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Design and Implementation of an Electric Actuated Valve for Precise Fluid Control

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Abstract

Fluid control is one of the essential automation application area in industry. In order to fluid control effectively and precisely, valves which are crucial components, need a controlled rotating motion which leads to implement electric motors, electronic controller and gear systems altogether. In this study, an electric motor actuated valve system is designed and prototyped. The design phases are including switch mode power supply (SMPS) design, motor controller circuit design, mechanical implementation and controller design. The designed valve system is manufactured and tested using multi-disciplinary fashion. The application problems are solved by using the proper control techniques and strategies. The precise position control of butterfly disc is also achieved. According to the related industrial standard and application requirements, the experimental results show the effectiveness of the design approach.

1. INTRODUCTION

Actuators are crucial elements of industrial fluid control systems. The major usage of valve actuator (VA) systems is to control fluid flow in pipeline systems [1,2]. Generally according to operation principle, VA are classified as pneumatic, electro-hydraulic and electric actuated. Electric VAs are generally used in food and chemical industry, pipelines, wellhead control and petro-chemical industry because of their high operative capabilities, fast response, precise performance [3,4]. Classical on-off open loop VAs do not meet the requirements of precise automated flow applications. Particularly, crucial, i.e. both flammable and toxic, flow control processes need smart specifications, easy-controllable and functional electric VAs [2]. Additionally, volume and cost-efficient solutions are other essential requirements for industrial applications. Various types of communication modules are preferred for centralized Supervisory Control and Data Acquisition (SCADA) systems to control of multiple VAs in same process. IoT (Internet of Things)-based communication protocols, which are better monitoring and to allow preventive maintenance, are used because of the remote access for naval and mining applications. Moreover, maintenance problems of VAs are another critical topic. Using microprocessor (MCU), Programmable Logic Controller (PLC) units make the continuous maintenance easier with the master, slave or host structure. In electric VA systems, electric motor (EM) is providing a mechanical energy according to speed and torque requirements. Moreover, the commissioning and maintenance costs are reduced due to the lesser component use. Choosing a proper EM is a critical attempt for minimum energy consumption, beneficial valve torque production and providing efficient performance. Selection of AC motors for applications of VAs are widespread because of high torque capability and wide-range variable speed performance capabilities [2,5]. However, conventional Permanent Magnet (PM) DC motors are suitable solution for VA systems because

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of volume constraints of three-phase EM drive systems, inefficiency of low power EM and low performance asynchronous motors in position control applications. PMDC motors can be typically used with encoders for precise position control which is provides position control error 0.5% [2]. Also, faster control responses are performed by valve system and high torque demand satisfied with high performance. Also, one of the major problems encountered in industry applications is motor winding fault which is resulted by high current demand by EM for high torque requirements [4]. For the first important design approach of actuators, the main target is to meet the high torque demand with low current by gearbox usage in order to obtaining the required low motor speed and provide a substantial torque level at that speed [6].

In this paper a VA system consisting of an EM for proportional position control of the valve, a potentiometer for capturing position feedback; a MCU based control circuit and a gear box design are explained. The unit is called actuator and assembled to the butterfly valve structure. The position sensor, i.e. potentiometer, captures the disc rotation angle and sends that information to the controller. Due to the target position which provides the proper flow rate, the motor rotates in both directions and keep the demanded position. An adequate cascaded arrangement of PI controllers is designed for large and small error changes. Especially for small disc rotations to control the flow, the position steady state error becomes important and therefore effect of integral control action is increased. In some precision fluid control applications, the position control of valve must be accomplished as traveled distance control. Thus, a control technique is implemented so that the amount of the fluid can be adjusted accurately. In this paper, an integrated approach to design a system having torque, velocity and position controls are presented. The feasibility and effectiveness of the proposed structure and control scheme are verified by an experimental study.

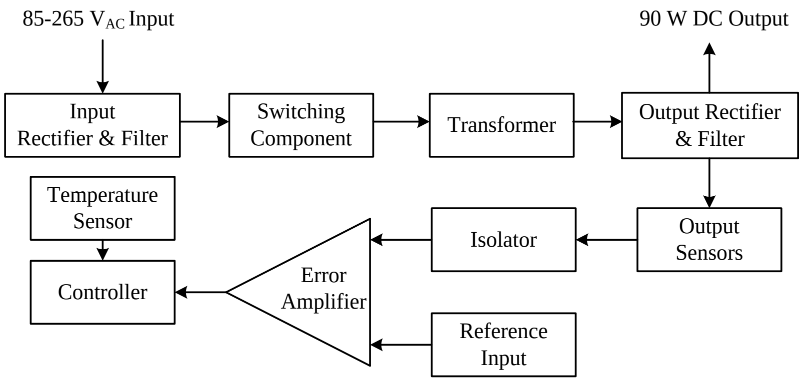

Figure 1. *Overall proposed SMPS block diagram*

2. SMPS DESIGN AND IMPLEMENTATION

For energizing PMDC motor and the peripheral units, a universal input SMPS circuit is designed. Due to the power level and isolation requirements, the flyback topology is selected. Besides being a cost-effective solution, flyback converter topology also provides size, weight, and efficiency advantages. In industry and other application areas, flyback converters are widely used as auxiliary power supplies [7, 8]. With the possibility of multi-output structure and wide range DC voltage input, flyback topology is one of the best choices as input power supply up to 120 W output power level. Beyond this level, simpler structure, buck-boost type operation principle and switching losses diminish the advantageous nature of flyback converters [9]. In the designed electric actuator, two isolated outputs of flyback converter serve as the motor supply and supply for peripheral circuits. The target design parameters of SMPS circuit are given in Table 1. Since the proposed design which is shown in Figure 1, will be used in industry applications, the universal (85-265 V_{AC}) input voltage levels have been selected [10]. The feedback control is applied for one of the outputs. The output voltage level of 24 V must be kept constant to satisfy the load demands. The variation of 9 V output can be tolerated due to the wide range input capabilities of the peripheral devices. In this design, 65 kHz switching frequency is selected because of the higher switching frequency causes smaller the transformer weight and size [11]. In experimental study, the efficiency values for various voltage inputs and constant output power are obtained experimentally. Figure 2 is showing the efficiency change of the converter along input voltage variation. And also, the variation of efficiency versus output power is given in Figure 3.

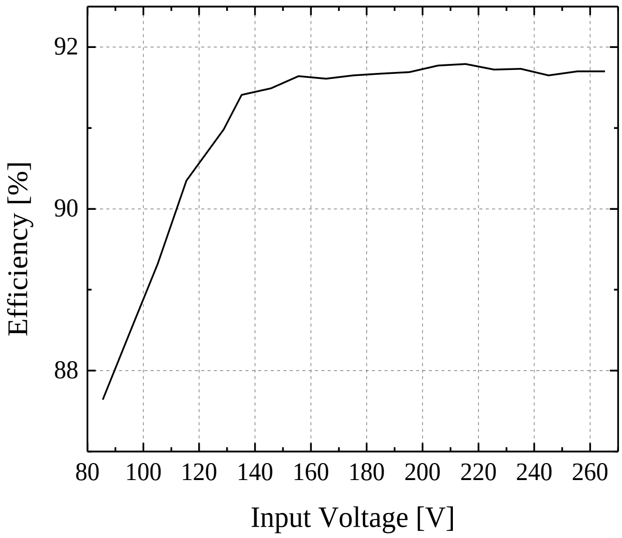

Figure 2. *Input voltage vs. efficiency*

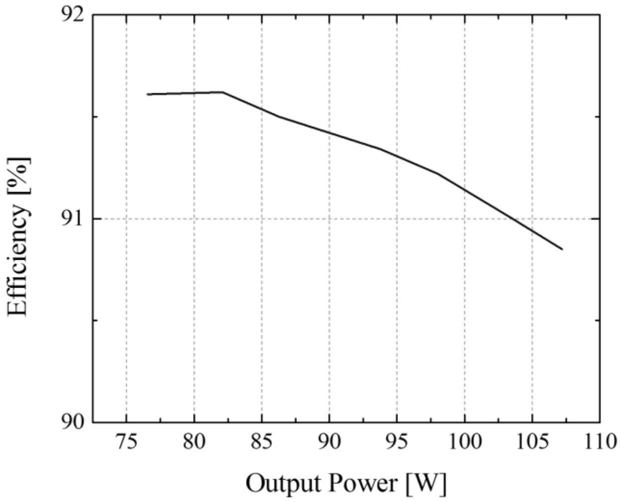

Figure 3. *Output power vs. efficiency*

Table 1. *Design parameters*

Description	**Value**
Input voltage (minimum)	85 V
Input voltage (maximum)	265 V
Grid frequency	50 Hz
Switching frequency	65 kHz
Output power	81 W
Measured efficiency	90%
Voltage & current output-1	24 V, 3 A
Voltage & current output-2	9 V, 1 A

3. SYSTEM DESIGN

As an industrial requirement, all actuators must have the flexibility of assembling according to ISO 5211 standard [12]. Also, the angle sweep range is adjusted as ± 45° which is satisfying all over flow rate control. Performance of valve is a direct impact factor to effectiveness of industrial processes. Dry opening or dry service which means the operating of valve without fluid material needs higher torques to overcome frictions due to mechanical structure. To avoid malfunctioning, high quality mechanical designs are required. The operating torque is depending on two factors: hydrodynamic torque due to fluid type and mechanical friction. The essential component of the torque is hydrodynamic torque which is strongly depending on viscosity of fluid material [13,14]. Designs are focused to overcome hydrodynamic torque and dry opening conditions especially for low temperatures. The factors affecting valve operation during opening and closing are given as following in Equation (1) and Equation (2),

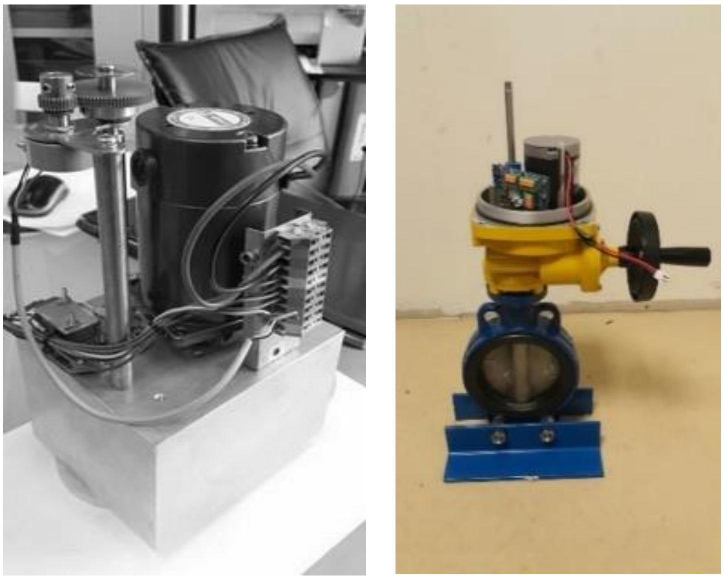

Figure 4. *Manufactured electric actuator*

$$T_o = T_d + T_b + T_g + T_h \tag{1}$$

$$T_c = T_d - T_b - T_g - T_h \tag{2}$$

where T_o, T_c, T_d, T_b, T_g and T_h are the opening torque, closing torque, hydrodynamic torque, bearing torque, center of gravity torque and hub torque respectively. The hydrodynamic torque response is also important to provide precise fluid mixtures by using butterfly valves. Center of gravity torque, T_g, is due to the offset center of gravity of the disc structure and occurs when the valve shaft is located in or near the horizontal plane. The bearing torque of valve is caused by bearing frictions and dominant at the near-closed position because of higher differential pressures. At fully open position, bearing torque is zero. The packing or hub torque is occurred by interaction between the shaft seal and the valve shaft, and further the friction between the disc and the body.

$$C_v = Q\sqrt{\frac{\gamma}{\Delta P}} \tag{3}$$

where C_v, Q, γ and ΔP are the flow coefficient, flow rate, specific gravity and pressure drop consecutively. Because the valve flow coefficient in (3) represents the effective opening cross-section of the valve, the cross-section change during valve disc motion must be known [15,16]. The valve flow coefficient which reflects the flow capacity is an essential parameter for manufacturers and users. In addition, flow velocity which is important design parameter, expressed as,

$$v = C\sqrt{2g\Delta h} \tag{4}$$

where v, C, g and Δh are the flow velocity, discharge coefficient, gravity and head of fluid respectively. To increase the controllability, flow rate and pressure change of fluid material must be known. These factors are also important for operation life of valve. The calculated design parameters due to the processed fluids are given in Table 2. By means of these calculations and the required torque, a small, compact valve which has 150 mm diameter is designed and manufactured as shown in Figure 4.

Table 2. *Design parameter calculation*

Angle (°)	**K_v (m³bar/h)**	**Q (m³/h)**	**T (Nm)**
10°	0.8	23	15.24
20°	44	59	34.36
30°	105	138	51.79
40°	205	257	75.45
50°	373	443	114.7
60°	617	612	130
70°	983	921	123
80°	1468	1136	117.48
90°	11.11	1622	122.3

4. CONTROLLER DESIGN

First, according to the different voltage levels in different countries, a universal power supply must be developed to operate the electric actuated valve. For control purposes, the measured position is captured using 4-20 mA or 0-10 V_{DC} or 0-5 V_{DC} signals coming from potentiometer coupled to actuator's shaft. The difference between reference and actual position signals are compared and processed for error compensation. According to comparison of desired and measured position motor driver circuit can provide rotation in both directions. For the bidirectional rotation speed control, the motor driver must be in *H*-bridge structure. Moreover, a high-resolution potentiometer is deployed for position feedback. Microchip dsPIC30F6015 MCU which has advanced communication protocols, is used in the developed actuator control and SMPS electronic board shown in Figure 5.

Figure 5. *Designed control and SMPS boards*

Using only proportional control brings the well-known problems of control systems such as a substantial steady-state error and oscillatory output. A properly tuned integral control is needed to nullify steady-state error. The controller gains must be kept quite lower in such systems which have higher system gain values. Also, a carefully tuned proportional act is required for not to amplify noise coming from feedback side. In most controller designs for valve actuation, the flow control characteristic of valve is taken as linear and the cascaded PID controller are used for error compensation. For low dynamic systems, e.g. butterfly valves, derivative control is not used due to the slowly changing errors. Instead a properly tuned integral control contributes to error nullification.

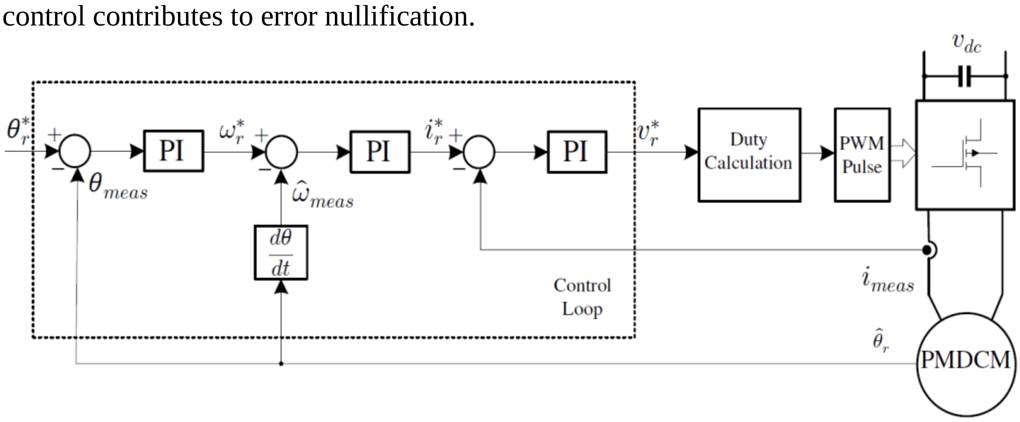

Figure 6. *Implemented control scheme*

The inner loops in cascaded control system are acting as dampers which are providing shorter settling times for system output. Further, the cascaded PI arrangement provides a better dynamic response, disturbance regulation and small starting current due to the current control loop [17]. In electric valve control system, the first loop is position loop which represents the main control intention, the speed and current loops serve as governing actors which bring more controlled action than a sole position loop time constant of the system. Speed, torque, current and position of PMDC motor are mostly controlled by cascade controllers as given in Figure 6.

5. EXPERIMENTAL RESULTS

A test bed shown in Figure 7, is used to test the performance of the prototype actuator according to ANSI/ISA-75.02-1996 standard [18]. Considering the overall automation system, flow control valves are essential devices which are affecting the performance quality of whole process. Thus, a proper feedback device, an effective control strategy and circuit, precise mechanical structure, adequate high-level functions must be deployed. The accuracy of flow control valve must be as high as possible for the overall process quality. The disruptive behaviors due to the nature of fluid applications must be compensated substantially by means of adequate designs. The variation of flow rate versus opening degree is shown in Figure 8. The flow rate is directly proportional to the opening cross-sectional area and nonlinearly, i.e. spherically, depended on disc travel.

Figure 7. *Experimental test bed*

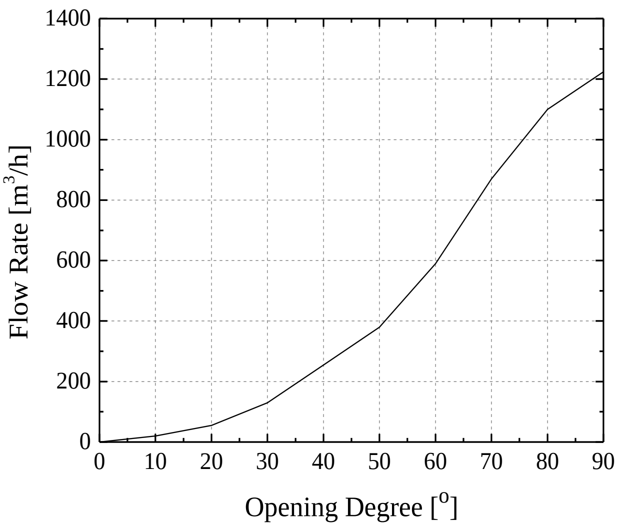

Figure 8. *Opening degree vs. flow rate*

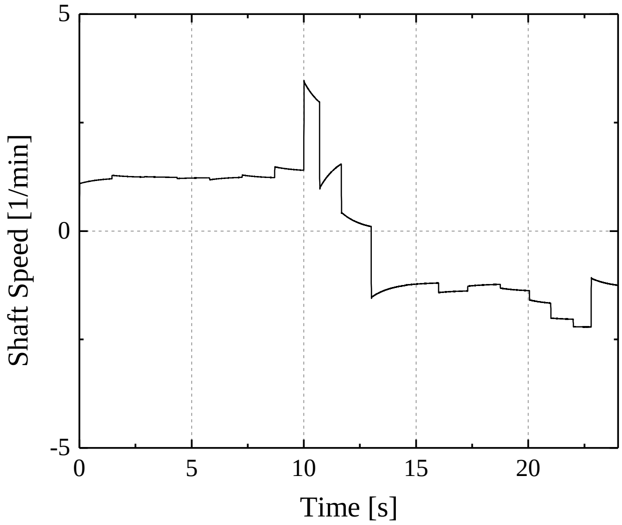

Figure 9. *Shaft speed variation with time*

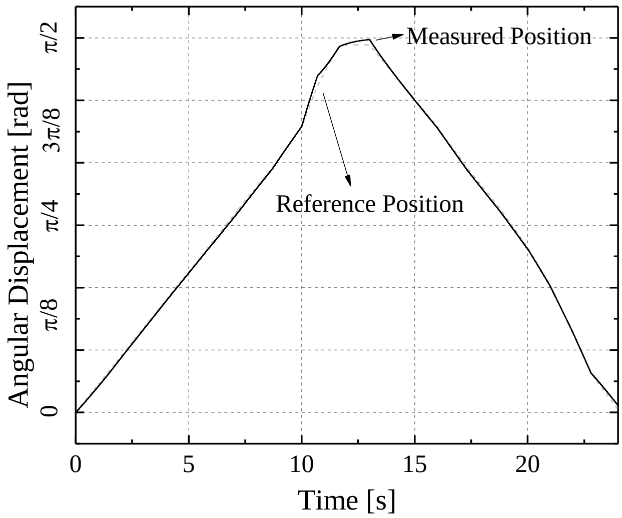

Figure 10. *Angular displacement variation with time*

Linear flow characteristics cause approximate change in flow per unit of valve stroke. When the disc is open at 90°, the flow rate is at its maximum. These types of valves can serve as effective flow controllers a wide range of fluid types besides water. In Figure 9, the experimentally captured valve shaft speed response is given. The valve can keep 1.125 min^{-1} rotational speed excluding opening and closing operation intervals. The speed stability is essential to implement an efficient position control in such systems. An uncontrollable amount of fluid occurs when all valves start to open. Depending on size of valve this situation which disrupts precise flow control is shown at a rotation angle between 10° and 20°. To avoid this undesirable behavior, an effective position tracking control which is contributed by the speed and current controllers is required. Therefore, both Newtonian and non-Newtonian fluids with different viscosity values can be controlled in similar manners. The disc travel control performance is also tested in the test bed. The angular displacement variation of a travel-controlled valve disc is shown in Figure 10. As it can be seen the difference between the reference and actual positions is hardly noticed. The amounts of controlled fluids are measured precisely and the validation of the design is obtained. The reason of using torque control, i.e. the current control for PMDC motor, is based on the dependence of hydrodynamic torque to volume of flow rate, pipe size and position of disc. The variation of valve shaft torque is given in Figure 11.

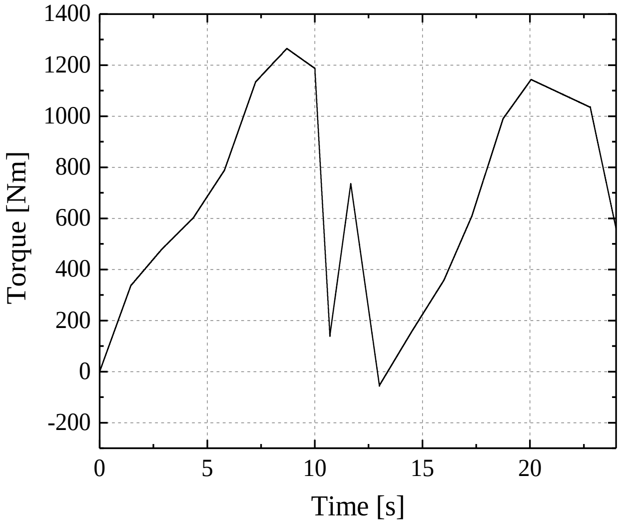

Figure 11. *Shaft torque variation with time*

Typically, dynamic torque reaches its maximum about 70° as it is seen in Figure 11. High differential pressures which occurs due to dynamic velocity and position of disc can be harmful for stems, connections and actuators. Sometimes some oscillatory behaviors can be seen in current control loop due to frictions. A well-designed overall torque control can solve this problem.

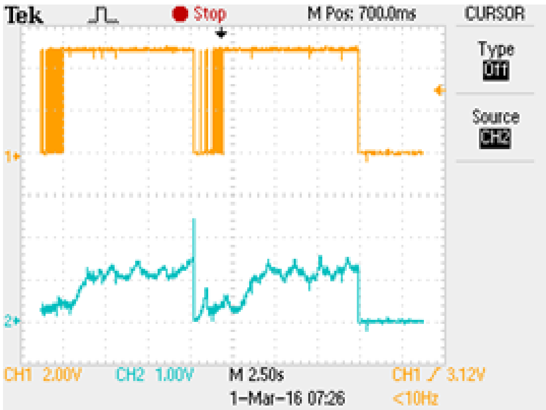

Figure 12. *On-off performance waveforms of designed actuator [17]*

The current controller can provide a damping action to prevent the motor form abrupt current peaks during starting and sudden load demands. The on-off performance of valve as both terminal voltage and current waveforms is shown in Figure 12. In Figure 13 a ramp action which is bringing a delay to solve aforementioned deteriorative problems due to valve operation and a start-up performance optimization is presented.

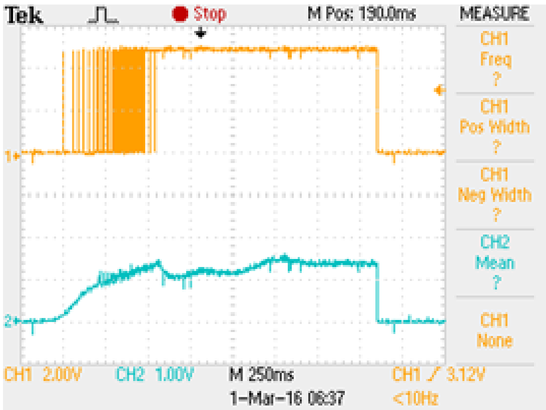

Figure 13. *Ramp acting for starting instantaneous [17]*

6. CONCLUSION

In this paper, an integrated design effort of electric motor driven flow control valve is presented. The design stages of main energizing circuit, control system and the experimental verification works are given. The SMPS and its controller circuit can be merged on a single circuit board and are packaged together with electric motor and mechanical assembly. This feature provides a compact and space-efficient design. A cascaded arrangement of the position, speed and current loops is used for feedback controller. The controller gains are calculated according to the nonlinear nature of both valve and fluid. The developed system can be implemented in any fluid process control. Also, an experimental study is conducted by using a special test-bed designed for the developed electric actuator. The design approach and the overall system performance are verified experimentally.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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