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Design of a 3-Stage Voltage Controller for EMV Actuation in SI Engines

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Abstract

Variable valve timing (VVT) provides SI engines several significant benefits in fuel economy, exhaust emission, and engine performance. Among all VVT mechanisms, electromagnetic valve (EMV) is a positive one by providing very high flexibility in valve timings and possibility of cylinder-by-cylinder VVT control. This paper presents a simple 3-stage voltage control method for EMV actuation to effectively reduce the contact velocity between EMV and valve seat. A voltage pattern for EMV actuation is derived first by a fuzzy logic controller. Then, this pattern is simplified into 3 level voltage in which the voltage magnitude and duration are analyzed and optimized. Simulation results show that the 3-stage voltage controller offers simple control algorithms and acceptable performance with low impact velocity.

Keywords: 3-stage voltage control, variable valve timing, electromagnetic valve

1. Introduction

Due to the stricter requirements in emission regulations for mobile vehicles, a vehicle engine with low fuel-consumption and low emission is one of the major objectives for car industries and research institutes. Among all methods of increasing engine efficiency and reducing engine emission, variable valve timing (VVT) is an effective and positive way.

The conventional mechanical variable valve timing system adopted several phases of valve timing. Such a system makes the valve opening timing and close timing not fully satisfy the demands of engine’s operating conditions for all engine speeds. Actually, an electromagnetic valve (EMV) train can improve this problem effectively.

For an engine with EMV valve train, voltage or current is used to control the opening or closing of cylinder valve to provide desired valve timings. An EMV VVT system can adaptively adjust the valve timing according to the instantaneous demand of engine operation, and each cylinder can have independently different settings for valve timing. By the aids of EMV VVT system, engine fuel consumption can have 15% reduction [1], or up to 23% reduction if other engine control method (i.e., cylinder deactivation) applied together. Also, the EMV VVT system can achieve 12~15% emission reduction and 20% enhancement of engine torque [2].

The EMV VVT system needs electric control to actuate the EMV properly to open or close cylinder valves. This paper focuses on the controller design for EMV soft-landing. The normal operating range of an automobile engine locates in the range of 1000 rpm to 6000 rpm. The motion of opening or closing of an intake/exhaust valve takes about 2~5 ms only, so the

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valve moves quite fast. However, fast moving valve causes high contact velocity when the valve touches its valve seat. And it results in valve wear and engine noise. Therefore, the contact velocity of the valve and armature in the EMV should be well controlled by the aids of soft-landing controller to prevent armature and valve from severe impact.

Some methods in controlling EMV soft landing have also been studied. A linear control law using an observer which is based on controlled output feedback has been introduced for valve landing velocity control [3]. It concluded that the impact velocity in EMV can be reduced down to 1 m/s. Tai et al. [4] proposed a learning feed forward controller for soft landing control of an EMV, and the lowest velocity obtained was 0.2 to 0.5 m/s. An open loop control was introduced to control valve impact velocity [5], resulting in a landing velocity of about 0.69 m/s as the valve moved a full stroke from top to bottom position. And a nonlinear self tuning was also proposed for soft landing control for providing low contact velocity [6].

2. Structure and Dynamic Models

2.1. EMV structure and actuation

A double-E-coil EMV generally consists of upper and lower-coils, armature, springs, and EMV body. An armature moves upwards and downwards between these two coils. The armature rests at the middle equilibrium position if no current applies to the coils (Fig. 1). When a proper current applies to the upper or lower coils, the resulted magnetic force will catch the armature and hold it in valve-closing or valve-opening position.

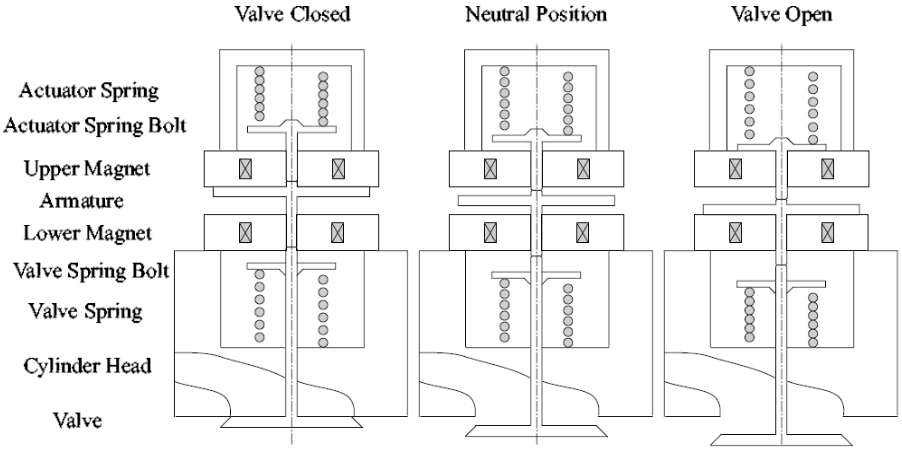


Fig. 1 Actuation of electromagnetic valve

2.2. Dynamic models of EMV

The dynamic models of an EMV are as follows:

$$\frac{di}{dt}=\frac{V_{in}-r\cdot i-X_1\cdot v}{X_2} \tag{1}$$

$$\frac{dz}{dt}=v \tag{2}$$

$$\frac{dv}{dt}=(F_{magup}-F_{maglow}-2k_s(\frac{L_{arm}}{2}-z)-k_b\cdot v)/m \tag{3}$$

$$X_1=\frac{2\cdot K_a\cdot i}{(K_b+\bar{z})^2} \qquad X_2=\frac{2\cdot K_a}{K_b+\bar{z}} \tag{4}$$

$$F_{mag}=\frac{K_a\cdot i^2}{(K_b+\bar{z})^2} \tag{5}$$

where V_{in} is the input voltage for coils, L_{arm} is the range for armature motion, z is armature displacement respectively. In our case, $z = 0$ mm is the location in which the armature contacts the lower coil, and valve is in its fully open position. On the contrary, $z = 8$ mm is the location in which the armature contacts the upper coil, and valve is in its fully closed position. And $z = 4$ mm is the equilibrium neutral position for armature. v is armature velocity and F_{magup} is the magnetic force produced by the upper coil, while F_{maglow} is the magnetic force produced by the lower coil. m is the mass for the moving part of EMV, and K_a and K_b are experimental parameters.

3. System Description

3.1. EMV fuzzy logic control

To actuate an EMV, a voltage is applied to coils to produce magnetic force for catching armature and then causing valve motion. Generally, the EMV actuation can be voltage control or current control. The voltage control is widely used since it is easier and less complicated than current control [6]. The control objective is to effectively reduce the valve contact speed and shorten the valve moving time at the same time. Also, the reduction of consumption of actuation energy is one of the objectives for EMV actuation.

A fuzzy logic controller is designed for EMV actuation first to understand the voltage pattern of EMV actuation. The two inputs for the EMV fuzzy logic controller are armature displacement and its velocity. After the fuzzy inference, a voltage output is provided to the coils to actuate the EMV. Fig. 2 shows the block diagram for EMV control.

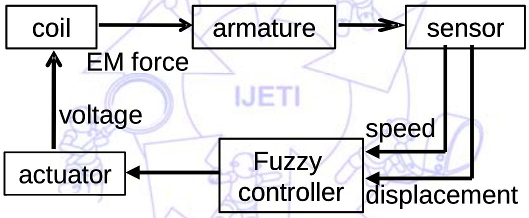
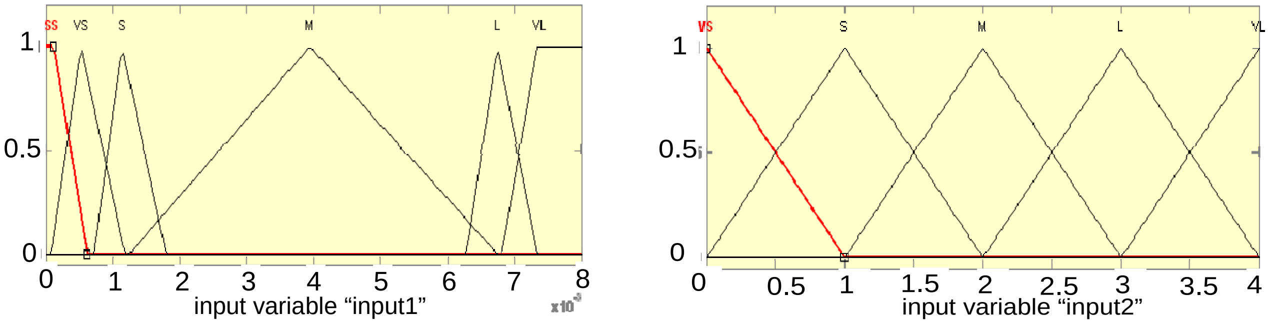


Fig. 2 Block diagram of EMV control

Since the armature displacement is a critical input parameter for the fuzzy logic controller, we set 6 membership functions for displacement fuzzification. But we use only 4 membership functions for voltage output defuzzification to avoid large voltage fluctuation and computing time. Fig. 3 shows the fuzzy membership functions for the inputs of armature displacement and speed. The displacement is limited in the range of 0 mm to 8 mm, in which the 0 mm is the fully valve open position and 8 mm is the fully valve closed position. The speed range is from 0 m/s to 4 m/s.

After the armature is released, the distance between armature and coils becomes large. Even a large voltage is applied to the coils at this moment; the consequent magnetic field is still too small to catch the armature. Voltage supply at this moment has very low actuating efficiency of voltage actuation. For a good control strategy, it had better not to have voltage supply at this moment.

When the EMV is in operation, the spring force helps EMV to push armature toward to the coils. Then, the needed voltage for valve actuation can be small. Accordingly, we put more control efforts when the armature is near the coils to increase actuating efficiency and reduce the consumption of actuating energy. That’s why we apply more input membership functions around the areas of 6 mm to 8 mm and 2 mm to 0 mm respectively to obtain precise voltage output.



(a) (b)

Fig. 3 Input membership functions of valve displacement (a) and speed (b) in a fuzzy controller

Fig. 4 shows the output membership functions, in which 0 and 1 are the minimum and maximum voltage output respectively. More precise actuation is needed if the armature is near the coils. So more output membership functions are assigned around the range of 0.1 to 0.4.

Table 1 shows the 6-by-5 rule base for the EMV fuzzy controller. This rule base is approximately divided into 5 areas. The first area is for the early stage of valve moving. There is minimum voltage output in this stage to reduce actuation energy consumption. The second stage uses a large voltage output to accelerate the valve. The third area is applied for the valve moving to middle position in which the valve has maximum speed. Thus, we apply a small voltage output to retard the valve speed to avoid large contacting speed and large actuation energy consumption. Under normal operating conditions, the situation of area 4 doesn’t occur because fast valve speed only happens around the middle equilibrium position. In the area 5, in which the armature is approaching to the coils, a middle voltage output is provided to catch the armature to make valve staying in the open or closed position.

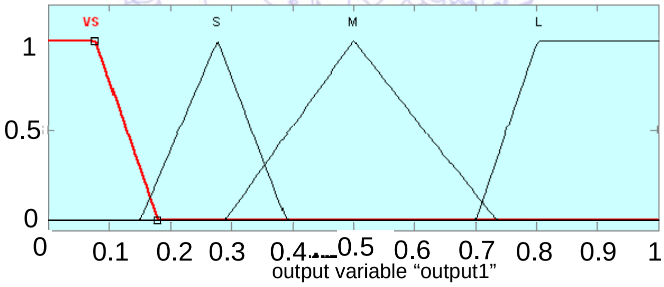


Fig. 4 The output membership function of actuating voltage in a 6x5 fuzzy controller

Table 1 Rule base of the 6x5 fuzzy controller

		Input_displacement					
		SS	**VS**	**S**	**M**	**L**	**VL**
Input speed	**VL**	**M**	**S**	**S**	**S**	**L**	**VS**
	L	**M**	**S**	**S 3**	**S**	**L**	**VS**
	M	**M 5**	**S**	**S**	**S**	**L 2**	**VS 1**
	S	**M**	**S**	**L 4**	**L**	**L**	**VS**
	VS	**M**	**L**	**L**	**L**	**L**	**VS**

VL：Very Large L：Large M：Medium S：Small VS：Very Small SS：Super Small

3.2. Simulation results of the fuzzy controller

Figs. 5 to 7 show the simulation results of output voltage, valve displacement and velocity by the fuzzy controller. When the armature starts to move away from its fully closed position, the large distance between the armature and coils causes small magnetic catching force, and consequently poor actuating efficiency and large actuation energy consumption. Thus small voltage output is provided for this 8 mm to 7 mm range. After the valve passes the 7 mm location, the controller provides large voltage output to accelerate the armature.

The valve reaches its maximum speed when it arrives the 4 mm middle position. At this moment, the controller starts to reduce the output voltage to slow the valve down gradually to avoid large contact velocity at the last stage. The subsequent actuation energy consumption is also reduced by this control strategy. When the valve moves very close to the coils in the range of 1 mm to 0 mm, the output voltage raises a little to make the armature be caught by coils. Afterwards the valve stays in its fully open position.

Under the actuation control by a fuzzy controller, the simulation results show that the contact velocity is about 0.4 m/sec, and valve moving time is maintained at about 4 msec. These results satisfy the general objective of 0.5 m/s contact velocity and 4 ms moving time.

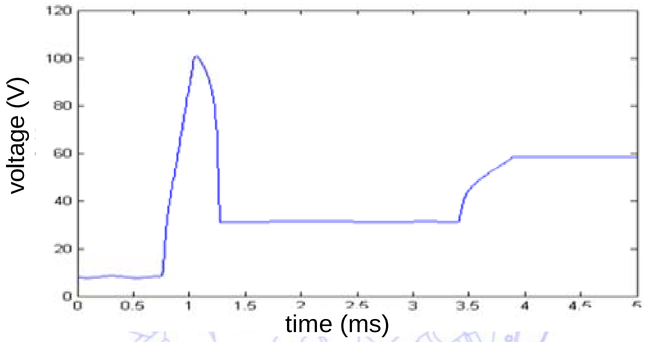


Fig. 5 Simulated output voltage (fuzzy controller)

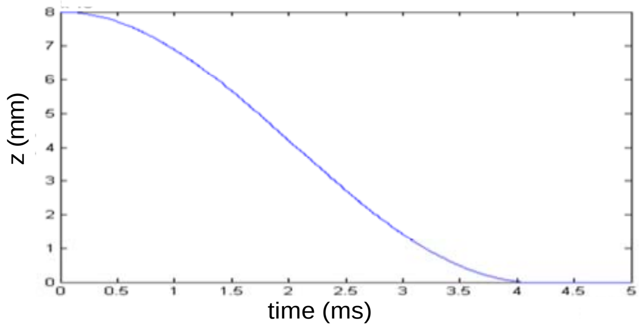


Fig. 6 Simulated valve displacement (fuzzy controller)

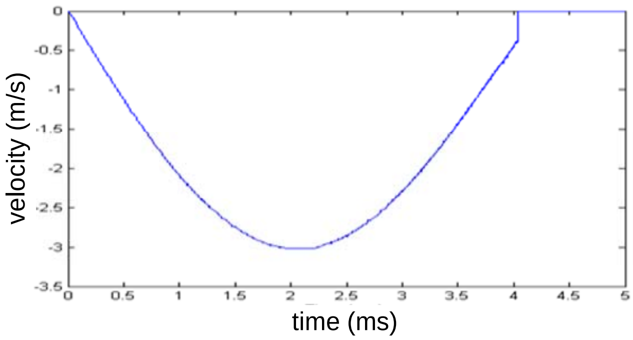


Fig. 7 Simulated valve velocity (fuzzy controller)

4. 3-Stage Voltage Control

The valve in an EMV moves very fast. The valve must finish its opening or closing action during several mini seconds. Thus it is not appropriate for the real-time control of EMV actuation performed by a Fuzzy Logic Controller. Therefore, we develop a 3-stage voltage control algorithm for real-time EMV control. This control algorithm is developed based on the previous controlled voltage patterns from a Fuzzy controller. A simple mapping control principle is applied to significantly reduce the computing time in real-time control.

4.1. Principle of 3-stage voltage control

According to the simulated results of controlled EMV dynamics, we find that the output voltage can be classified into 3 stages. Based on this understanding of voltage pattern, the actuating voltage of EMV is divided into 3 voltage levels as in Fig. 8.

The first stage of voltage: In this stage, a large voltage is provided to cause enough magnetic force to accelerate the valve. The second stage of voltage: The valve has maximum speed near the middle position. It is necessary to provide a low voltage to retard the valve to avoid large contact velocity. Besides, low actuating voltage can reduce the subsequent actuation energy consumption.

The third stage of voltage: In this stage a middle voltage is provided to keep the armature fully caught by the coils after contacting, and also maintain the valve in its fully open or closed position.

Since the magnitudes and timings of these 3 stage-voltages are very important to the EMV dynamics and actuation energy consumption, the rise time, contact velocity and actuation energy consumption of valve actuation are analyzed for determination of proper voltage magnitude and timing.

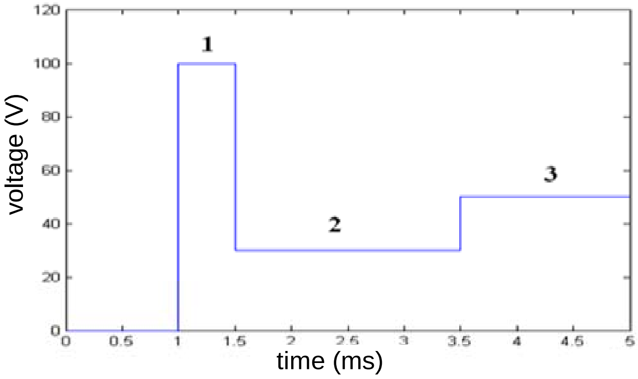


Fig. 8 3-stage Voltage control for EMV actuation

4.2. Effects of the first stage voltage

The important feedback information of 3-stage voltage control is valve displacement. Initially, we set 100 V, 30 V and 50 V for the first, second and third stage voltages respectively. The timing of voltage applying is determined as 1 mm location for stage 1, 4 mm for stage 2, and 6 mm for stage 3 respectively. We check the effects on valve rise time, contact velocity and actuation energy consumption by the timing of first stage. Fig. 9 shows the corresponding timing effects. The timing of the first stage voltage is changed from 0.5 mm to 1.75 mm. From the simulated results, the velocity and rise time have optimal values if the voltage time is in the range of 1.25 mm to 1.5 mm. So the voltage timing for the first stage voltage is chosen between 1.25 mm to 1.5 mm.

Fig. 10 shows the effects by different duration time of the first stage voltage. The results indicate that good performance exists for voltage duration of 0.75 mm to 1 mm. Too short voltage duration causes long valve rise time, while too long voltage duration gets large contact velocity.

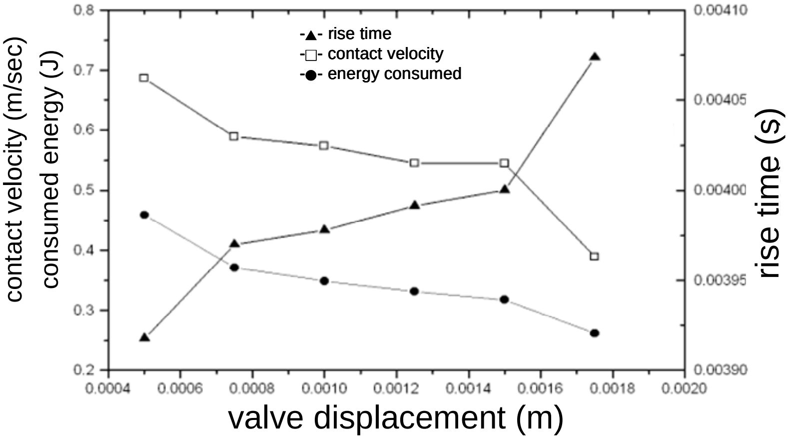


Fig. 9 Effect of voltage timing in the first stage voltage

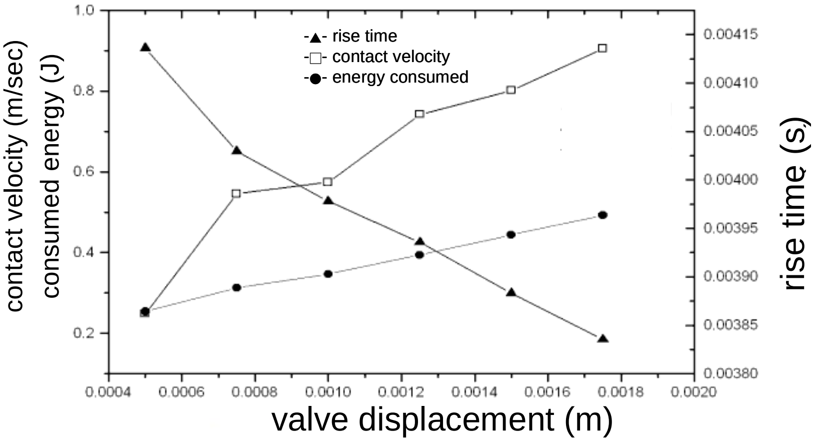


Fig. 10 Effect of voltage duration in the first stage voltage

4.3. Effects of the second stage voltage

Fig. 11 shows the magnitude effect of second stage voltage. The results indicate that the magnitude of the second stage voltage has significant influence on valve rise time and contact velocity. A large second stage voltage will cause too large contact velocity. Therefore, a low second stage voltage not only significantly reduces the valve contact speed, but also reduces actuation energy consumption. According to the simulated results, a 30 V second stage voltage is a good choice for EMV actuation.

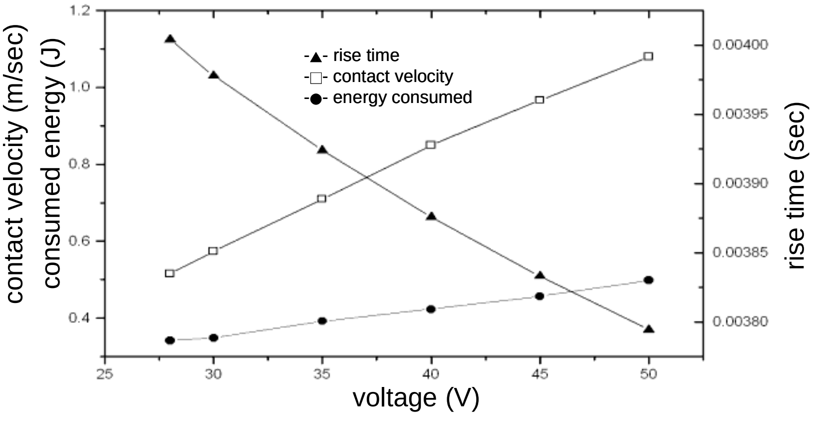


Fig. 11 Effect of the voltage magnitude in the second stage voltage

4.4. Effects of the third stage voltage

The timing effect of the third stage voltage is shown in Fig. 12. The results show that the timing has minor effect on actuation energy consumption because of the short voltage duration. A good choice of timing is from 6 mm to 7 mm because early or late voltage timing causes large contact velocity or rise time respectively.

Fig. 13 shows the magnitude effect of the third stage voltage. The magnitude also has minor effect because of short voltage duration. Since the voltage duration is quite short, large voltage magnitude doesn’t take too much actuation energy. Although a large voltage magnitude causes large contact velocity, this problem can be compensated by the first and second stage voltages. Thus the appropriate third stage voltage is above 50 V.

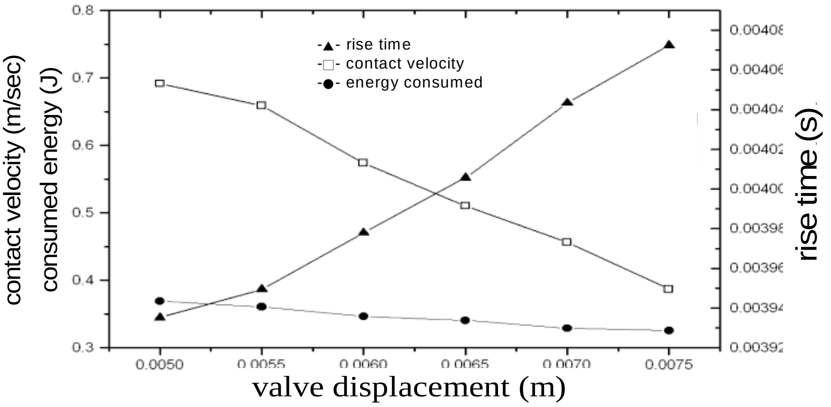


Fig. 12 Effect of the voltage timing in the third stage voltage

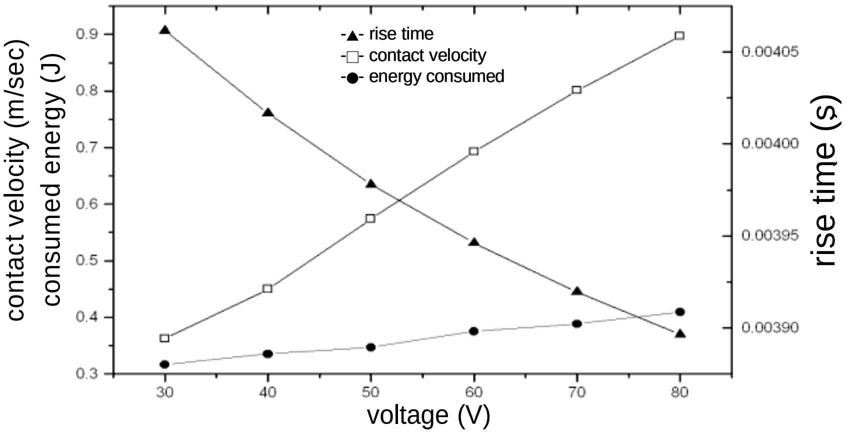


Fig. 13 Effect of the voltage magnitude in the third stage voltage

4.5. Results of 3 stage voltage control

According to the previous simulation results, for the first stage voltage, we choose 100 V for magnitude, 1.5 mm for timing, and 0.75 mm for duration. And 30 V is chosen for the magnitude of second stage voltage, and 6.5 mm and 60 V for the timing and magnitude for the stage 3 respectively.

Figs. 14 and 15 are the simulated results using the chosen voltage timings and magnitudes. Under the control of 3-stage voltage, the contact velocity keeps under 0.5 m/s while the rise time is controlled at about 4 msec. Therefore, the controlled results satisfy the desired performances.

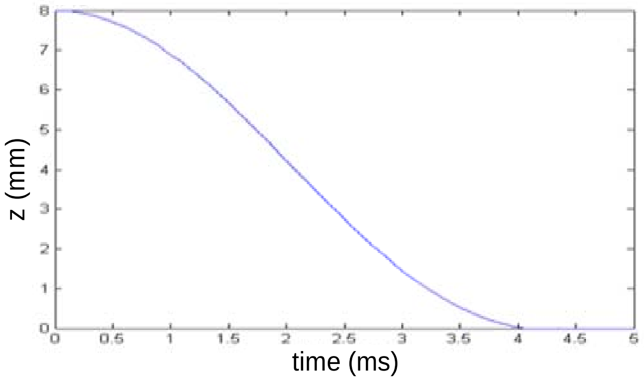


Fig. 14 Simulated valve displacement by 3-stage voltage control

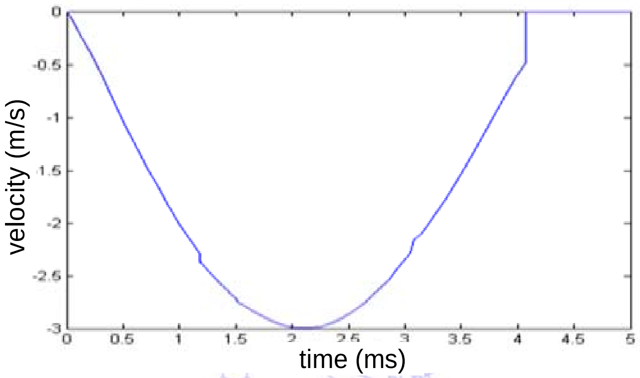


Fig. 15 Simulated valve velocity by 3-stage voltage control

5. Conclusions

This paper focuses on the design of a soft-landing controller for EMV. The objective is to maintain valve rise time below 4 ms and contact velocity below 0.5 m/s. A fuzzy logic controller is used first to obtain voltage pattern, and then a simple but effective 3-stage voltage controller is obtained. Although the fuzzy logic controller can provide good EMV dynamic performance, large computing time by fuzzy controller will cause problems in real-time EMV control. Thus the simple 3-stage voltage control algorithm is a good solution for real-time EMV control. Simulated results also indicate that the controlled EMV performance satisfy the objective.

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