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ACTUATION AND CONTROL OF ELECTRIC VALVES FOR A MAGNETIC REFRIGERATOR

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Abstract. *Synchronization between the hydraulic and magnetic circuits in a magnetic refrigerator is fundamental to its operation and overall efficiency. Most of the prototypes reported in the literature apply face-to-face sealing (rotary valves) or some other mechanically actuated flow distribution systems to allow oscillatory fluid flow through the active magnetic regenerators. However, the use of such mechanisms in magnetic refrigerators has demonstrated limited versatility in controlling the synchronization between the hydraulic and magnetic circuits. Additionally, they are frequently the largest contributor to the energy consumption of the device, compromising its efficiency. Therefore, the aim of this work is to develop a control system for a new hydraulic circuit with a set of electric valves in place of the mechanically-actuated valves. This control system ensures the desired synchronization of the fluid blows with the magnetic field variations. The results indicate that the use of such valves and control system allows for better flexibility in the operation and synchronization of a magnetic refrigerator as well as lower energy consumption.*

Keywords: *Magnetic refrigeration, electric valve, synchronization*

1. INTRODUCTION

Magnetic refrigeration is a cooling technology based on the magnetocaloric effect (MCE), which is the thermal response of certain magnetic materials to a variation in magnetic field. Room-temperature magnetic refrigeration applies thermal regenerators composed of magnetocaloric materials, known as *active magnetic regenerators* (AMRs), to enable heat transfer from the working fluid to the thermal reservoirs, while also amplifying the temperature span. The heat transfer in AMRs occurs during oscillatory flow steps (cold-to-hot and hot-to-cold blows) of a thermodynamic cycle, which also includes magnetic field variation steps (magnetization and demagnetization) that must be synchronized with the fluid flow.

Commonly, the control of such synchronization is performed by piston-pump and check valves combinations (Tura and Rowe, 2011; Trevizoli, 2015) or mechanically-actuated valves (Hirano *et al.*, 2010; Engelbrecht *et al.*, 2012; Jacobs *et al.*, 2014; Aprea *et al.*, 2014; Lozano, 2015; Ericksen *et al.*, 2015; Nakashima *et al.*, 2017). The rotary valves stand out among those valves as the same mechanical transmission system can be used to power both, the magnetic and the hydraulic circuits, thus synchronization is guaranteed. However, torque oscillations in the magnetic circuit causes flow imbalance between the blow periods of the cold and hot flows, and the face-to-face sealing mechanism employed in rotary valves requires high power consumption due to friction. An alternative solution was proposed by Ericksen *et al.* (2015), who applied cam-actuated poppet valves. Although this has proven to be efficient and less energy intensive, recent developments in magnetic cooling point to a need for more flexible flow parameters, such as the duration of the fluid flow (Nakashima, 2017). Therefore, Cardoso *et al.* (2016) proposed to replace the mechanical-actuated valves by electric valves, whose electronic control could result in lower energy consumption and greater versatility to operate the system.

The application of electric valves in a magnetic refrigerator requires an electrical circuit to actuate the valves, a system to detect the applied magnetic field and an actuation logic that ensures the desired synchronization of the fluid blows with the magnetic field variations in the AMR. Therefore, this work aims to develop a control system for the hydraulic circuit of the AMR test apparatus originally developed by Trevizoli *et al.* (2016) and recently updated for operating with electric valves by Dutra *et al.* (2017). This control system will allow reproducing and extending the synchronization analysis proposed by Nakashima (2016). Fluid flow distribution in the present version of the apparatus has been put into practice using four electric valves, whose opening and closing times were synchronized with respect to the applied magnetic field measurement by a transistor-based control system. Blow time *fraction* variation was also included in the control logic. The results showed good agreement between the expected and the actual synchronization, establishing the electric valves as a viable option for low energy consumption and flexible hydraulic and control solutions for AMRs.

2. EXPERIMENTAL SETUP

The active magnetic regenerator apparatus developed by Trevizoli (2015) at Polo/UFSC has been updated by Dutra *et al.* (2017) to include four solenoid valves to replace the rotary valves applied previously in the hydraulic circuit by Nakashima (2017). The main purpose of this apparatus is to obtain experimental data of cooling capacity, fluid temperatures and energy consumption of a single AMR, therefore enabling an in-depth characterization of this component. Figure 1 shows a schematic diagram of the main components of the modified AMR apparatus.

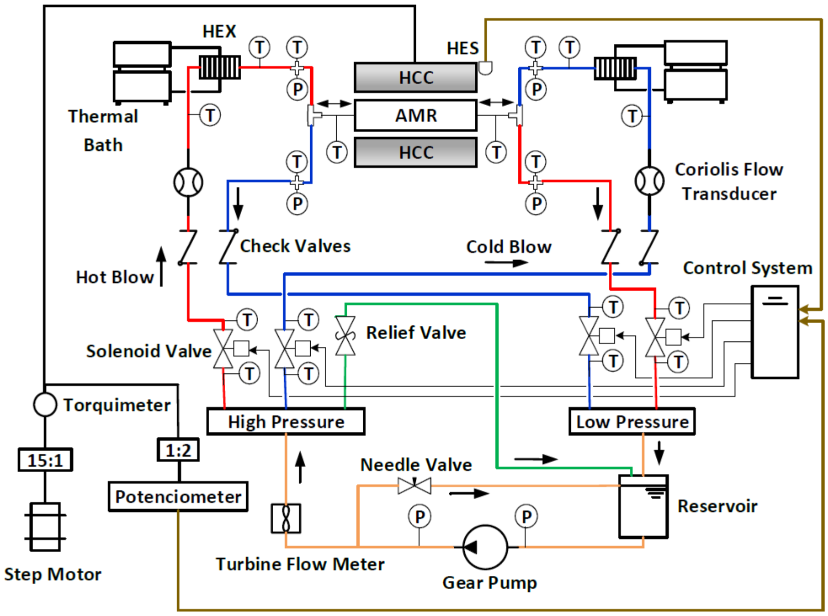


Figure 1. Schematic diagram of the AMR apparatus developed by Trevizoli (2015) and updated by Dutra *et al.* (2017) to use electric valves as the flow distribution system.

The working principle of the AMR apparatus consists in continuously pumping the fluid as indicated by the arrows in Fig. 1, and starting at the high-pressure manifold. In parallel, a step motor drives the magnetic circuit composed of two Halbach concentric cylinders (HCC). The rotation of the HCC promotes variation of the magnetic field intensity, and its waveform is measured by a Hall effect sensor (HES). The synchronization of the flow with the magnetic field applied to the AMR is controlled by the opening time of the electric valves. When an AMR is magnetized, a fluid blow from the cold reservoir to the hot reservoir occurs through the AMR, thus, the control system actuates two electric valves (high and low-pressure valves). When the material is demagnetized, the control closes this pair of valves and opens the other pair to allow the fluid flow in the opposite direction, from the hot reservoir to the cold reservoir.

The magnetic field applied on the AMR has a sinusoidal behavior over time, which varies from a minimum to a maximum value. A complete rotation (360º) of the HCC system comprises two complete AMR cycles (two magnetization and demagnetization processes), as represented in Fig. 2(a). The definition of the steps of the AMR cycle is influenced only by the intensity of the magnetic field, regardless of its polarity. So, for a better understanding, the magnetic field is presented as both normalized and absolute values to facilitate the visualization of the magnetization and demagnetization intervals, as shown in Fig. 2(b). These intervals are delimited in Fig. 2 by the dotted line at $\sin(\pi/4)$.

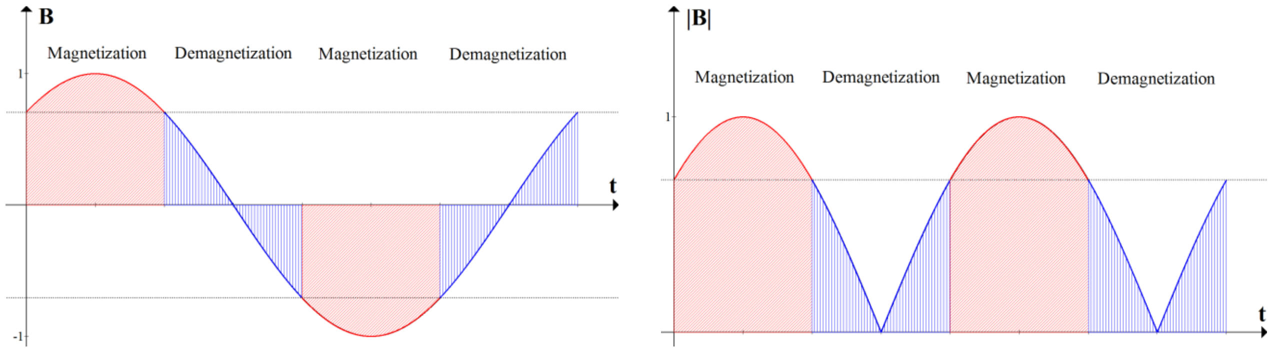


Figure 2. Magnetic field behavior during a complete rotation of the HCC system in (a) normalize and (b) normalized and absolute values.

The detection of the applied magnetic field applied on the AMR is fundamental to an adequate synchronization of the profiles. The magnetic field transient waveform allows definition of the magnetization and demagnetization processes, which are necessary for the AMR thermodynamic cycle. Due to the presence of the porous regenerator and the limited space inside the magnetic gap of the HCC system, the Hall effect sensor has to be placed near one of the ends of the HCC system during operation. Measurements of the magnetic field were performed without the AMR inside the inner magnet to define the most appropriate location for the sensor and to determine the correlation between the waveform measured by the sensor positioned near the end of the HCC and those in other locations inside the magnet system. Figure 3 shows three data sets corresponding to different positions along the center line of the HCC. Near the ends of the magnet system, (L = 87.5 and 112.5 mm) the magnetic field is much less intense than in the center position of the magnetic gap (L = 0 mm), but all waveforms are in phase, which means that the Hall effect sensor (HES) can be positioned virtually anywhere in the magnetic gap. Therefore, the Hall effect sensor (HES) was positioned at L = 105.5 mm, where the HES is capable of accurately detecting the applied magnetic field without interfering with the positioning of the AMR.

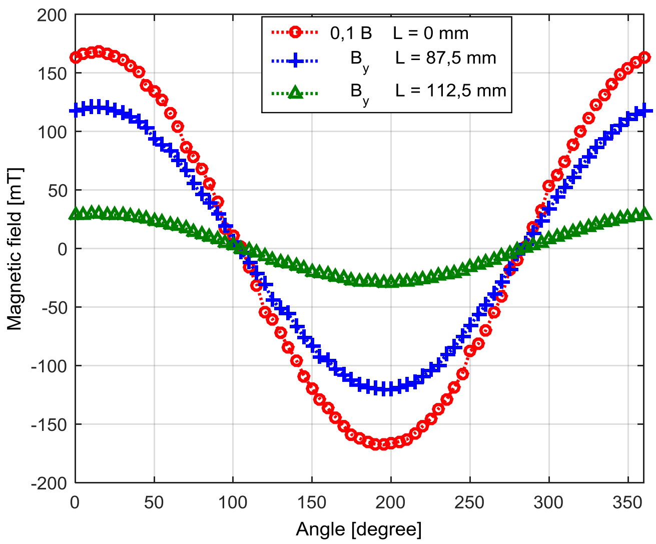


Figure 3. Magnetic field measurements in different longitudinal positions of the magnetic gap length.

The energy consumption required to actuate the electric valves may not influence greatly the overall energy consumption of a magnetic refrigerator when compared to other operating equipment, such as the pump or the motor. However, in an attempt to maintain the overall efficiency of the device as high as possible over a wide range of operating conditions, components with low energy consumption, short response time and low noise are always desired. Therefore, MOSFET transistors were selected to drive the electric valves. The MOSFET is a voltage device that, upon receiving a trigger voltage applied by the control system, closes the power circuit thus triggering the electric valves. The MOSFETs selected for this application have a lower energy consumption (~10 mW) and a faster response time (~100 ns) in comparison to other switches, such as relays.

3. SYNCHRONIZATION LOGIC

In the present apparatus, the cold and hot blows are synchronized and in phase (i.e., centered) with respect to the maximum magnetization and minimum demagnetization fields, respectively. However, the control system developed in this work is capable of shifting this synchronization, if necessary. It is also desired that the flow distribution system allows for adjustments of the fluid blow parameters, such as the blow time fraction (F_B) through the regenerator (Nakashima, 2017). F_B is the fraction of the total cycle period during which the blows are executed. The replacement of mechanical valves by electric valves requires a synchronization control logic to actuate the valves at appropriate times with the applied magnetic field on the AMR and to allow correction of flow imbalance. In this work, it has been assumed that both blows have always the same F_B and the system does not require imbalance correction because the flows are independent of the torque in the magnetic circuit. Figure 4 illustrates the triggering signal to the electric valves for different values of F_B, assuming no time delay associated with the opening and closing of the valves (response times).

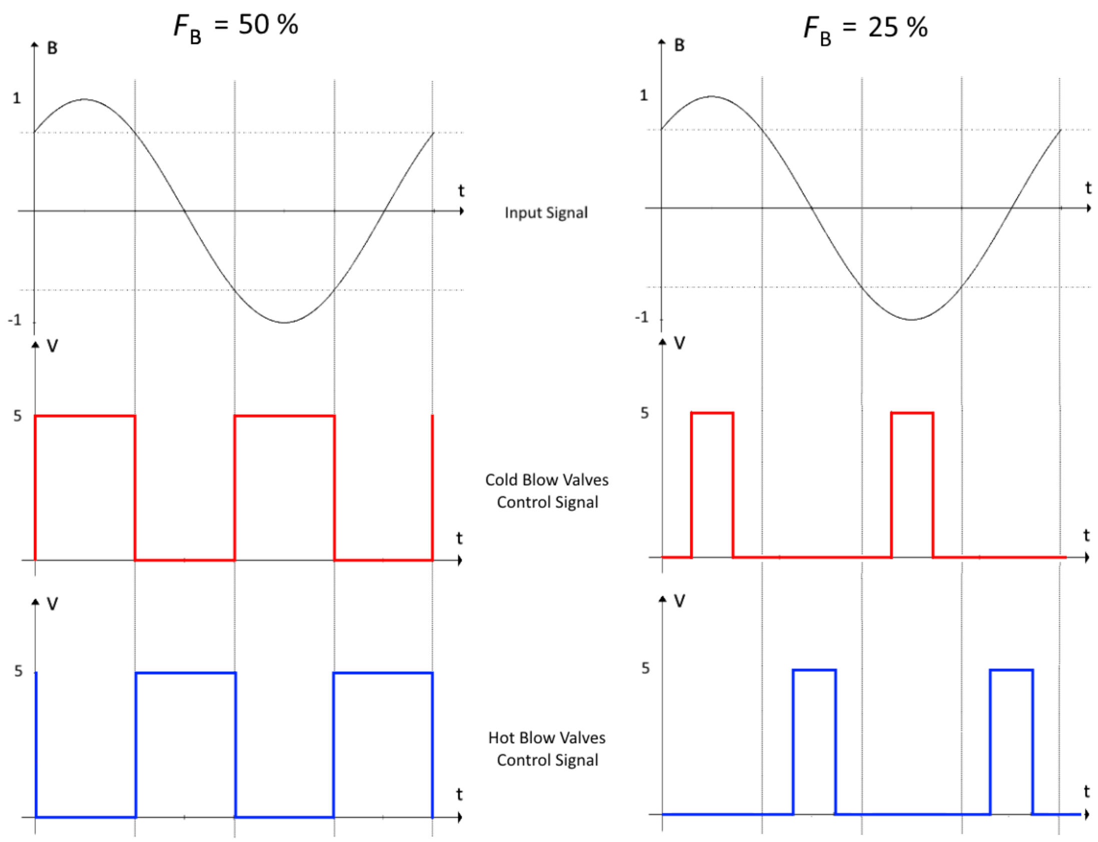


Figure 4. Representation of magnetic and electrical control signals for different blow time fractions.

The actuation control of electric valves requires some knowledge on the transient behavior of the fluid flows and should also consider the delay due to valve response time (opening and closing response). If this delay is not considered in the control logic, the blows would not occur within the expected times and the system would not perform at its best. Different types of valves and system components influence the response time of the system in different ways. Therefore, it is necessary to analyze each particular system to determine these response times. The response closing time (τ_C) of an electric valve is defined in this work as the sum of the time it takes until the valve spool begins to close (τ_{SC}) after the control signal is sent and the time required for the flow to reduce to 10% of its initial value ($\tau_{C10\%}$), as shown in Eq. (1). Similarly, the response opening time (τ_O) of an electric valve is calculated as the sum of the time it takes for valve spool to start opening (τ_{SO}) and the time until the flow reaches 10% of its final value ($\tau_{O10\%}$), as shown in Eq. (2). These response times are highlighted in Fig. 5, in which typical experimental results of the regenerator pressure drop and the current applied to the corresponding pair of solenoid valves are shown during the closing and opening processes.

$$\tau_C = \tau_{SC} + \tau_{C10\%} \tag{1}$$

$$\tau_O = \tau_{SO} + \tau_{O10\%} \tag{2}$$

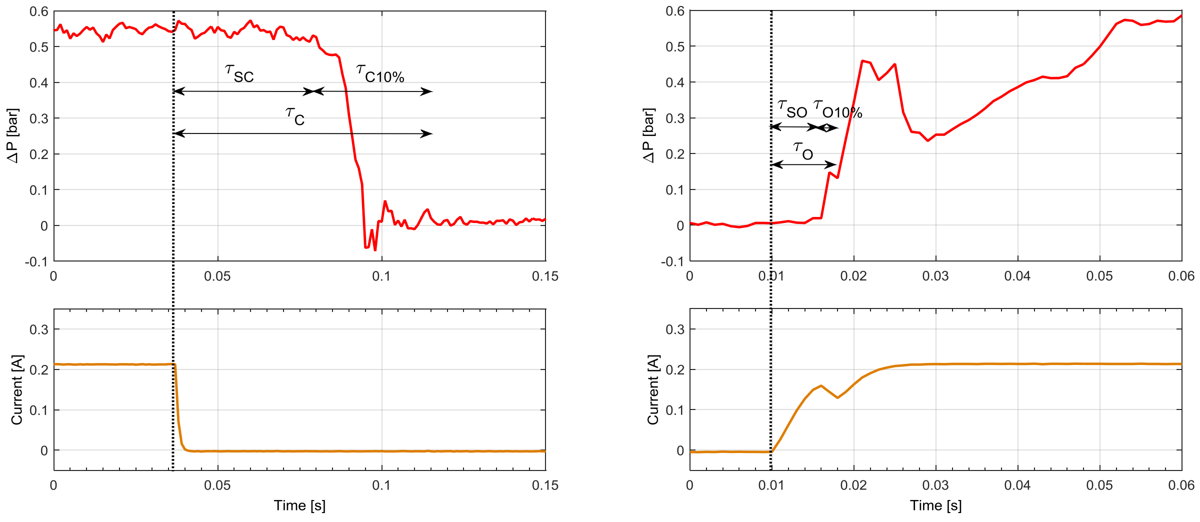


Figure 5. Experimental analysis to obtain response times of the system.

The control logic implemented in this work anticipates the opening times of the valves by τ_O and the closing times by τ_C, so that the hydraulic blows occur at the desired instants through the AMR. The synchronization logic has been divided into three interconnected modules, as show in the diagram in Fig. 6.

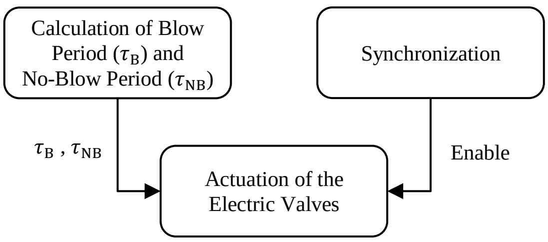


Figure 6. Synchronization control logic proposed in this work and its three modules.

The blow period, τ_B, is defined as the time duration of a blow over the AMR, while the no-blow period, τ_{NB}, is defined as the time duration with no blows in the AMR, when the fluid is by-passed through the relief valve at the high-pressure manifold back into the reservoir. The synchronization logic calculates these periods with the experimental data obtained from HES and a pre-defined F_B value entered as an input to the software. Furthermore, as the system suffers from parametric perturbations over time until it reaches steady state (e.g., AMR cycle frequency minor variations), these values are periodically updated.

The calculation of the blow periods starts by measuring the magnetic field (B) during a pre-defined time window (τ_{aq}). After the field measurement, the data are used to determine the amplitude field (B_{amp}), and the AMR cycle frequency (f_{AMR}) as follows:

$$f_{AMR} = \frac{f_{MF}}{2} \tag{3}$$

where f_{MF} is the magnetic field frequency, detected by the HES, and with this value it is possible to determine the blow period,

$$\tau_B = F_B \times \frac{1}{f_{AMR}} \tag{4}$$

and the no-blow period,

$$\tau_{NB} = \frac{1}{2 f_{AMR}} - \tau_B \tag{5}$$

These values are updated and reported to the actuation module. The module of the calculation of the blow and no-blow periods is shown in Fig. 7.

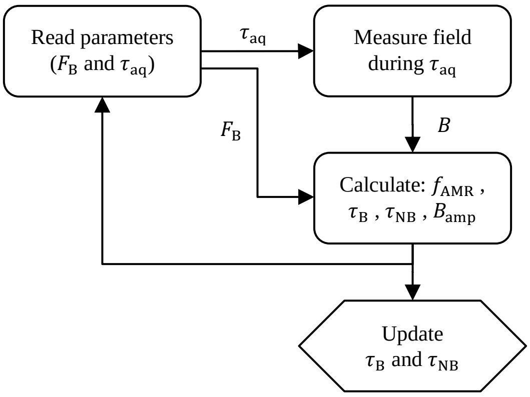


Figure 7. Module responsible for the calculation of the blow and the no-blow periods.

The module corresponding to the synchronization is shown in Fig. 8. This module is responsible for measuring the magnetic field in real time in order to activate the electric valves at the correct times when the field reaches the expected trigger value. The data obtained by HES are normalized and modularized to range from 0 to 1, obtaining a rectified sinusoidal waveform over time (as that in Fig. 2(b)). The trigger point to the actuation module occurs when the signal reaches 0, corresponding to the center of the demagnetization period and the minimum applied magnetic field on the AMR.

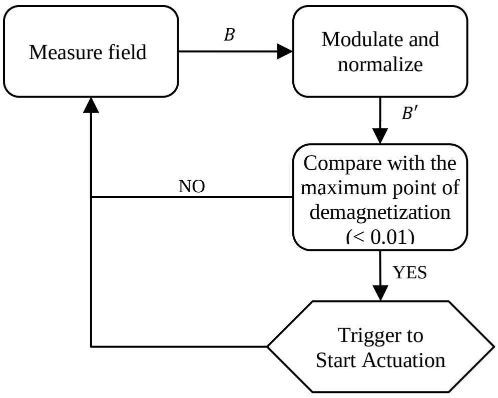


Figure 8. Module responsible for identifying the initial moment for the actuation of the electric valves.

The module for actuation of the electric valves, shown in Fig. 9, is responsible for sending the drive signals to the electric circuit of the valves at the appropriate times. When the actuation module receives the trigger signal from the synchronization module, the AMR is in the middle of the demagnetization process. So, the valve pair which was initially open (PAIR 1), is closed after half hot blow period to guarantee synchronization between the blows and the maximum/minimum absolute values of the magnetic field. The wait times between the valves actuation always consider the response time of the valves (τ_C and τ_O). At the end of the actuation cycle, the hot blow valves are open and the logic waits for the trigger that will start the cycle again.

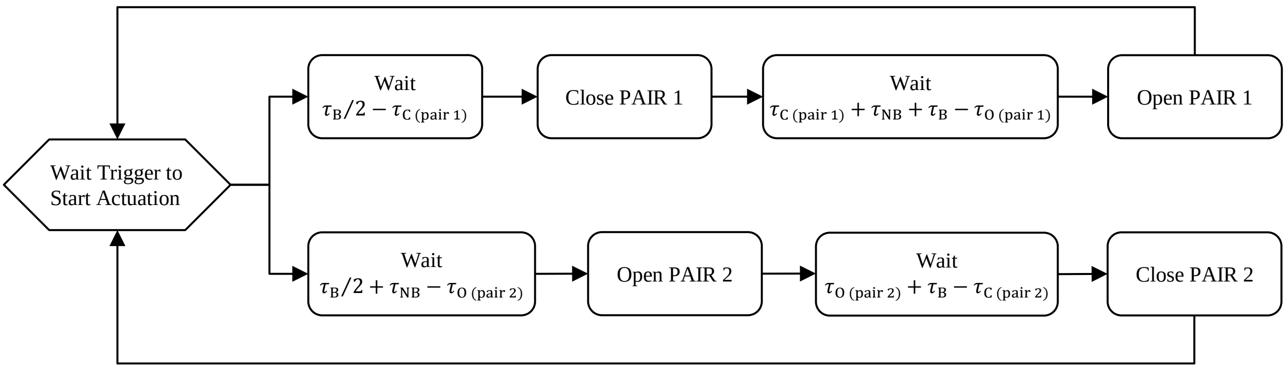


Figure 9. Module responsible for actuating the electric valves.

The synchronization control logic mentioned in this section was implemented in the LabVIEW software and the results are presented in the next section.

4. RESULTS AND DISCUSSION

This section is devoted to the presentation of the results obtained after the synchronization logic was implemented in the updated AMR apparatus operating with electric valves. The actuation and control logic allows for synchronizing the blows with the actual magnetic field according to pre-defined input parameters, such as the blow time fraction.

The response time of the valves was preliminarily defined by analyzing the flow behavior when a valve pair was triggered, as shown in Fig. 5. Analysis of the flows obtained as a result of the actuation of the electric valves was performed in different pressure drop in the AMR, which indicates the flow waveform in the regenerator. Therefore, a null value means that there is no blow, while a positive difference means that cold blow is occurring and negative difference indicates the hot blow, as show Fig. 10.

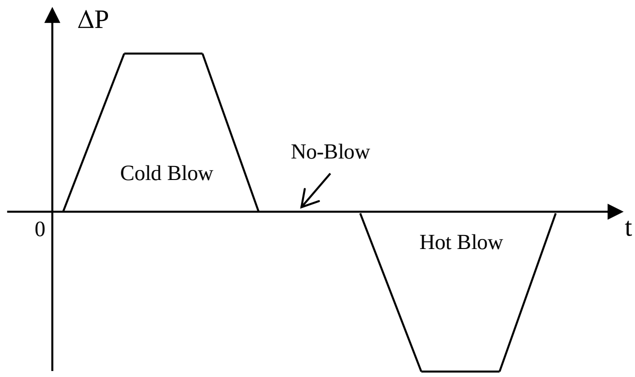
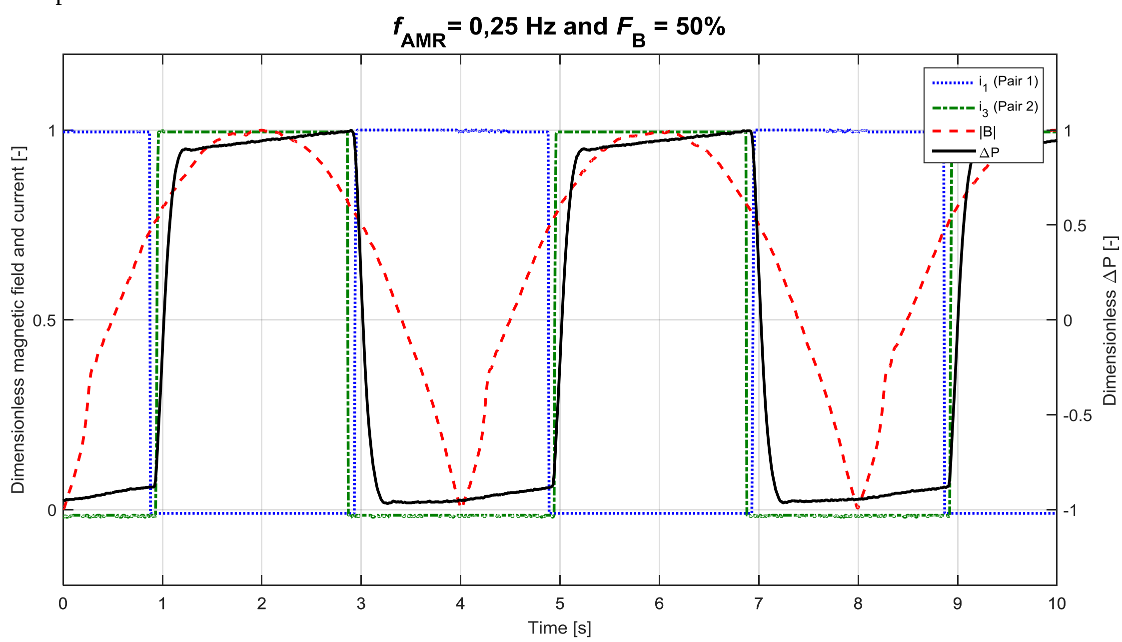


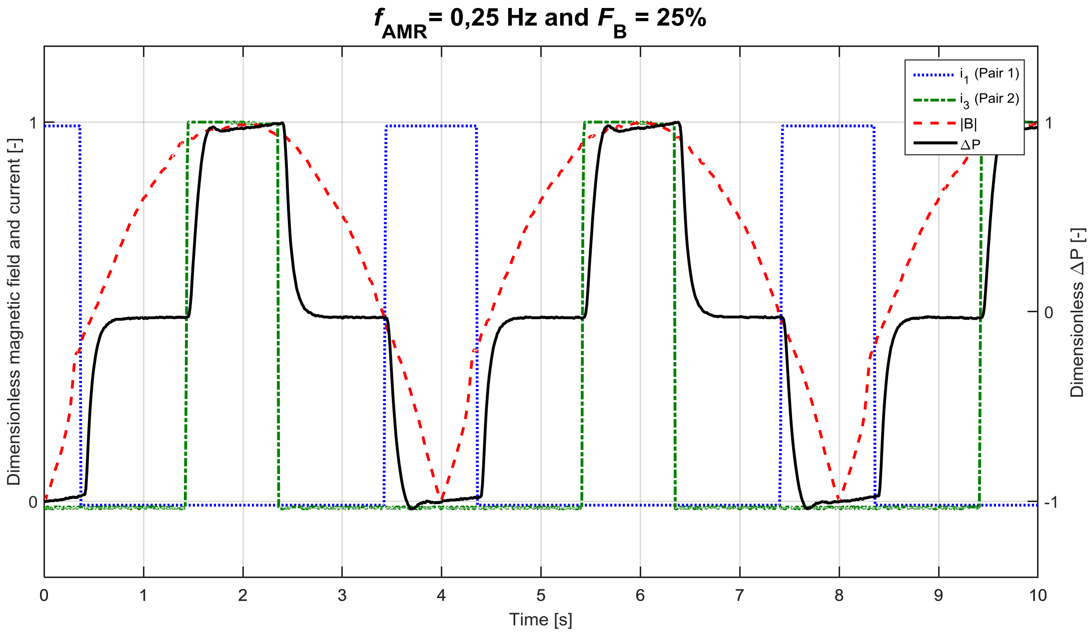
Figure 10. Representation of the flows indicates by the different pressure drop in the AMR.

Figure 11 shows the measured magnetic field signal (red line) and treated by the synchronization module, along with the valves electric current signals and the pressure drop in the AMR. All signals were normalized for better visualization. The results in Fig. 11(a) were obtained during the AMR operation with a blow time fraction of 50% and an AMR frequency of 0.25 Hz. The current signals show that there is a relatively short time interval between the closing and opening of different pairs of valves. This is related to delay correction of the valve response time (τ_C = 78 ms and τ_O = 8 ms). Figure 11(b) shows similar results for a F_B of 25%.

Pressure drop results show that the blow variation in the AMR occurred synchronously with the magnetic field, and they were also centered with the maximum and minimum points of the magnetization and demagnetization processes, as it was expected.



(a)



(b)

Figure 11. Synchronization of blows with the magnetic field at (a) F_B of 50% and (b) F_B of 25%.

5. CONCLUSIONS

An actuation and control system for a set of electric valves required to operate an active magnetic regenerator (AMR) apparatus was proposed in this work. A control logic was developed and shown to successfully actuate the electric valves and synchronize the oscillatory flows with the applied magnetic field for a specified blow time fraction (F_B). Thus, the operation of a magnetic refrigerator with electric valves allows for great flexibility when compared to the use of mechanically-actuated valves, especially when flow imbalance effects need to be corrected. The application of electric valves as a flow distribution system in AMRs has the potential to improve efficiency of a magnetic refrigerator and reduce the energy consumption of an AMR if low energy consumption valves are employed.

6. ACKNOWLEDGMENTS

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