EXPERIMENTAL ANALYSIS OF ENERGY CONSUMPTION OF PIEZO ACTUATORS USED IN HYDRAULIC SWITCHING VALVE

Marko Simic[1]*, Niko Herakovic[1]

[1] *University of Ljubljana, Faculty of Mechanical Engineering, Askerceva 6, 1000 Ljubljana, Slovenia*

* Corresponding author: Tel.: +386 1 4771 797; E-mail address: marko.simic@fs.uni-lj.si

ABSTRACT

This paper presents a four-way digital piezo valve system (*4WDPVS*) composed of four high-response switching piezo valves. The main part of the new switching valves introduces the piezo actuator system (PAS) used instead of conventional solenoids. One of the important aspects in digital hydraulic systems is the use of energy-efficient switching hydraulic valves that assure low switching energy and low holding power consumption in the steady-state open valve state. First, the theoretical background of piezo technology is presented. Second, a detailed description of the new piezoelectric actuator system used in switching valves and four-way digital piezo valve system. The main part presents experimental analysis of the electrical energy consumption of the new piezoelectric actuator system. To validate and compare the electrical switching energy and the holding power consumption, several existing switching valves were used as reference. The results show a huge reduction of electrical energy consumption when using the new PAS for hydraulic switching valve actuation. Especially the holding power consumption in the stationary active state is about 6 times lower compared to other existing hydraulic switching valves controlled by solenoids.

Keywords: hydraulic switching valves, piezo actuators, energy consumption, digital piezo valve system

1. INTRODUCTION

The development of smart and energy-efficient hydraulic and pneumatic systems is demanded to design sustainable production systems for the factories of the future. Besides the hydraulic energy efficiency, the improvement of the electrical energy efficiency of the control components, i.e. the valves, has a major potential on the overall energy consumption reduction of the hydraulic and pneumatic system.

There were several developments in the past two decades that show the potential how to improve energy efficiency of hydraulic and pneumatic systems. Optimizing the shape of hydraulic valve housing and spools to reduce both, the static and dynamic flow forces, presents one of the solutions [1]. Lower flow forces lead to a reduced actuation force requirement for the valve, enabling the use of low-power solenoids.

A more promising solution for energy-efficient hydraulic and pneumatic systems is digital fluid power technology. The primary challenge in digital hydraulics and switching technology remains the development of fast, reliable, and energy-efficient on/off valves [2]. To significantly reduce electrical energy consumption, a single on/off valve within a digital fluid control unit (*DFCU*) can benefit from appropriate boosting control methods [2]. This involves using a high initial switching control voltage and then maintaining a lower voltage to keep the valve open in a stationary state, leading to reduced holding power and energy consumption in steady-state conditions. Alternatively, high-response, low-power valve actuators are being explored. Concerning switching energy, miniature valves with flow rates up to 6 l/min have reasonably low switching energy ranging from 0.7 to 0.011 J [3]. Developing high-response and energy-efficient on/off valves with a larger nominal size remains a challenge. A promising solution involves the use of piezoelectric actuators. FESTO has demonstrated their integration into pneumatic high-response valves for pneumatic linear drives, with piezo on/off valves boasting a remarkable 20-times reduction in switching energy compared to conventional solenoid counterparts [4]. There are some studies focused on developing low-power, high-response piezo valves suitable for electrohydraulic direct-drive servo valves and pilot-operated servo valves [5]. In terms of energy efficiency, amplified piezoelectric actuators, combining flexure joints with piezo stacks, have been employed in brake systems. These piezo actuators consume a mere 21 mJ of energy, as opposed to the 950 J consumed by solenoid actuators, showcasing substantial energy savings [6]. Other studies in piezo technology concentrate on methods for conserving and reusing energy through piezo effects and efficient control systems. Energy-harvesting units, featuring piezoelectric elements placed in oscillating systems like bridges, walkways, motorways, and railways, generate and store electrical power. These units can produce up to 11.7 mW of output power using piezo stacks [7]. Additionally, units embedded in walkways offer 3-120 mW of output power [8]. Energy harvesting can extend to rotational motion through rotational shafts with integrated bending piezo actuators [9]. Results suggest suitability for low-speed rotation, with an average power output of up to 0.564 mW. Research in the field also explores how bridge vibrations impact energy harvesting, with optimal electronic resistance and location enhancing the potential energy savings, reaching approximately 579 μJ [10].

Existing literature lacks a detailed analysis of the electrical energy consumption of direct-operated on/off piezo valves. This paper addresses this gap by providing a comprehensive examination of the energy consumption of a novel piezo actuator system (*PAS*), which serve as an actuator in direct-operated hydraulic on/off valves. Understanding the behaviour and electrical characteristics of piezo stacks during hydraulic valve operation empowers us to anticipate the electrical energy consumption of *DFCU* during development.

2. PIEZOELECTRIC ACTUATORS

Considering the piezoelectric stacks as main elements of the hydraulic on/off valve actuators, the energy consumption depends on several parameters such as the maximum operating voltage, the capacitance of the piezo stacks and the switching frequency. In this investigation the focus is in the determination of the switching energy per single piezo stack, that is the energy, needed to fully charge the piezo stack and maintain active state.

2.1. Piezoelectric actuator as RC electrical circuit

The piezoelectric actuator can be described with an *RC* electrical circuit (**Figure 1**), where *R* is the electrical resistance and *C* the capacitor representing the piezo stack.

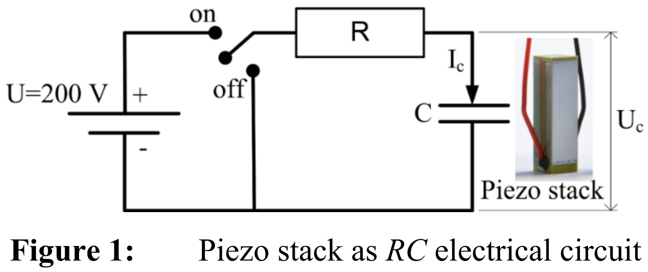


Figure 1: Piezo stack as *RC* electrical circuit

Charging and discharging the piezo stack is achieved by applying the electrical voltage to the capacitor through the switching connector (on-off). The electrical current I_c appears in the *RC* circuit in the charging and discharging phase, which is determined by equation (1), where q is the electrical charge, C is the capacitance of piezo stack, and U_c is the measured electrical voltage.

$$q = C \cdot U_c \tag{1}$$

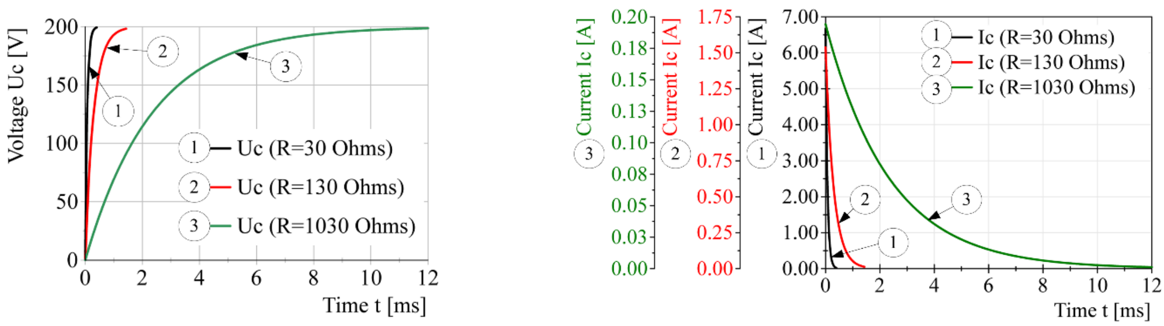
The step response of the first-order system is characterized by time constant τ presented by equation (2). By considering the *RC* electrical circuit, the final equation describing the electrical voltage $U_c(t)$ and the electrical current $I_c(t)$ can be formed with equations (3) and (4), respectively.

$$\tau = R \cdot C \tag{2}$$

$$U_c(t) = U_0 \cdot \left(1 - e^{\frac{-t}{R \cdot C}}\right) \tag{3}$$

$$I_c(t) = I_0 \cdot e^{\frac{-t}{R \cdot C}} \tag{4}$$

Figure 2 and **Figure 3** represent the theoretical curves of electrical voltage and the electrical current. For the given examples including different electrical resistances R and consequently different time constant τ, the parameters of the mathematical models were set to the real conditions of piezo control electronics and piezo stack. In this investigation the maximal operating voltage U_0 =200 V, the electrical resistance of the electronics R=30 Ω, 130 Ω, 1030 Ω and the capacitance of the piezo stack C = 2.285 μF were considered. The minimum electrical resistance R=30 Ω (curve No. 1) is chosen according to the initial measurements of the step response of the piezoelectric actuators and the on/off valves. Other possible electrical resistances, such as R=130 Ω (curve No. 2) and R=1030 Ω (curve No. 3) can be achieved by adding the external resistance unit to the primary piezo control electronic circuit.



a) Charging the piezo

b) Discharging the piezo

Figure 2: Electrical voltage U_c and current I_c as a function of electrical resistance R

The theoretical results of the electrical voltage and electrical current presented in **Figure 2a** and **Figure 2b** show major differences in terms of the voltage increase and current decrease. The low electrical resistance R=30 Ω leads to the superior step response of the electrical voltage (U_c) increase, as well as the electrical current (I_c) decrease. The step response is approximately 0.2 ms. On the other hand, higher electrical resistance (R=1030 Ω) leads to the poor step response of the voltage U_c, and the electrical current decrease I_c.

2.2. The electrical power and energy consumption determination

The power $P(t)$ can be calculated by using the equation (5). A graphical presentation of the power curves for the different electrical resistances R is shown in **Figure 3**. Very high peak power, up to 330 W, is achieved due to high electrical current when using low electrical resistance R=30 Ω. On the other hand, high power is needed for a very short time period (approximately 0.2 ms to charge the piezo stack up to 99%). Curves No. 2 and No. 3 represent the power defining the electrical resistances of 130 Ω and 1030 Ω, respectively. According to the theory, there is no need for any power to maintain the piezo stack's elongation after the piezo stack is charged. One of the important tasks of our investigation is to validate this theoretical statement considering the real working conditions.

$$P(t) = U_c(t) \cdot I_c(t) \tag{5}$$

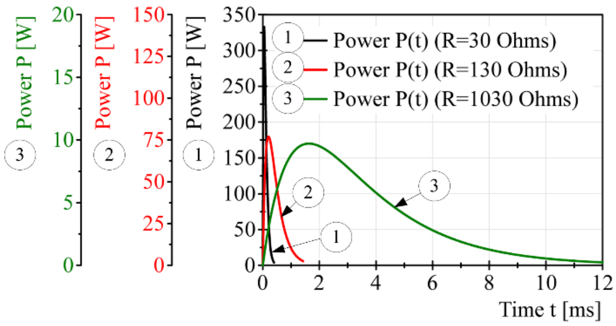
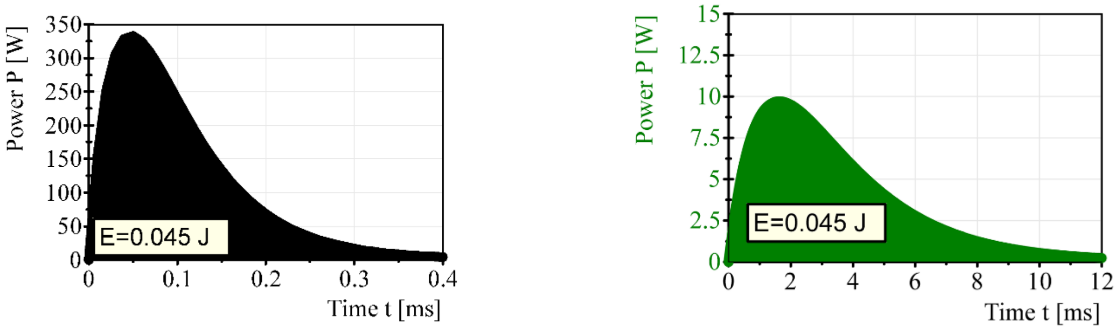


Figure 3: Power *P* as a function of electrical resistance *R* - charging the piezo stack

The energy consumption, i.e., the switching energy (E_{switch}) of the piezo stack for all three cases, presented in **Figure 3**, is defined as the area under the power curve. For a better understanding the power curves and the areas representing the switching energy for the electrical resistances of *R*=30Ω and *R*=1030Ω are shown in **Figure 4a Napaka! Vira sklicevanja ni bilo mogoče najti.**and **Figure 4b**. Equation (6) is used to calculate the switching energy. By comparing both switching energies, we can conclude that the energy needed to charge the piezo stack remains the same and it is not dependent on the electrical resistance *R* (E_{switch}=0.045 J).

$$E = E_{switch} = \int_{t1}^{t2} P(t)dt \tag{6}$$

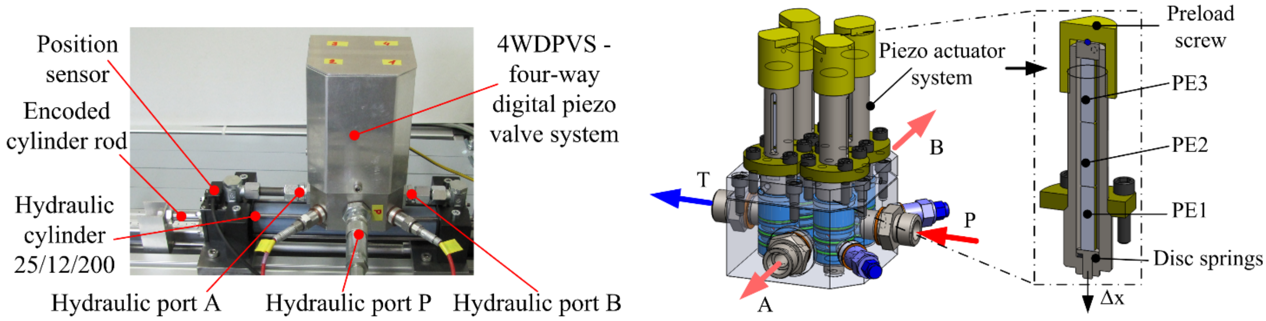


a) *R*=30 Ω b) *R*=1030 Ω

Figure 4: Switching energy as a function of electrical resistance - charging the piezo stack

3. DIGITAL PIEZO VALVE SYSTEM

The main component of the hydraulic linear drive (**Fugure 5a**) is a 4-way digital piezo valve system (*4WDPVS*). It consists of 4 on/off seat valves and 4 piezoelectric actuator systems (*PAS*), one per each valve. Peizoelectric actuator system is composed of 3 piezo stacks (*PE*) placed in serial (**Figure 5b**). The *PAS* with three piezo stacks enables several positions of the main spool of on/off valve and thus several discrete flow rates. The proper initial pretension of the piezo stacks is achieved with a preload screw and three disc-type springs placed in serial, thus preventing decoupling of piezo stack ceramic layers and achieving stable control. Activation of the piezo stacks corresponds to the piezoelectric actuator system stroke *Δx*. The different activation of piezo stacks corresponds to discrete *PAS* stroke *Δx* and discrete flow rates of a single on/off valve. As we deal with on/off control technology, activation of one piezo stack results in 28 microns of *PAS* stroke, the activation of two or three piezo stacks results in 52 and 72 microns of *PAS* stroke, respectively. Based on the static performance testing the stability of the *PAS* stroke as well as the valve spool displacement (valve opening) is high, which means the stroke error below 1%. *PID* control in combination with Pulse Number Modulation strategy was used to control all 12 piezoelectric actuators (4 on/off valves). For the experimental investigation, gear pump with a constant flow rate Q_P=3,7 l/min, the pressure filter with 3µm and return line filter with 10 µm filtration rate were used. The pressure relief valve with the nominal size of Q_{RV} = 10 l/min, was set to p_s= 60 bar. Two stage, single rod hydraulic cylinder PARKER HMI ISO (25/12/200, piston/rod/stroke) was used for all tests. The nominal size of the valve is up to 20 l/min at pressure drop $Δp$=5 bar. The position sensor was integrated with the position resolution of 1µm in order to perform the closed-loop position control.



a) Hydraulic linear drive under investigation *b) 4WDPVS*

Figure 5: Hydraulic linear drive and new piezo valve.

4. MEASUREMENT METHODOLOGY AND EXPERIMENTAL SETUP

The experimental tests are performed in order to analyse and verify the theoretical prediction of the energy consumption of individual piezo stack. The scheme of hydraulic linear drive is shown in **Figure 6.**

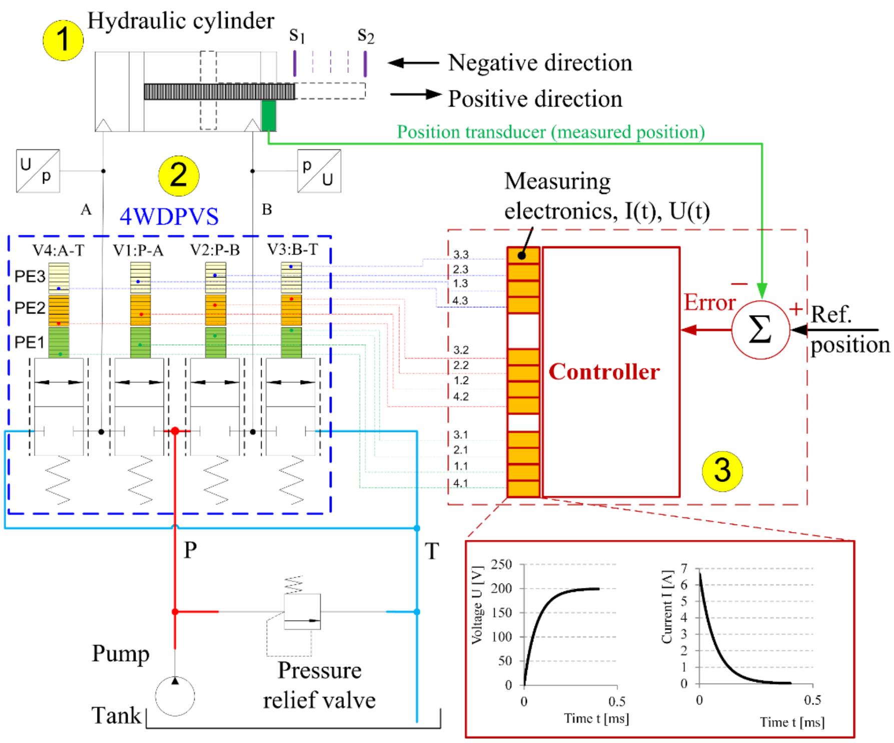


Figure 6: Measurement of electrical voltage and electrical current

The electrical energy consumption of the entire *4WDPVS* can be defined by considering all the active piezo stacks during the control cycle. It is also important to verify the theoretical prediction regarding the electrical energy consumption while the piezo stacks have already been charged and remaining in the stationary active state. Based on the fact that the *PAS* is exposed to external variable forces such as variable spring force of *PAS* and fluid forces during the operation we assume to measure small values of electrical current *I(t)*.

The detailed analyses of correlation between the active state of the piezo stacks and the electrical energy consumption of the piezo valves demands the electrical voltage (control signal) and electrical current measurement of the individual piezo stack during the test cycles. In order to measure the electrical current, the external measuring electronics with electrical current sensors ACS714 (measuring range up to ±30A and total output error of ±1.5%) was integrated in the controller unit [11]. The electrical voltage (U_c) is measured directly at the output signal of the control electronics. By measuring U_c and I_c, the power curve (P_c) and the energy consumption (E_c) are calculated. As we deal with on/off piezo valves and *PNM* control method, the electrical energy consumption represents the switching energy, which is needed to fully charge the piezo stacks, i.e., to open the single on/off valve.

The test cycle consists of the cylinder extension (positive direction) and cylinder retraction (negative direction) to the desired reference position. Four different reference positions s_2=25 50, 75 and 100 mm for the positive stroke of the cylinder and one reference position s_1=0 mm for the negative stroke of the cylinder were chosen for the test cycles (**Figure 7**).

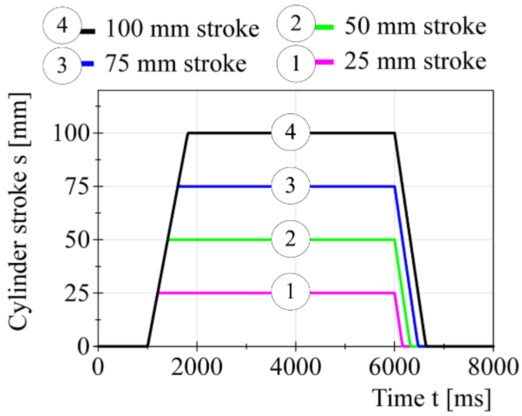
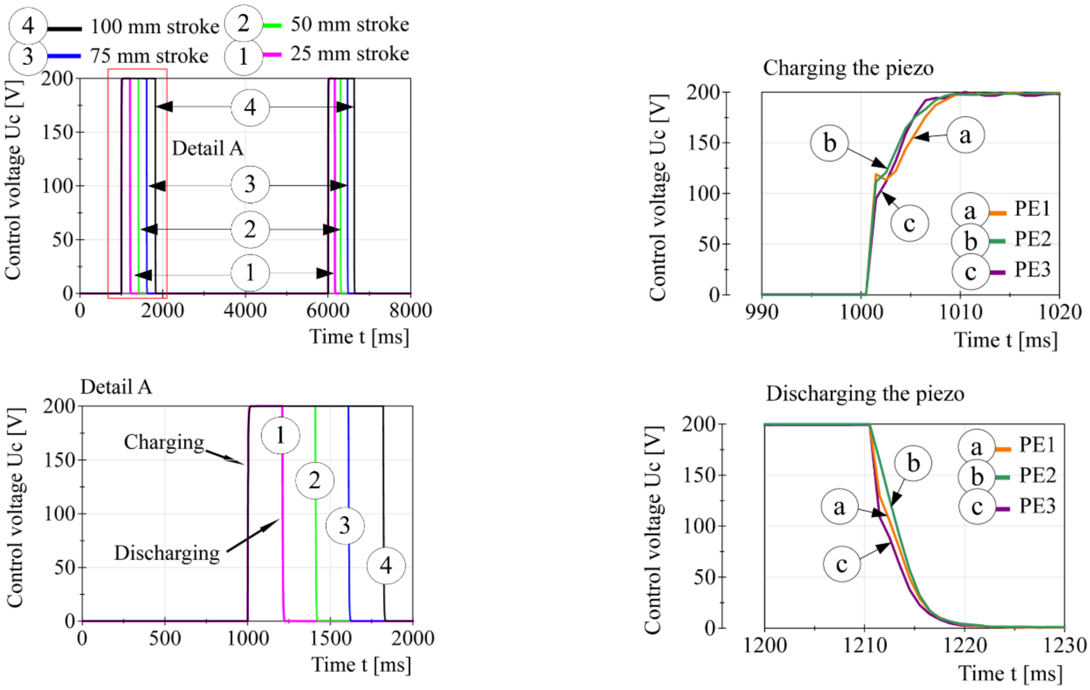


Figure 7: Cylinder stroke for test cycles

For each reference stroke of hydraulic cylinder five measurements were performed to measure *U(t)* and *I(t)*. The standard deviation of the measured parameters and the mean value were calculated using the statistical function in the NI DIAdem. The average results, calculated on the basis of five tests, of the electrical voltage and electrical current were considered in the interpretation of the results and in the final calculations of electrical power *P* and electrical energy consumption *E*. Since new *4WDPVS* operates with 12 control signals, one for each piezo stack *PE* of the on/off valve, the highest energy consumption is expected when all three piezo stacks of the on/off valve are activated at the same time during the test cycle (*P-A* and *B-T* valves for positive stroke and *P-B* and *A-T* for negative stroke of the cylinder). For our experimental tests the electrical resistance of the piezo control electronics *R*=1030 Ω was used that defines a measured step response of approximately 10 ms. We chose such electrical resistance for practical reasons. First, the *4WDPVS* has a sufficiently fast step response for closed-loop position control. Second, using a lower resistance would risk damaging the piezo stacks or necessitate increased pretension, reducing stack elongation. Third, theoretical analysis confirms that varying the *R* has no effect on energy consumption measurement results.

5. RESULTS AND DISCUSION

Figure 8a displays measured voltage curves for various test cycles, each based on five measurements per piezo stack. The standard deviation of measured voltage is less than 1 V. Notably, these curves correspond to individual reference position cycles. In **Figure 8a**, we observe two periods of maximum voltage amplitude for charging the piezo stacks during positive and negative cylinder strokes. During the positive stroke, each piezo stack requires a 200 V control signal (Detail A, Charging). After reaching the desired position, all piezo stacks in active on/off valves are switched off (Detail A, Discharging). This activation/deactivation strategy repeats for the negative cylinder stroke. For a 25-mm stroke cycle in valve *V1:P-A*, **Figure 8b** presents details of the average voltage curves for all three piezo stacks (*PE1*, *PE2*, and *PE3*) during the charging and discharging phases.



a) Measured U_c at stroke cycles

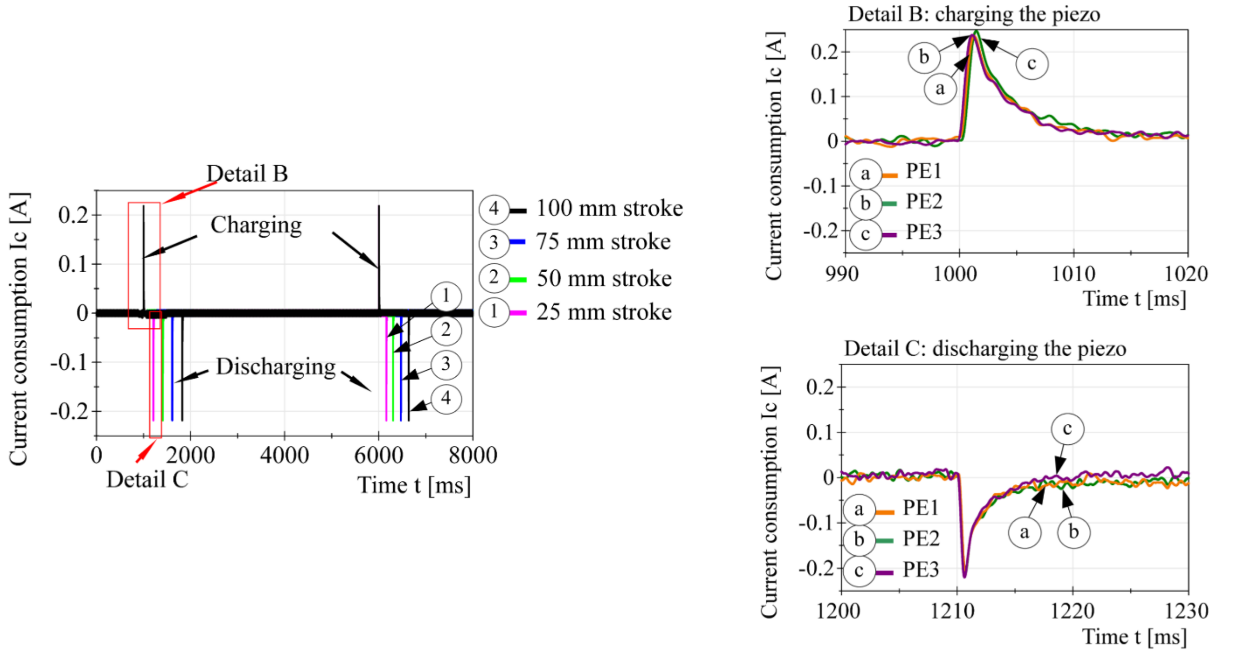
b) Detailed U_c (charging, discharging)

Figure 8: Measured electrical voltage during the test cycles

The results presented in **Figure 9a** and **Figure 9b** show the average electrical current consumption measured at piezo stacks in valve *V1:P-A* when performing test cycles. The average current-consumption curves are calculated based on five measurements for each piezo stack. The standard deviation of the measured current consumption does not exceed 0.01 A.

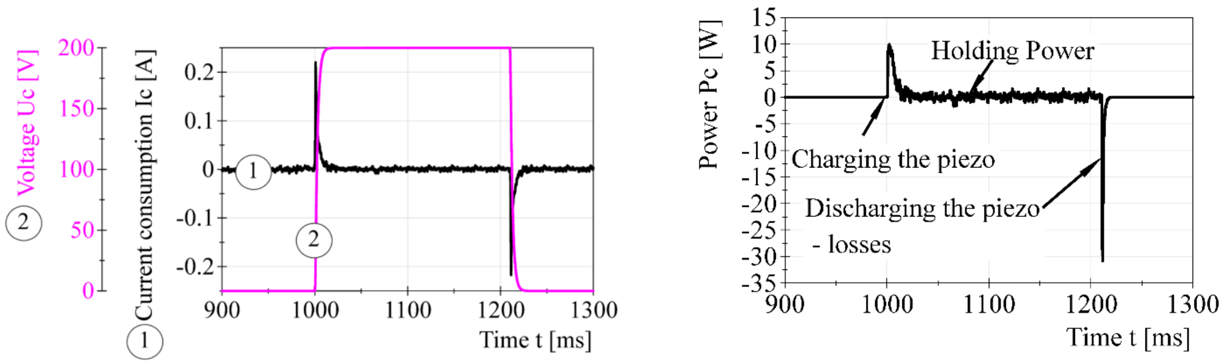
In line with theory, power is calculated using the average voltage and electrical current consumption for each piezo stack. **Figure 10a** illustrates the average voltage and current for piezo stack *PE1* in *V1:P-A*, specifically for the 25 mm test cycle. In **Figure 10b**, we calculate power (P_c) using equation (5). The crucial aspect of the P_c curve, regarding energy consumption, is the high-power demand during the charging phase. The peak power reaches 9.96 W, reflecting the piezo stack's maximum switching power. While this peak power is notably high, it's required for a short period, lasting around 3-4 ms for values exceeding electrical current 5 A. The calculated average power over the 210 ms duration of active piezo stack operation is a modest 0.46 W. When considering the activation of all three piezo stacks in the actuator system, the average power increases to 1.38 W.

Analyzing signal U_c (**Figure 10a**) alongside P_c (**Figure 10b**), we determine the energy consumption of a single piezo stack, *PE1* (**Figure 11**, curve No. 2). While charging the piezo stack, the energy consumption, denoted as $E_{c,PE}$, amounts to 0.07 J, exceeding the theoretical prediction of E_c=0.045 J. This increased energy consumption arises from the necessary low constant holding power during the stationary active state, approximately 11.9 mW. Over a 210 ms period, the energy consumption rises from 0.07 J to 0.095 J, impacting the overall energy usage of a single piezo stack in an on/off piezo valve. In essence, to maintain constant piezo stack elongation and keep the valve open, energy consumption increases by 0.0119 J per second.



a) Measured I_c during the test cycles, *PE1* b) Detailed I_c (charging, discharging)

Figure 9: Measured electrical current during the test cycles



a) Average voltage and current consumption b) Power curve of a single piezo stack

Figure 10: Average voltage and current consumption for 25 mm test cycle, *PE1*

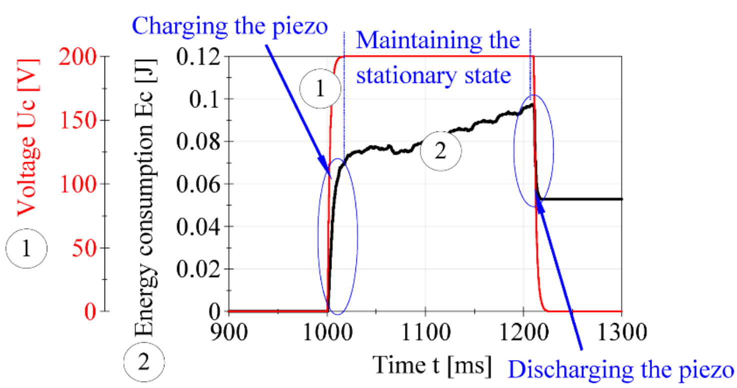


Figure 11: Energy consumption of piezo stack *PE1*, *P-A*

The energy-consumption curve shows an opportunity to save electrical energy when discharging the piezo stack. As we can see from **Figure 11**, the energy consumption drops from 0.095 J to approximately 0.055 J in the discharging phase. So potentially, 0.040 J of energy can be saved (up to 55% by considering the charging phase and the necessary switching energy). The energy savings can be made with proper new control electronics (energy harvesting circuit) and a new control algorithm, which is one of the main future goals.

The overall energy consumption of *4WDPVS* during the test cycles is presented in **Table 1**. The energy consumption considers the activation of all three piezo stacks per valve at the same time (activation of *PE1+PE2+PE3* of a single on/off valve). The energy consumption can be calculated by using empirical equation (7), where n is the number of activated piezo stacks, E_{switch} is the switching energy for the single piezo stack (0.07 J), T_{period} is the time period of active state of the piezo stacks and W_{hold} is the holding power (0.012 W) needed to maintain stationary state.

$$E\,[J] = n \cdot \left(E_{switch}[J] + \left(T_{period}[s] \cdot W_{hold}[J/s]\right)\right) \tag{7}$$

We also have to consider that the switching energy depends on piezo stack characteristics (capacitance), the type of the valve and operating pressure, i.e., the size of disturbance forces acting on the actuator during the valve operation. We can also conclude that the energy consumption is proportional to the time period and the number of the active piezo stacks.

Table 1: Energy consumption as a function of the active state of piezo stacks in *4WDPVS*

Cylinder stroke cycle [mm]	Active state *4WDPVS*	Period T_{period} [ms]	E_{4WDPVS} [J]
0 - 25		210	**0.435**
0 - 50	*P-A (3PE)*	410	**0.449**
0 - 75	*B-T (3PE)*	610	**0.464**
0 - 100		820	**0.479**
25 - 0		160	**0.432**
50 - 0	*P-B (3PE)*	300	**0.442**
75 - 0	*A-T (3PE)*	470	**0.454**
100 - 0		630	**0.465**

One of the goals of this study is to compare the energy consumption of the new on/off piezo valve with other on/off valves on the market or prototypes. **Table 2** presents the characteristics of our *4WDPVS* unit compared with some other on/off valves. The new *4WDPVS* has three possible discrete opening and thus three piezo actuators states (1*PE*, 2*PE* or 3*PE*). The remarks in the table mean: (p) - peak power, (h) - holding power and / - no data available.

Traditional 2/2-way direct operated seat valves are often powered by 22 W solenoids, leading to high holding power and energy consumption. Some commercial valves have been modified to use low-power solenoids, while others employ a boosting control method. This approach uses a high voltage signal initially and then reduces the holding voltage to the minimum required to keep the valve open, thereby decreasing holding power. For example, valves like SUN DLV and SI-1000 have reduced peak power from 22 to 15 W and operate with 2 W and 3 W of holding power. The optimized on/off valve (*WHV*), coupled with new control electronics and an intelligent boosting control method, achieves significantly lower switching energy and holding power consumption compared to traditional valves. Although the switching energy is comparable to our new on/off piezo valve, the prototype *WHV* still exhibits over six times higher average holding power consumption for valves of the same size. Furthermore, a prototype small water hydraulic valve for pilot-stage control achieves low switching energy of 0.011 J through innovative pilot-stage design and advanced *PWM* control.

Table 2: Characteristics of *4WDPVS* in terms of energy consumption

Characteristics Manufacturer	Valve type	Switching energy [J]	Power [mW]
UL FME LASIM *4WDPVS*	**Directional seat, piezo actuator**	**0.07 (1*PE*)** **0.14 (2*PE*)** **0.21 (3*PE*)**	**9.96*10^3 (p)** **12 (h)** **14 (h)** **36 (h)**
Rexroth KSDER0 N/P [12]	2/2 seat valve	/	22*10^3(h)
Hydac WS08W [13]	2/2 seat valve	/	20*10^3(h)
Parker GS02-73 [14]	2/2 seat valve	/	22*10^3(h)
SUN DLV [15]	2/2 seat valve	/	15*10^3 (p)
Bucher WS22GD [16]	2/2 seat valve	/	15*10^3(h)
Tampere University of Technology WHV [17]	2/2 seat valve	≈0.05 (WHV1 AC) ≈0.07 (WHV2 AC) ≈0.15 (WHV2)	120(h) 80(h) 75(h)
Tokio Institute of Technology [18]	Pilot-operated seat valve	0.011	/

6. CONCLUSIONS

This paper presents an extensive experimental analysis of a novel piezo actuator system (*PAS*) comprising three piezo stacks integrated into hydraulic on/off valves, forming a four-way digital piezo valve system (*4WDPVS*). These digital valve systems serve as the primary control components for high-performance, energy-efficient hydraulic drives, replacing traditional hydraulic solenoid on/off valves in the *DFCU*.

The experimental findings demonstrate a substantial reduction in electrical energy consumption for hydraulic on/off piezo valves compared to conventional direct operated solenoid on/off valves. Switching energy is comparable to the best low-power on/off valve prototypes, ranging from 0.1 to 0.3 J. The key distinction lies in the stationary state, characterized by holding power consumption. Conventional on/off valves for digital hydraulics require high holding power, typically around 20 W, to keep the valve open. This power demand can be minimized by employing low-power solenoids and an intelligent boosting control method for activation, resulting in a minimum holding power of approximately 80 mW.

With the new *PAS* and on/off piezo valves integrated into the *4WDPVS*, a single piezo valve consumes 0.07 J when activating one piezo stack, 0.14 J with two, and 0.21 J with three. The holding power needed to sustain piezo stack elongation is low at 12 mW. Consequently, these new on/off piezo valves (comparable in size) require over six times less holding power than the best existing on/off valves suitable for digital hydraulics.

One significant advantage of utilizing piezo on/off valves is their suitability for various *DFCU* configurations that demand numerous on/off valves to achieve high-performance hydraulic drives. This, in turn, translates into substantial energy savings.

NOMENCLATURE

C	Capacitor, capacitance	[F]
DFCU	Digital Flow Control Unit	/
E, E_c	Energy consumption	[J]

E_{switch}	Switching energy	[J]
$E_{c,PE}$	Energy consumption of a single piezo stack	[J]
I_c	Electric current consumption at piezo stack	[A]
$I_c(t)$	Electric current consumption at piezo stack as a function of time	[A]
p_s	Hydraulic system pressure	[MPa]
$P(t)$	Electric power as a function of time	[W]
PAS	Piezo actuator system	/
PE	Piezo element, piezo stack	/
q	Electric charge	[C]
Q	Flow rate	[l/min]
Q_1	Flow rate of a single on/off piezo valve	[l/min]
R	Electrical resistance	[Ω]
RC	Resistance-capacitance electrical circuit	/
s_1	Reference position of hydraulic cylinder (negative stroke)	[m]
s_2	Reference position of hydraulic cylinder (positive stroke)	[m]
t	Time	[s]
T_{period}	Period in time domain	[s]
U	Voltage	[V]
U_c	Voltage at piezo stack	[V]
$U_c(t)$	Voltage at piezo stack as a function of time	[V]
U_o	Operating voltage	[V]
$U_{o,max}$	Maximum operating voltage	[V]
V	Valve, hydraulic on/off valve	/
W_{hold}	Holding power	[W]
Δx	Stroke of piezoelectric actuator system	[m]
τ	Time constant of *RC* electrical circuit	[s]
4WDPVS	four-way digital piezo valve system	

REFERENCES

[1] Li, R.; Sun, Y.; Wu, X.; Zhang, P.; Li, D.; Lin, J.; Xia, Y.; Sun, Q. Review of the Research on and Optimization of the Flow Force of Hydraulic Spool Valves. Processes 2023, 11, 2183. https://doi.org/10.3390/pr11072183

[2] Huova M, Linjama M, Huhtala K. (2015) Energy Efficient Digital Hydraulic Valve Control. (Tampere University of Technology. Publication; Vol. 1298). Tampere: Tampere University of Technology.

[3] Johnson, B., Massey, S. & Sturman, O. 2001. Sturman Digital Latching Valve. Proceedings Seventh Scandinavian International Conference on Fluid Power, May 30 – June 1, 2001, Linköping, Sweden, pp. 299–314 (Vol. 3).

[4] Wirtl H, Sixt U. White paper - Piezo technology in pneumatic valves. Festo AG & Co. KG, Germany, June 2017.

[5] Reichert M. Development of High-Response Piezo-Servovalves for Improved Performance of Electrohydraulic Cylinder Drives. Von der Fakultat fur Maschinenwesen der Rheinisch-Westfalischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation, 04.02.2010.

[6] Tsukahara S., et al. "Design Method for Buckling Amplified Piezoelectric Actuator Using Flexure Joint and Its Application to an Energy Efficient Brake System." Volume 2: Legged Locomotion;

Mechatronic Systems; Mechatronics; Mechatronics for Aquatic Environments; MEMS Control; Model Predictive Control; Modeling and Model-Based Control of Advanced IC Engines, 17-19 October, 2012, Fort Lauderdale, Florida, ASME, 2012, p. 95. © 2012 by ASME.

[7] Wang Ch, Wang Sh, Li J Q, Wang Xi, Gao Z, Zhang L. Fabrication and performance of a power generation device based on stacked piezoelectric energy-harvesting units for pavements. Energy Convers Manage 2018; 196:207-163. https://doi.org/10.1016/j.enconman.2018.02.045

[8] Ju Song G., Cho J. Y., Kim K-B., Ahn J. H., Song Y., Hwang W., Hong S. D., Sung T. H. Development of a pavement block piezoelectric energy harvester for selfpowered walkway applications. Applied Energy 256 (2019) 113916. https://doi.org/10.1016/j.apenergy.2019.113916

[9] Zou H-X, Zhang W-m, Li W-b, Wie K-X, Gao Q-H, Peng Z-K, Meng G. Design and experimental investigation of magnetically coupled vibration energy harvester using two inverted piezoelectric cantilever beams for rotational motion. Energy Convers Manage 2017; 1391:1398-148.

[10] Zhang Z, Xiang H, Zhan J. Experimental investigation on piezoelectric energy harvesting from vehicle-bridge coupling vibration. Energy Conversion and Management 2018; 169:179-163.

[11] Alegro MicroSystems, LLC. ACS714, Automotive Grade, Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 2.1 kVRMS Voltage Isolation and a Low-Resistance Current Conductor. Alegro MicroSystems, LLC 2012; Rev.9 November 16.

[12] Rexroth Hydraulics. Hydraulic valves, on/off directional seat valves, direct operated, https://www.boschrexroth.com/en/xc/products/product-groups/industrial-hydraulics/on-off-valves/directional-valves/directional-seat-valves/direct-operated [accessed 22 April 2023].

[13] HYDAC International. Directional direct operated hydraulic valves, https://www.hydac.com/no-en/products/valves/directional-valves.html [accessed 22 April 2023].

[14] Parker Hydraulics. Bi-Directional Poppet Type, 2-Way Valve, Series GS02 72/73, https://www.parker.com/literature/Hydraulic%20Cartridge%20Systems/Product%20Series%20PDFs/SV/2%20Way%20Poppet%20Type%20Bi-Directional%20Solenoid%20Valve.pdf [accessed 22 April 2023].

[15] Scully L. New Line of Solenoid Valves Outperforms Previous Models, Hydraulics & Pneumatics, AUG 18, 2016, https://www.hydraulicspneumatics.com/technologies/hydraulic-valves/article/21885246/new-line-of-solenoid-valves-outperforms-previous-models [accessed 22 April 2023].

[16] Bucher Hydraulics. 2/2 Cartridge Seat Valve, Size 5, Series WS22GD…/ WS22OD…. Reference: 400-P-121110-EN-00, Issue: 09.2015.

[17] Paloniitty M. Novel Water Hydraulic On/Off Valves and Tracking Control Method for Equal Coded Valve System. Doctoral thesis, Tampere University of Technology. Publication 1577, 2nd of November 2018. http://urn.fi/URN:ISBN:978-952-15-4239-8.

[18] Park, S.-H., Kitagawa, A., Kawashima, M., Lee, J.-K. & Wu, P. 2002. A Development of Water Hydraulic High Speed Solenoid Valve. January 2005 TRANSACTIONS OF THE JAPAN FLUID POWER SYSTEM SOCIETY 36(1):8-14, DOI: 10.5739/jfps.36.8.