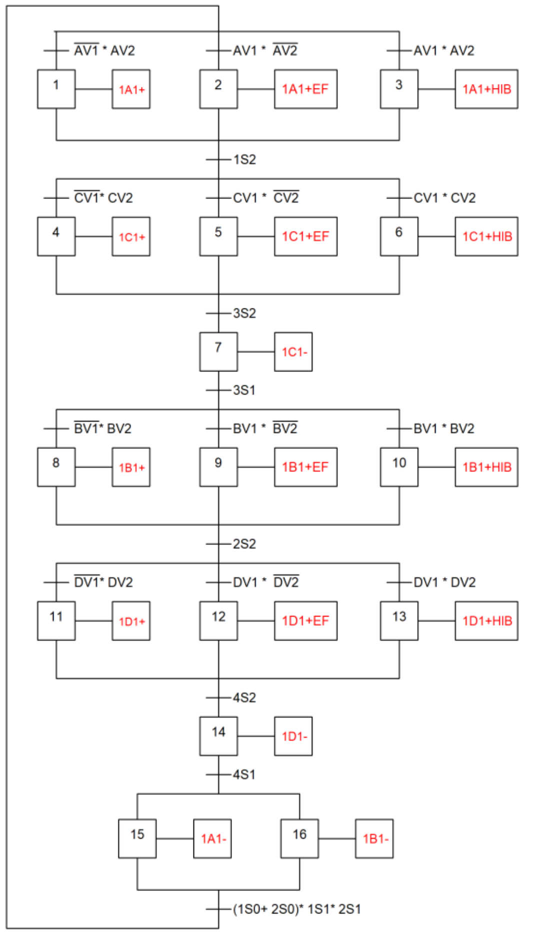

Fig. 10. GRAFCET for sequence of bending of glasses frames using the proposed methodology. Source: Own elaboration.

In addition, there are eight sensors for the monitoring the state of each cylinder. Sensors are listed in Table III. Like the previous case, the variables 1S0 and 2S0 are for the single and continuous cycle respectively. In the Fig 11. the final pneumatic circuit is presented.

Table III
SENSORS – BENDING OF GLASSES FRAMES

Names	State of cylinders
1S1	Start of stroke of cylinder A
1S2	End of stroke of cylinder A
2S1	Start of stroke of cylinder B
2S2	End of stroke of cylinder B
3S1	Start of stroke of cylinder C
3S2	End of stroke of cylinder C
4S1	Start of stroke of cylinder D
4S2	End of stroke of cylinder D

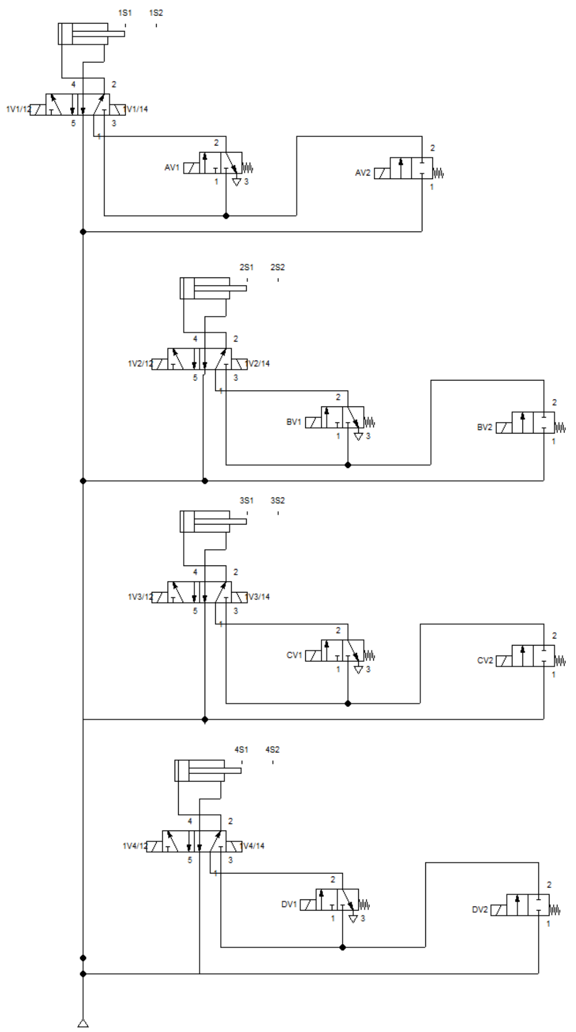

Fig. 11. Pneumatic circuit for case 2. Source: Own elaboration.

6 Results

The simulations were carried out according to the characteristics proposed in the documents provided by (FESTO, 2017) :

Piston Diameter: 20 mm
Stroke: 200 mm
Load: 5 kg
Friction considered: steel-steel

After implementing the proposed methodology for the case studies, the results obtained are presented in Table IV.

Table IV
TIME AND TOTAL AIR CONSUMPTION OF A CYCLE

AV1	Time (s)	Consumption (L)
Bending of glasses frames		
Conventional	3.221	4.05
Efficient	7.454	2.65
Hybrid	6.6	3.03
Labeling of pieces		
Conventional	1.8	2.25
Efficient	3.636	1.54
Hybrid	3.331	1.75

The obtained results were, as expected, beneficial.

As can be seen, using the efficient expansion mode, the air consumption is reduced by almost 35% for the first case and 32% for the second case at the expense of adding 4.2 seconds and 1.8 seconds respectively.

In the other hand, using the hybrid expansion mode, the saving is reduced by almost 26% for the first case and 23% for the second case, this time at the expense of the addition of 3.4 seconds and 1.5 seconds respectively.

7 Conclusions

- The effectiveness of the proposed methodology depends on the correct and orderly implementation of the established steps.
- Through simulation verifies that the consumption of compressed air is considerably reduced at the expense of the increase in the time of operation.
- The type of expansion depends on the application to be made in the industry, since it will be prioritized between air consumption or expansion time.
- This save of compressed air affects directly the electric energy consumption used in compressors, which means a considerable save of money for the owner of the system.
- A subject of later works will be the developing of a mathematic equation that can help choose the suitable type of expansion.
- Another subject of later works will be to facilitate the selection of the type of expansion through the development of a computer tool.

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