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Original scientific paper

DEVELOPMENT OF THE ALGORITHM FOR IMPLEMENTATION OF ENERGY-EFFICIENT COMPRESSED AIR SYSTEMS WITH ENERGY RECOVERY

Milan Šešlija[1], Vule Reljić[2], Valentina Mladenović[3], Miroslav Novaković[4], Zoran Jovanović[5]

[1]Elektroprivreda Republike Srpske, Trebinje, Bosnia and Herzegovina
[2]University of Novi Sad, Faculty of Technical Sciences,
Department of Industrial Engineering and Management, Novi Sad, Republic of Serbia
[3]Technical College of Applied Sciences at Zrenjanin, Zrenjanin, Republic of Serbia
[4]Academy of Applied Studies Šumadija, Department Trstenik,Trstenik, Republic of Serbia
[5]University of Niš, Faculty of Electronic Engineering, Department of Control Systems, Republic of Serbia

Abstract. *In order to improve the energy efficiency of pneumatic systems, this paper presents an algorithm for the devlopment and implementation of an energy efficient pneumatic control system with energy recovery of compressed air. Two different ways of forming closed pneumatic circuits that reuse already used compressed air are presented. Compared to traditional pneumatic control, significant energy savings are achieved.*

Key words: *Closed pneumatic circuit, Energy efficiency of compressed air systems, Systematic procedure, Algorithm*

1. Introduction

Compressed air systems are very reliable and safe for performing many functions in the field of industrial automation, but their economy is rarely taken into account. This leads to the fact that compressed air can, due to improper use, despite all the advantages, become one of the most expensive forms of energy for carrying out work in industrial plants [1]-[4]. In order to avoid this, it is necessary to pay special attention to the design and functioning of this segment of the factory system.

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Corresponding author: Vule Reljić
University of Novi Sad, Faculty of Technical Sciences, Department of Industrial Engineering and Management, Trg Dositeja Obradovića 6, 21000 Novi Sad, Republic of Serbia
E-mail: vuketa90@uns.ac.rs

An energy efficient compressed air system is one that is [5]:

- appropriately designed, with the aim of reducing the pressure drop, taking into account all elements of fittings, valves, air preparation and pipelines,
- regularly monitored with monitoring of specific energy consumption values based on collected data,
- well-maintained with all necessary services, replacement of consumable components at scheduled times and testing for equipment that requires it,
- used by personnel who are aware of the importance and costs generated in the compressed air system and who are trained to use the given equipment in an appropriate, energy efficient manner,
- the subject of a permanent program for the identification and elimination of compressed air leaks.

In accordance with the above, it is clear that in every compressed air system, subsequent introduction of measures to increase energy efficiency is necessary, because most systems have evolved from the originally designed state. Namely, as new machines that consume compressed air arrive, the requirements for compressed air are increasing and the above-mentioned system is being upgraded. Such systems can hardly be optimal because they are not subject to a structured design process.

Therefore, as already mentioned, the subsequent introduction of measures is necessary and applies equally to the production side (compressors, preparation and distribution of compressed air) and to the side of compressed air consumption. Accordingly, in this paper, an algorithm for the implementation of energy efficient compressed air systems with energy recovery is presented. This algorithm implies the transformation of existing compressed air systems by installing additional or modifying existing components in order to form a closed pneumatic circuit and increase the energy efficiency of the system. Therefore, the main contribution of this paper is to present to the designers a new approach for modifying existing or developing completely new pneumatic control systems, all with the aim of increasing energy efficiency.

The paper is organized as follows: Section 2 presents the necessary theoretical foundations, materials and methods; in Section 3 are shown the most important results of the work and the discussion is carried out; and finally, the most important conclusions are drawn in Section 4.

2. METHODOLOGY

In the usual mode of operation of pneumatic control systems, compressed air is released into the atmosphere after use in the consumption part of the system [6], as shown in Figure 1a. This discharge of the used air, which is still compressed, represents energy loss [7]-[12], and the atmosphere is also polluted with the expelled impurities.

The main reason for the formation of a closed pneumatic control circuit is to increase the energy efficiency of the pneumatic system [7]-[12]. In addition to the above, there are other benefits such as lower emissions of pollutants into the atmosphere, noise reduction, the possibility of using smaller compressors, etc.

There are two basic ways to form a closed pneumatic circuit by recuperating of compressed air, namely [5]:

- returning of the used compressed air to the production section, to the suction branch of the compressor (Figure 1b), and
- returning of the used compressed air to the consumption section (Figure 1c).

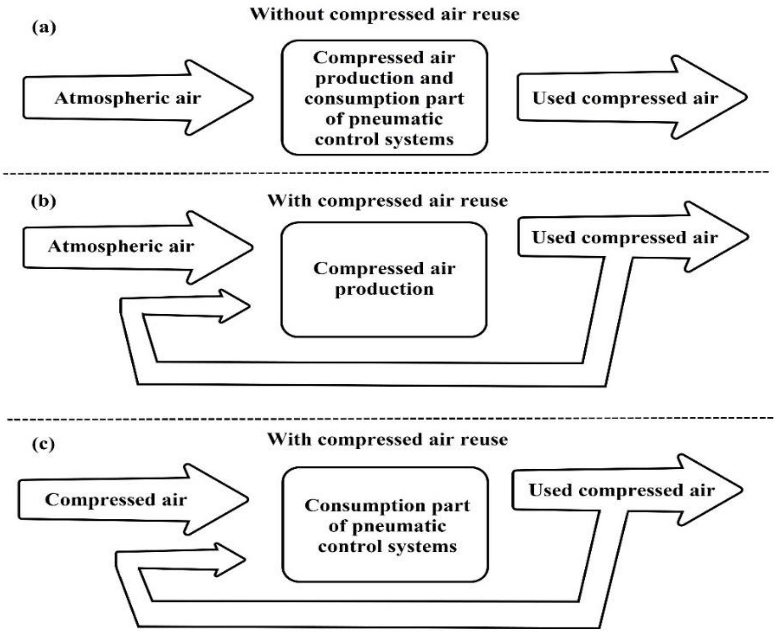

Fig. 1 Three different concepts of using compressed air in pneumatic control systems

Examples of the pneumatic control schemes with the returning of used compressed air to the production and consumption section are shown in papers [13] and [7], respectively.

2.1. Returning of used air to the section for the compressed air production

Compressors are machines used to increase gas pressure and the supply of compressed air begins with production in compressors. Namely, compressors suck atmospheric air and increase its pressure to the required level. In order to increase the energy efficiency of the system by shortening the operating time of the compressor, it is possible, as previously mentioned, to bring the already used compressed air from the system, which is released into the atmosphere during the standard mode of operation, to the inlet of the compressor, in addition to the standard atmospheric air [13].

To achieve this, it is necessary to go through several steps:

- In the first step, it is necessary to define the minimum values of the operating pressures for starting each of the actuators.
- In the next step, it is necessary to modify the compressor in such a way that, in addition to the standard suction from the atmosphere, an alternative suction of air from another source is possible, because there are no commercially available, standard compressors that could do it [13]. The mentioned another source is an additional tank (Figure 2, little orange rectangle), which needs to be installed in the existing system, in order to enable the collection of already used compressed air. In addition, it is necessary to add one 3/2-way reversible directional control valve, which is connected to the suction branch of the compressor, in order to enable the selection of the air suction method (Figure 2, big orange rectangle).

- After that, it is necessary to transform the existing pneumatic control scheme into a compressed air recovery scheme by selecting the actuators from which the exhaust air collection will be carried out and adding the appropriate components (in this case, non-return valves) in order to obtain a meaningful system. As the existence of air exhaust in the system is mandatory, it is clear that air can not be collected from all actuators. Figure 2 therefore shows that air is collected from *n* actuators (positions 1A1-1An) and that there are *m* other actuators (positions 2A1-2Am) in addition.
- In order to enable the smooth operation of the entire system, it is necessary to define the minimum and maximum value of the operating pressure in the additional tank where the air is collected. The minimum value is the value that ensures stable operation of the compressor and it is approximately 0.9 bar [13]. On the other hand, the maximum value is the value at which the dynamic characteristics of the system will not be disturbed, and it must not exceed 52.8% of the actuators inlet pressure value [14]. It is understood that the value of the input pressure is equal to the highest value of all the minimum values that are required to start the actuators.
- At the very end, it is necessary to start the system in automatic operation mode and monitor the state of pressure in the additional tank. If the pressure value in the additional tank is within a predefined range, the compressor would only use the alternative suction from the additional tank. Also, if the amount of compressed air is excessive, the excess of the collected compressed air will need to be exhausted into the atmosphere. For this reason, it is necessary to install one additional 2/2-way directional control valve (Figure 2, little green rectangle), which is connected to tank. Otherwise, if the collected amount of air is insufficient, after some time, the compressor has to use the main suction line and ambient air again.

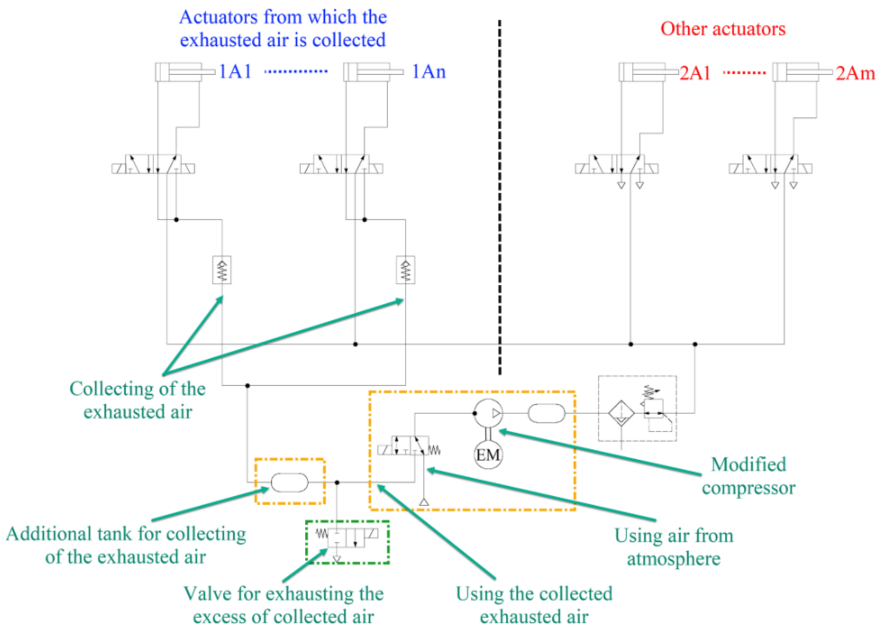

Fig. 2 Concept for transformation of the existing pneumatic control scheme into a compressed air recovery scheme by returning of the used air to the production section

For the sake of easier understanding of the defined mode of operation, Figure 3 shows the algorithm for development and control of the energy efficient system with energy recovery of compressed air in such a way that it is returned to the section for the compressed air production.

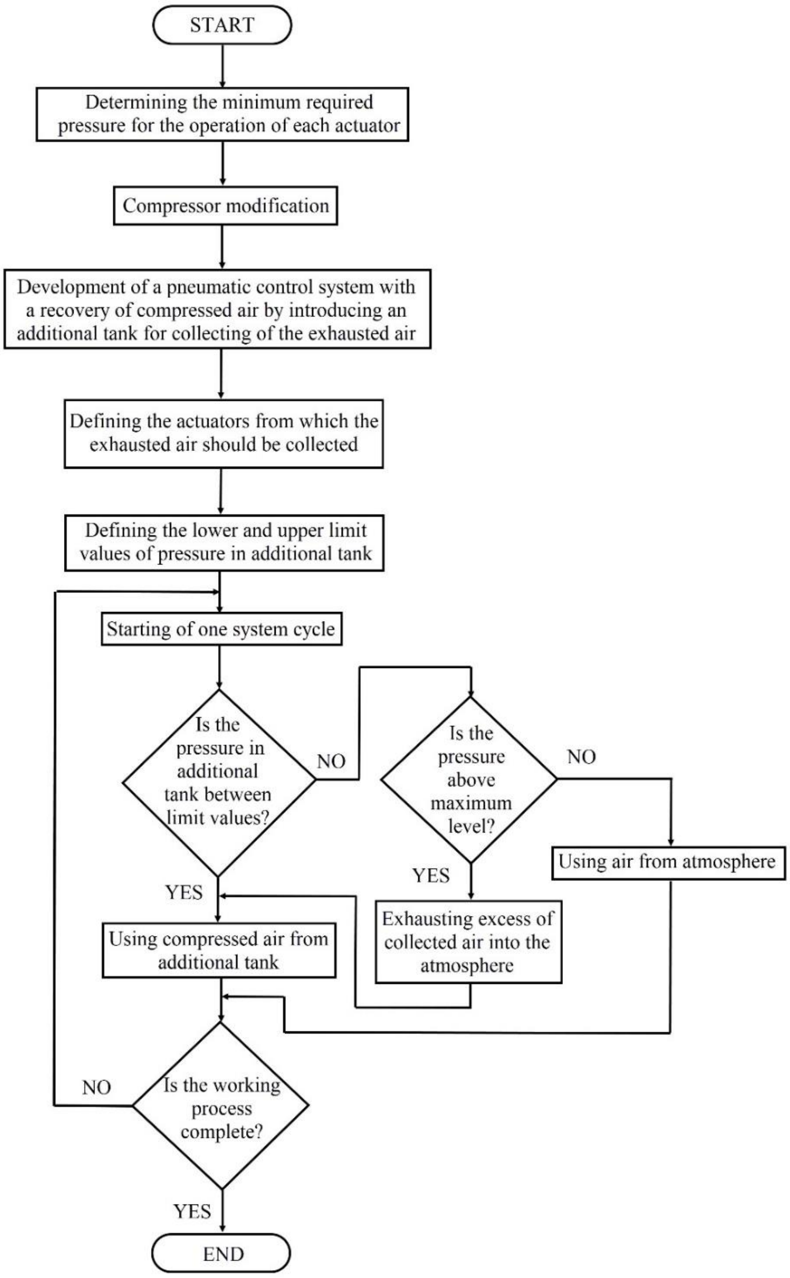

Fig. 3 The process of returning of the used air to the production section

2.2. Returning of used air to the consumption section

To collect used compressed air and return it to the consumption part of the system, it is necessary to implement a complex control scheme, and the control of such a system is quite complicated [7]. In order to implement such a control scheme, as in the previous case, it is necessary to go through several steps:

- At the very beginning, it is necessary to define the minimum values of the operating pressures, that is, the minimum forces required to start each of the actuators.
- In the next step, it is necessary to transform the existing pneumatic control scheme into a scheme with compressed air recovery by selecting actuators from which exhaust air will be collected (Figure 4, positions 1A1-1An) and adding appropriate components in order to obtain a meaningful system. In addition, it is necessary to define the actuators that will use the collected compressed air (Figure 4, positions 2A1-2Am) from the additional tank (Figure 4, little orange rectangle) for the working or return stroke in the appropriate work cycles. Also, it is possible that there are actuators that work in the traditional operation mode in the system. In the case of actuators from which exhausted air is collected, the mentioned additional components are non-return valves. On the other hand, in the case of actuators that use collected air, it is necessary to add two 2/2-way directional control valves, in order to allow the use of compressed air from two separate sources (Figure 4, big orange rectangle). In addition, it is necessary to add one quick exhausted valve to allow unhindered air exhausting and at the same time to speed up the process as much as possible. It is clear that this is not the only solution. For example, it is possible to use OR logic valve and 3/2-way directional control valves, but all that would additionally increase the investment costs.
- After that, it is necessary to define the minimum and maximum value of the operating pressure in the additional tank in which the air is collected. The minimum value is the value that ensures stable operation of the actuator that uses compressed air from the additional tank at a given time and may vary depending on the system [7]. On the other hand, as in the previous case, the maximum value is the value at which the dynamic characteristics of the system will not be disturbed, and it must not exceed 52.8% of the actuators inlet pressure value [14]. It should be noted that, in this case, it is also assumed that the value of the input pressure is equal to the highest value of all the minimum values required to start the actuators.
- At the very end, it is necessary to start the system in automatic mode and monitor the pressure value in the additional tank. If the value of the pressure in the additional tank is within the predefined range, the system will constantly use the collected air for the successful performance of the defined work operations. If it happens that the pressure value in the additional tank exceeds the maximum, in order not to impaire the dynamic characteristics of the system, it is necessary to release all the excess of collected air from the additional tank into the atmosphere. For this reason, it is necessary to install one additional 2/2-way directional control valve (Figure 4, little green rectangle), which is connected to tank. On the other hand, if the collected amount of air is insufficient, after some time, the system will again have to use air directly from the compressed air supply.

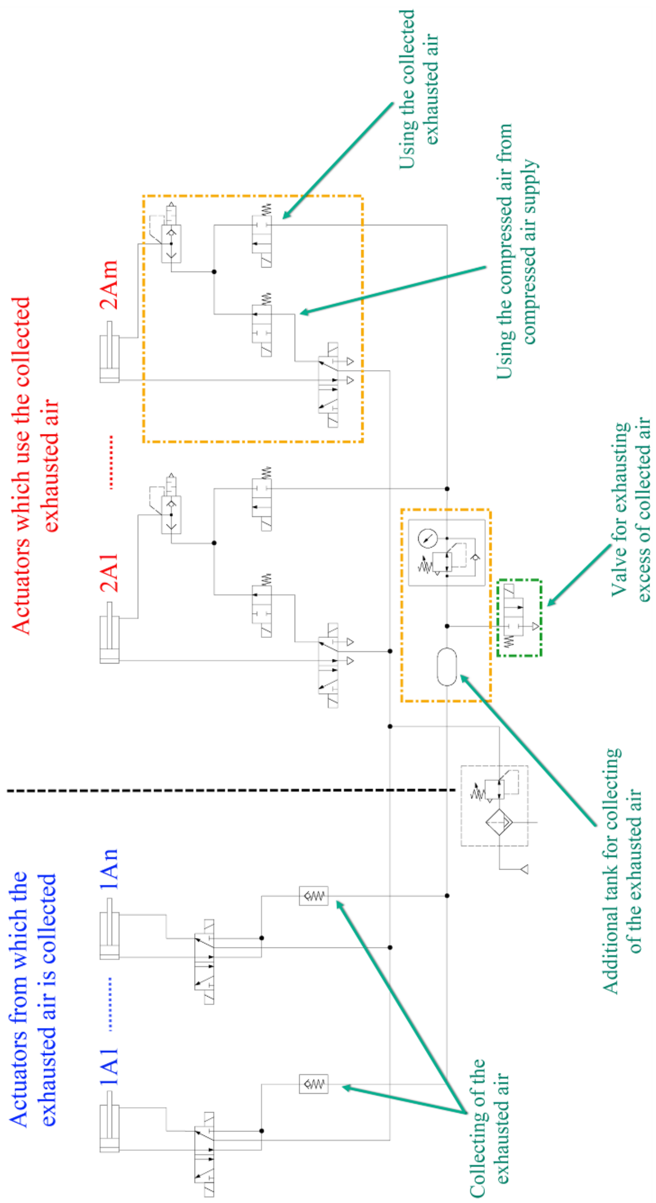

Fig. 4 Concept for transformation of the existing pneumatic control scheme into a compressed air recovery scheme by returning of the used air to the consumption section

For the sake of easier understanding of the defined mode of operation, Figure 5 shows the algorithm for development and control of the energy efficient system with energy recovery of compressed air in such a way that it is returned to the consumption section.

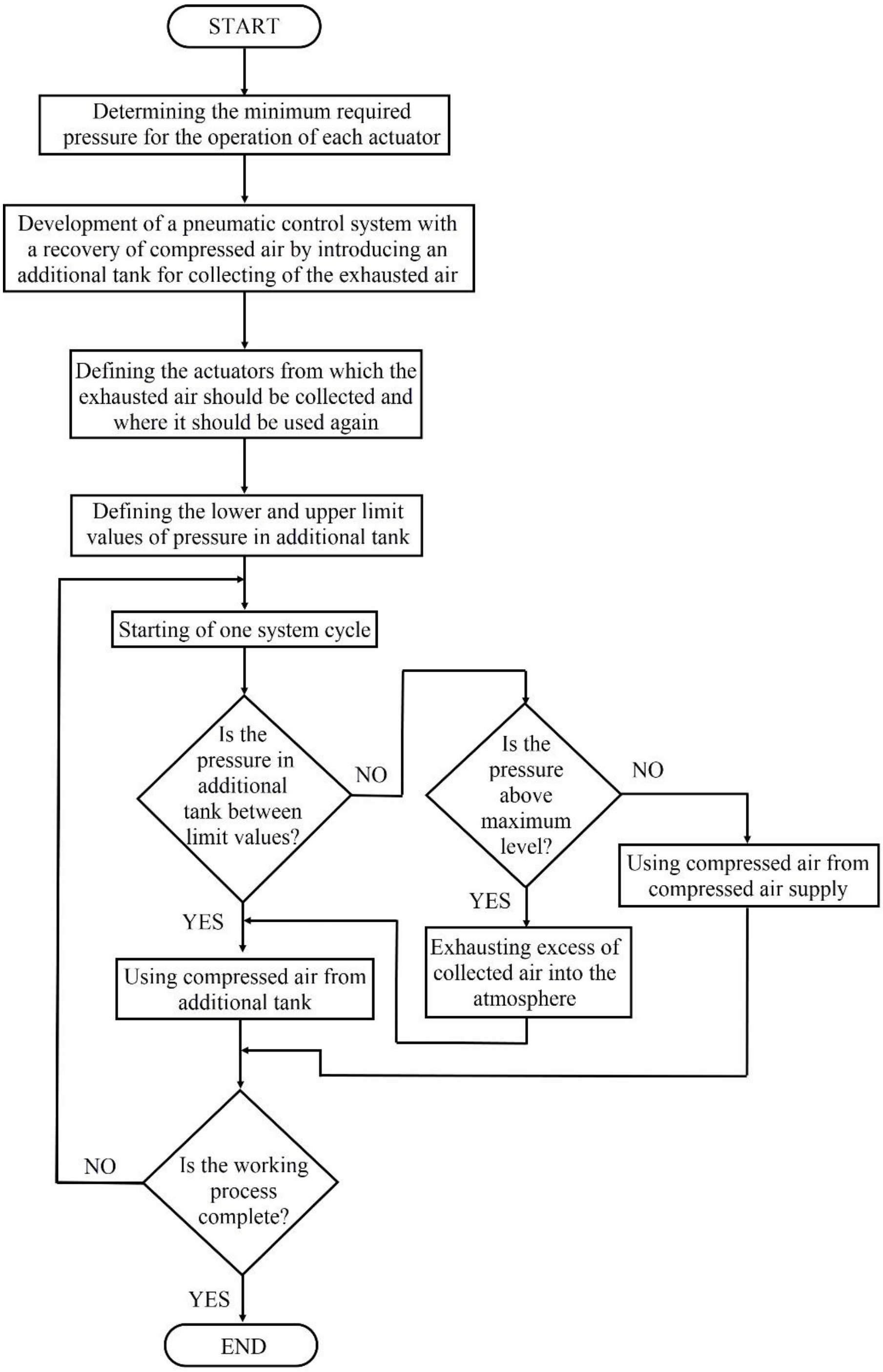

Fig. 5 The process of returning of the used air to the consumption section

3. Results and Discussion

In the manner described in Section 2, it is possible to develop and implement pneumatic control schemes and systems with energy recovery of compressed air. Thus, more energy efficient systems are obtained in terms of compressed air consumption. Namely, in paper [13] it was shown that, by returning of the used compressed air to the production part, up to 24% can be saved, and in paper [7] it was shown that, by returning of the used compressed air to the consumption part, can save up to 37% of energy. Of course, it should be borne in mind that the mentioned percentages directly depend on the initial state, the very choice of actuators from which the used compressed air will be collected and, in the case of return to the consumption section, on the choice of actuators that will use the collected air. Accordingly, the savings in some cases can be even greater, and it is really justified to talk about significant energy savings by applying the mentioned procedures.

What is particularly interesting for analysis is the very way of using the collected compressed air. Namely, in Figures 3 and 5 it is shown that, in case of exceeding the maximum allowed pressure value in the tank, all excess air must be released into the atmosphere because the dynamic characteristics of the actuator and the smooth operation of the system must not be impaired. This is also a net loss because that compressed air was collected previously during system operation. An alternative option is that, when the upper limit of the operating pressure in the tank is reached, the collection process is stopped and, in the next few cycles of the system, the air from the additional tank is just consumed. However, this entails a higher investment cost because the electrically activated directional control valves would need to be installed on each line leading to the additional tank, that is, between each of the actuators from which the air is collected and the additional tank. If the first option is used, which implies the release of excess air from the additional tank, only one additional control valve is needed, which would allow/interrupt the release of air from the reservoir to the atmosphere, as shown in Figures 2 and 4.

Additionally, the increase in cycle time that occurs in cases where an additional tank is implemented to collect already used air from the system is particularly interesting for analysis. Namely, in the paper [7] it was shown that the increase in the duration of the work cycle goes up to 38%. Therefore, the productivity of the system is reduced.

Therefore, on the basis of the above, it is clear that the process of energy recovery of compressed air brings significant energy savings, but that, depending on how the system is designed, there are also negative consequences, in terms of unnecessary release of collected air or extension of the duration of production cycle. All this leads to the conclusion that the system with energy recovery of compressed air needs to be carefully designed in order to use the advantages of recovery in the best possible way, and reduce the disadvantages to the smallest possible extent. For this reason, in the continuation of the paper, an algorithm is given that represents the systematic procedure for the development of an energy efficient system with energy recovery of compressed air (Figure 6).

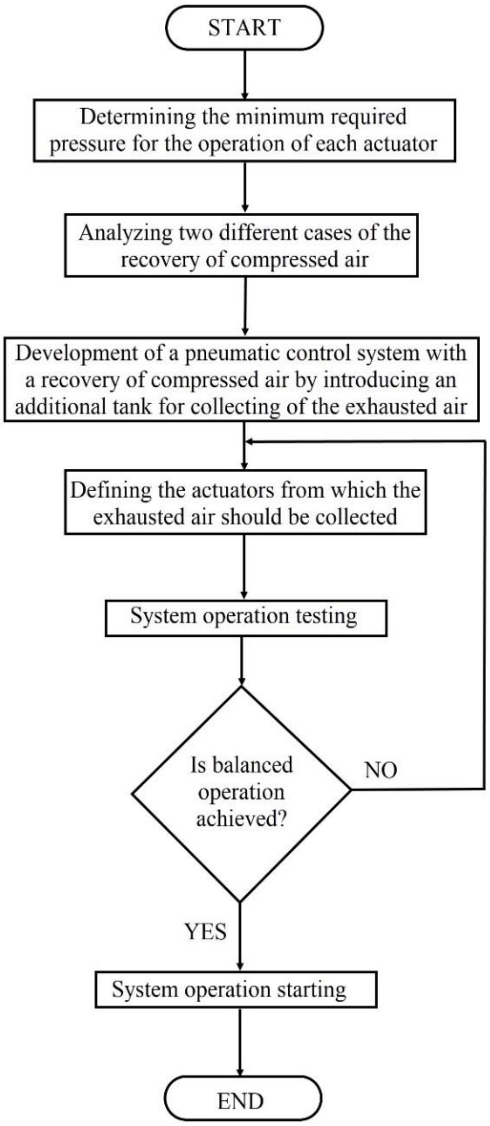

Fig. 6 Systematic procedure for the development of an energy-efficient system with the recovery of compressed air

The proposed algorithm includes several steps:

- In the first step, it is necessary to define the minimum required forces for starting each of the actuators. Based on this, a conclusion is made about which actuator requires the highest pressure value, that is, which actuator sets the critical conditions of the system. This operating pressure value is also the lowest possible inlet pressure value at which the entire system can operate without problems. In addition, in this step, a conclusion is made about which movement of actuators require the least force, that is, which work operations are the easiest to perform. Those work operations can potentially be performed by using the compressed air from an additional tank.

- In the next step, it is necessary to do a careful analysis of what type of recuperation is possible, that is, whether it is necessary to apply recuperation with the return of the collected air to the consumption section or to the section for compressed air production. It is important to note that the upper value of the operating pressure in the tank, defined as 52.8% of the actuators input pressure value, is identical for both cases and that, as already mentioned, it depends on the critical conditions, that is, on the actuator that requires the highest value of the operating pressure. On the other hand, the lower value, in the case of returning of the used air to the production part, is limited to 0.9 bar, and in the case of returning of the used air to the consumption part, it depends on the actuators that require the least force. If this value is less than 0.9 bar, the wider permissible range of operating pressure is obtained in the additional tank than when returning of the used air to the consumption section. If this value is greater than 0.9 bar, the wider permissible range of operating pressure in the additional tank is when returning of the used air to the section for compressed air production. The width of the permissible operating pressure range in the tank is a very important parameter for choosing the desired recovery mode, but certainly not the only one. It is necessary to additionally analyze the investment costs and draw appropriate conclusions based on that.
- After choosing the recovery method, it is necessary to modify the existing control scheme by adding appropriate components in order to obtain a meaningful system and define the actuators from which exhaust compressed air collection will be performed, as shown in Figures 2 and 4.
- The proposed solution needs to be tested in the continuation of the work. As previously mentioned, three scenarios are possible during the system operation: the pressure value in the additional tank is below the lower limit, it is in the defined range, and it is above the upper limit. In the cases where the value of the operating pressure in the additional tank is below the lower limit, there is not enough air to perform the desired operation, so it is necessary to either restart the main intake (if a system with air return to the production section is used) or use compressed air directly from the supply source (if a system with air return to the consumption section is used). On the other hand, if the value of the operating pressure in the additional tank is above the upper limit, in both cases of recuperation, it is necessary to either stop the collection process until the pressure value in the additional tank falls to the permitted level, or release all the excess air at the appropriate moment in time so that the pressure value fell to the permitted level. Based on the above, it is concluded that it would be best if none of these two unwanted situations would occur, that is, the best possible case would be if the pressure value in the additional tank would always be within the defined limits. In that case, a balanced operating mode is obtained, that is, the system approximately consumes as much collected air from the additional tank as was collected during the previous operating cycle in each subsequent operating cycle.
- In case of obtaining a balanced operating mode of the system, it would also be the final solution. In case that the balanced operation mode is not obtained in the proposed way, it would be necessary to modify the control scheme again by determining a new group of actuators from which air will be collected and retest the operation of the system. The described procedure should be repeated until a balanced operating mode is obtained.

4. Conclusion

In this paper, a brief overview of the possibilities for implementation of energy efficient compressed air systems with energy recovery is presented. Two different ways of forming closed pneumatic circuit by recuperating compressed air (with returning the used air to production or consumption section) as well as the potential energy savings in these cases were analyzed. In accordance with that, a comprehensive systematic procedure for implementation of energy efficient compressed air systems with energy recovery was developed in the form of an algorithm. This algorithm shows how it is possible to modify existing or develop new pneumatic control systems in order to increase their energy efficiency in an optimal way.

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