# Enhancement of Lifespan and Operating Reliability Using a New Intelligent Control Method

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*Abstract:* - This paper presents a bounce-duration reduction method for electromagnetic contactor systems. It combines the experience-based fuzzy algorithm and the hysteresis comparator with simple structure to form a newly fuzzy-hysteresis methodology, which is a valuable for minimizing the bounce duration after contacts closing. The proposed method is implemented in a microcontroller program with a specially designed data structure for obtaining the dynamic spring anti-force and the upper and lower force error limitations of the hysteresis comparator. Tests on the experimental prototype show that the newly proposed method is valid and fast in practical applications.

*Key-Words:* - Electromagnetic contactor, Bounce duration, Fuzzy, Hysteresis, Microcontroller, Contacts, Controller.

# **1** Introduction

Currently, numerous automatic control systems and power distribution systems have used the contactor to break/make the load power. When the movable contacts of contactor impact the fixed contacts, in general, a series of bouncing problem after contacts closing is produced. Unfortunately, for certain loads, their online starting or inrush current, like induction motor, flows through these contacts after contacts closing, an arc with high temperature must be produced between movable contacts and fixed contacts and results in the erosion of the contacts [1-3]. Therefore, we can conclude that the using life of contact should be greatly affected by the bouncing phenomenon after contacts closing and may even results in the malfunction of the equipment.

Regarding to the bouncing problem for the contacts after closing, many investigators have researched the reduction of contact bounce by using lots of approaches. In 1997, Nouri *et al.* [4] showed that contact bounces were produced due to excessive kinetic energy acts on the armature prior to two contacts impact. Therefore, they used the power electronic technology, and refer to the change of the armature position as feedback signal, the kinetic energy acts on the armature before contacts impact is controlled through timing coil energizing periods. In addition, other similar works were done as well [5,6]. For an ac electromagnetic contactor, Li *et al.* [7] showed that the moving velocity of

armature is profoundly affected by different initial phase angles during closure process. Hence, the optimizing initial phase angle of ac voltage source was found by taken as the optimization objective [8], taking moving velocities lower than their worst values as restrictions, the optimization model was established. Game theory was adopted to solve this optimization problem. Xu and Zhang [9] proposed a special contact de-bounce method to solve the bouncing issues. The zero crossing point of the applied voltage source must be found first, and in which the coil is energized. In principle, no arcing results should be obtained by means of making/breaking the load circuits at zero load voltage or load current instant. However, this method may only be achieved in his special experimental contactor mechanism, and does not fit for the existing products. Moreover, with the help of the feedback system, there was so-called intelligent contactor were designed and announced it can effectively controlled the kinetic energy of contactor's contacts during closure process [8,10].

In the pursuit of the best operating characteristics, such as fast transition and energy saving, the coilvoltage value should be regulated based on different operating status. Such an attempt is able to be achieved by carefully selecting the voltage-changed time point. The purpose of this paper is to integrate a new fuzzy hysteresis controller with a pulse width modulator to produce a programmable energizing period of coil voltage. Therefore, the movable contacts engaged with the fixed contacts with a soft landing process.

# **2** Mathematical Models

Contactors are a typical electromechanical device. Fig. 1 indicates that an electromagnetic contactor can be partitioned into three portions, such as electrical portion, magnetic energy-conversion portion, and mechanical portion. For simplifying the analysis, the loss included in the magnetic energyconversion portion is assumed to be considered in the electric portion and mechanical portion, respectively. Therefore, the magnetic energyconversion portion can be viewed as a lossless and conservative system, it also referred to as a lossless magnetic conversion system. Based on the law of conservation [11], the energy balance relationship inside an electromagnetic contactor system is given by

$$W_e = W_f + W_m + W_h \tag{1}$$

where

- $W_e$ : The input electrical energy is supplied by the external voltage source u(t);
- $W_f$ : The magnetic field energy is reserved in the magnetic energy-conversion system;
- $W_m$ : The total work done by the mechanical system;
- $W_h$ : An amount of heating loss is dissipated in all the system.





Because the magnetic field energy conversion system is a lossless system, the heating loss depicted in (1) can be ignored. If the dynamic and differential changing behavior related to the three subsystems of electromagnetic contactor is considered, the differential work done by the mechanical system is expressed as shown below.

$$dW_m = dW_e - dW_f \tag{2}$$

### 2.1 Electrical Model

The supplied electric energy from the external voltage source u(t) over a time interval dt is

$$dW_{e} = i u \, dt \tag{3}$$

As a result of the external voltage source u(t) equals the number of windings of coil N times the derivative of flux with respect to time, that is  $N(d\phi/dt)$ . Substituting the representation of the u(t) into (3), we obtain

$$dW_e = i N \, d\phi \tag{4}$$

When there is electromagnetic force  $F_e$  acts on the armature and leads to the armature displacement dx, the differential work done on armature by the mechanical system can be described as follows

$$dW_m = F_e \, dx \tag{5}$$

During differential armature displacement, the amount of the flux in the magnetic circuit and the coil-current value are almost not affected. This phenomenon means that the instantaneous changing amount of flux and coil current are zero. Equation (2) yields the following form.

$$F_e \, dx = -dW_f \tag{6}$$

The simplified expression shown in (6) indicates the work done acts on the armature by the electromagnetic force that is determined by the reduced amount of field stored energy. The field energy stored in the lossless magnetic energy conversion system is commonly equivalent to the stored energy in the inductor, it can be written by

$$W_f = \frac{1}{2}L(x)i^2$$
(7)

Equation (7) is substituted into (6), the electromagnetic force acts on the armature is represented in terms of the coil current and the

derivative of the inductance with respect to armature displacement as follows:

$$F_e = -\frac{dW_f}{dx} = -\frac{1}{2}i^2 \frac{dL(x)}{dx}$$
(8)

As a result of the inductance L(x) varies inversely proportional with the armature displacement x, so that the electromagnetic force shown in (8) illustrates that it is a function of square of the coil current and varies inversely proportional with the square of the armature displacement. Obviously, the electromagnetic force acts on the armature not only depends upon the coil current and the armature displacement, but also reveals a complex and nonlinear characteristics.

#### **2.2 Mechanical Model**

The mechanism appearance of the electromagnetic contactor shown in Fig. 2 depicts that it consists of an armature and a fixed iron core. One complete closing course of the electromagnetic contactor includes two stages: the first stage means that the time interval is from the opening state to contacts closing. The movable iron core is linked with one or triple sets of contacts moves toward the fixed iron core. The counter force acts on the armature is produced by the springs' tension force. After the movable contacts have engaged with the fixed contacts, the second stage begins. The armature continues to move toward the fixed iron core until they are closed together. During this stage, the counter force acts on the armature comes from the combinations of the return springs' and the contacts' tension force. Therefore, the mechanical model should be considered by two stages [12,13].

#### **2.2.1 First stage:** $(d_A - d_C) \le x \le d_A$

The symbol  $d_c$  is the aperture between movable contacts and fixed contacts. In contrast, the symbol  $d_A$  represents the aperture between movable iron core and fixed iron core. By employing the Newton's law of motion, the mathematical model of mechanical system can be expressed as follows:

$$\sum F = ma \tag{9}$$

The resultant force  $\sum F$  is equivalent to the armature mass multiplies its acceleration. However,  $\sum F$  should be the addition of the electromagnetic force, spring anti-force and the friction force. In

addition, the moving acceleration of the armature can be described as the second order differentiation of the time. Equation (9) can be rearranged and represented in the following form.

$$\sum F = F_e - F_f - F_b = m \frac{d^2 x}{dt^2}$$
(10)

where

 $F_e$ : electromagnetic force;

 $F_f$ : return spring anti-force;

 $F_{h}$ : friction force;

*a* : moving acceleration of the armature;

*m* : armature mass;

*x* : armature displacement.



Assuming the representation of the electromagnetic force shown in (8) is simplified and presented as a function of the coil current and armature displacement, that is  $F_e = -f(i, x)$ . Moreover, the spring tension force varies proportionally with the armature displacement; it can be described as  $F_f = 2K_1x + a_1$ , where  $a_1$  is a constant initial pressure force of the spring system. Furthermore, the viscous friction force  $F_b$  is determined by the armature velocity during the considered time interval and represented as  $F_b = -b(dx/dt)$ , where the symbol b is constant coefficient. The armature mass mainly comes from the combination of the movable-iron-core mass  $m_A$  and the movable-contacts mass  $m_C$ .

### **2.2.2 Second stage:** $0 \le x \le (d_A - d_C)$

During this stage, the movable contacts have engaged with the fixed contacts and the armature continue to move toward the fixed iron core. As a result of the disappearance of the contact aperture, this moving process is also called as the super path of the armature. Part of counter force is caused by the spring system here is different from the former working stage and showed as below:

$$F_f = (2K_1 + 3K_2)x + a_1 + 3d \tag{11}$$

where  $K_2$  is the coefficient of the contacts' spring. *d* is the initial pressure of contacts' spring acts on the armature. During armature super path, the movable iron core uniquely continues to move, but not all the armature mechanism. Therefore, the total armature mass is then equivalent to the movableiron-core mass  $m_A$ .

## **3** Generation of Contact Bounce

Fig. 3 shows the complete operation of an electromagnetic contactor. There are three processes, such as closing process, holding process, and opening process, are included in each operation of contactor. The using life and operating reliability of contactor have been published is profoundly affected by the bouncing phenomenon during closing process. Therefore, we will concentrate on our attention in this region. Fig. 3 shows the coil current that varies exponentially with applied external voltage source. If the resultant magnetic force produced by the coil current is sufficient to overcome the spring anti-force, the armature then begins to move towards the fixed iron core until closed together. All the closing process have been diagrammed in the Fig. 3 and the meaning of several parameters are described as follows,  $\Delta t_c$  represents the closing time,  $x_a$  is the contact aperture, and  $x_s$ is the super path.





Generally speaking, after the movable contacts first touches the fixed contacts until they are permanently closed together. A series of contact bounces after contacts closing are produced between the movable contacts and the fixed contacts, as the tremble after contacts closing shown in Fig. 3. The bounce duration may be different from each of closing operation. If contactors are used to directly control the on-line starting load current, the produced arc with high temperature results in the erosion of the contacts' surface. The lifespan of the contacts is shortened. In critical condition, the equipment may lead to an abnormal operation because the breaking course of contactor is unfeasible. According to the researching report related to the two contacts impact during closing process, Nouri depicted the bounce duration after contacts closing depends upon the produced amount of kinetic energy on armature prior to two contacts impact [14]. The relationship between the produced kinetic energy on the armature and its moving velocity can be described as follows:

$$E = \frac{1}{2}mv^2 \tag{15}$$

Equation (15) clearly shows that the kinetic energy attached on the armature is a function of the square of armature moving velocity. Simultaneously, (15) also reveals that the kinetic energy attached on the armature before contacts closing is determined by the armature moving velocity. If an optimal armature moving velocity can be obtained by using a control approach, thus, the shortest bounceduration after contacts closing should be achieved. Since the movable contacts is mechanically linked with the movable iron core and assumes the viscous friction force is small enough to be ignored, the mechanical model of electromagnetic model shown in (10) can be rearranged and presented below:

$$v = \int \frac{F_e - F_f}{m} dt \tag{16}$$

Equation (16) depicts the armature moving velocity that can be directly determined by the electromagnetic force acts on the armature. Furthermore, the representation indicated in (8) also shows that the electromagnetic force varies proportionally with the square of coil current. Therefore, it is a reasonable inference to the control of the armature moving velocity prior to two contacts impact can be achieved by purposely controlling the coil current.

### **4** Solution of Bounce Reduction

By taking advantage of the benefits with the fuzzy algorithm, which the precision controlled system

model is not necessary, and the structure of hysteresis comparator is simple and programmable, this paper proposes a new close-loop control approach based on the combination of the fuzzy algorithm and hysteresis comparator. It is referred to as fuzzy-hysteresis controller. The newly proposed fuzzy-hysteresis controller has many outstanding characteristics, such as robustness and intelligence. In particular, the armature displacement is always needed for the control of the kinetic energy attached on the armature before contacts closing [6]. At present, the armature displacement is not needed. The upper and lower limitations related to the inputs of hysteresis comparator  $f_{error,upper}$  and  $f_{error,lower}$  are provided by a simple fuzzy inference machine [14].

The sketch of the functional block related to the newly proposed fuzzy-hysteresis controller is shown in Fig. 4. First of all, the armature displacement and moving velocity are taken as the input of the fuzzy inference machine and the outputs are the upper and the lower force-error limitations of the hysteresis comparator, such as  $f_{error,upper}$  and  $f_{error,lower}$ . The fuzzy rules are constructed and built in the fuzzy inference machine by using the experienced input-output mapping relationships that are obtained when a uniquely hysteresis comparator is used. The basic configuration for the fuzzy inference machine is demonstrated in Fig. 5 [15].



Fig. 4. Block diagram representation of the proposed fuzzy-hysteresis controller.



Fig. 5. Shows the embedded logic functional block of the fuzzy inference machine.

#### 4.1 Fuzzier

During fuzzification process, the membership function is obtained by using experimental approach. For simplifying the number of processes and reducing the amount of the calculation time, the simpler triangle and trapezoid shapes membership functions are adopted to describe the input and output variables. The relavant boundary values are set based on the measured results of experiments.

As we known. one of the input variables of fuzzy inference machine is the armature displacement and its membership function is programmed and shown in Fig. 6. There are four types of scale are designed, such as NB(Negative Big), ZE(Zero), PS(Positive Small), and PB(Positive Big).



ig. 6. Plots the membership function of armature displacement.

The other one input variable of the fuzzy inference machine is the coil current and its membership function is programmed and shown in Fig. 7. There are three types of scale are designed, such as N(Negative), Z(Zero), and P(Positive).



Fig. 7. Plots the membership function of coil current. As mentioned above, the fuzzy inference machine has two types of output variable, such as the upper force-error limitation  $f_{error,upper}$  and lower force-

error limitation  $f_{error,lower}$ . For these two variables, as indicated in Fig. 8, there are five types of scale are designed to program the individual membership function, such as NB(Negative Big), NS(Negative Small), ZE(Zero), PS(Positive Small), and PB(Positive Big).





#### 4.2 Fuzzy knowledge base (FKB)

In general, the fuzzy rules are constructed based on the people intuitions and expert's experiences. Currently, x and i are taken as the input variables of the fuzzy inference machine and  $f_{error,upper}$  and  $f_{error,lower}$  are the outputs. The input-output mapping relation is 2 by 2. The designed fuzzy rules are listed in Table 1 and Table 2.

#### **4.3 Inference engine**

Based on the designed fuzzy rules shown in Table 1 and Table 2, the fuzzy inference conclusions will be obtained by applying the well-known Mamdani approximate reasoning method. To infer the output w, that is  $f_{error,upper}$  and  $f_{error,lower}$  here, from the given process input x, i and the fuzzy relation  $\mu_R$ , a compositional rule of inference is applied.

$$\mu_w(z) = (\mu_u(x) \wedge \mu_v(y)) \circ \mu_R \tag{6}$$

where  $\circ$  is a max-min composition of fuzzy relation matrices. The output of the inference process is a fuzzy set specifying a possibility distribution of control actions. For on-line control a specific control action is required.

Table 1. Fuzzy rules of  $f_{error,upper}$ .

i x	NB	ZE	PS	PB
Ν	NS	NB	PB	NS
Z	NS	NB	PS	NS
Р	NB	NB	ZE	NS

Table 2. Fuzzy rules of  $f_{error,upper}$ .

x	NB	ZE	PS	РВ
Ν	NS	NB	PB	NS
Z	NS	NB	PS	NS
Р	NS	NB	ZE	NS

#### 4.4 Defuzzier

The output of the inference process is a fuzzy set specifying a possibility distribution of control actions. For on-line control a specific control action is required. Consequently, one must defuzzify the fuzzy control action inferred from the fuzzy control algorithm. A common used technique is the center of area method, which generates the center of the gravity of the possibility distribution of a control action. In the case of a discrete universe, this method yields

$$z = \frac{\sum w_i \mu_w(z_i)}{\sum w_i} \tag{7}$$

where

- $w_i$ : is the weighting factor for the membership function  $\mu_w(z_i)$ .
- $\mu_w(z_i)$ : is the membership function of the fuzzy element  $z_i$ .

Figs. 9 and 10 show the completed input-output mapping relations of the fuzzy inference machine with the use of three dimensions.



Fig. 9. Plots the mapping relation related to the upper force-error  $f_{error,upper}$  versus x and i.



Fig. 10. Plots the mapping relation related to the upper force-error  $f_{error,lower}$  versus x and i.

After the fuzzy inference machine has taken the variables x and i as the input variables and justified, the output variables are the  $f_{error,upper}$  and  $f_{error,lower}$  and fed to the input of the hysteresis comparator. The flow chart of the microcontroller program is illustrated in Fig. 10. The running steps of the microcontroller program can be sequentially performed and explained as follows:

Step 1: Sample the coil voltage, coil current and the armature.

Step 2: Calculate the electromagnetic force and look-up table to find spring anti-force out.

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- Step 3: Calculate the force error.
- Step 4: Take the armature displacement and coil current as the input variables of fuzzy inference machine and output the upper and the lower force-error limitations of the hysteresis comparator.
- Step 5: Dynamically program the hysteresis range of comparator and decide whether the PWM pulse is enabled or not.
- Step 6: Enable the PWM pulse to energize the power switch; the coil voltage will be regulated to 20.4 V. Otherwise, the power switch is not energized.



Fig. 11. Illustrates the software flow chart of microcontroller.

# **5** Tests and Discussions

To verify the effectiveness of our proposed control strategy, a contactor prototype had been established in our laboratory. The rated coil voltage of contactor is dc or ac 24 V, the number of windings is 497 turns, contact's rated voltage and current is ac 600 V and 130 A, respectively. The cores aperture is 8 mm and the contacts aperture is 5.2 mm.

#### 5.1 Construction of Experimental Prototype

As the control module shown in Fig.12 depicts that the rectified dc voltage, coil current, and the dynamic armature displacement are detected by different sensors. The rectified dc voltage is sampled by microcontroller PIC 16F877 through reading the voltage  $V_o$  across the resistor  $R_x$ . According to the voltage division law, the sampled dc voltage is converted to equivalent rectified dc voltage  $V_{+}$  and the next operation of contactor is decided by microcontroller. Fig. 12(a) also shows there is a fixed resistor  $R_i$  acted as a current sensor is connected with the contactor coil in series. The current flow through fixed resistor  $R_i$  is the same as the coil. Therefore, after the voltage across the current sensor  $R_i$ , namely  $V_i$ , has been read by microcontroller, the equivalent coil current i is calculated by  $V_i/R_i$ . In addition to the rectified dc coil voltage and current. the armature displacement xalso is sampled by the microcontroller, but it is not drawn in Fig. 12(a). Fig. 12(b) indicates the completed photograph of abovementioned block diagram shown in Fig. 12(a).



Fig. 12. An electronic control module: (a) block diagram and (b) completed photograph.

#### 5.2 Evaluation of Proposed Controller

Unlike the contactor where the fuzzy controller is uniquely used [14], the newly proposed fuzzyhysteresis controller needs not to justify the changing time point of reprogram the upper and lower force-error limitations of hysteresis comparator. Here, the hysteresis range can be entirely determined by the fuzzy inference machine based on the armature-displacement and coil-current dynamic values. Currently, several tests on experimental prototype were carried out in our laboratory scale prototype. The feasibility and effectiveness of the proposed fuzzy-hysteresis controller used in the reduction of bounce duration after contacts closing were validated.

Fig. 13 shows the time-varying curves concerned with the driving signals of the power MOSFET, coil current, armature displacement, and contact closing status. In addition, the electromagnetic force, spring anti-force, force error, and part of enlarged force error were also demonstrated in Fig. 14. Note that there is a red dash line is marked on the time position in which the movable contacts first touches the fixed contacts. Compared with the contactor where the hysteresis controller is assumed to be used, the closing time is taken by the proposed fuzzy- hysteresis controller is much shorter. Moreover, because the fuzzy- hysteresis controller is an intelligent control approach and not relied upon people; many efforts are used to control the closing behavior before can then be simplified.



Fig. 13. Shows the time-varying curves under the control of fuzzy-hysteresis controller: (a) driving signal of power MOSFET, (b) coil current, (c) armature displacement, and (d) contact closing status.

### **5.3 Bounce-Reduction Performance**

Refer simply to the reference number, as in [16]; the effects of the proposed close-loop fuzzy-hysteresis control strategy upon the contact bounce were carried out by a series of experiments. The designed testing rig as shown in Fig. 15, one of the three contacts pairs was connected in series with a circuit including a dc voltage source and a small resistor  $R_{t}$  acted as the contact bounce measuring device. One node is remarked with a circle, it is referred to as TP, is the contact-bounce testing point. If the voltage at TP was set to E, since the contacts close together; otherwise, the voltage at TP would be set to zero voltage. There were two types of voltage source, namely directing current and alternating current. The neighbouring voltage source value would have the difference of 5% rated voltage of contactor, acted as the typical testing voltage. For each testing voltage source, ten closing sequences were made and recorded with and without closure control. For the measured voltage value of each testing condition, the arithmetic averages of the bounce times were calculated and shown in Table 3. Several important conclusions were made based on the testing results.

- (1) Contactor with much lower bounce duration after two contacts impact when the newly proposed fuzzy-hysteresis close-loop control strategy was used.
- (2) Bounce duration for the dc voltage source case was generally longer than that for the ac voltage source case.
- (3) In a dc voltage source case, the percentage of bounce-reduction result between with and without close-loop closure control was about 94%.
- (4) In an ac voltage source case, the percentage of bounce-reduction result between with and without close-loop closure control was about 95%.
- (5) The bounce-reduction performance of contact in an ac voltage source is better than that in the dc voltage case.
- (6) Regardless of ac or dc voltage-source type was used to supply with the experimental contactor, we found that the contact bounce could be sometimes entirely eliminated with the use of proposed control strategy.



Fig. 14. Shows the time-varying curves: (a) electromagnetic force, (b) spring anti-force, (c) force error, and (d) part of the enlarged force error.

# **6** Conclusion

In this paper, a new control strategy has been developed for the ac or dc types of electromagnetic contactor to minimize the bounce duration after the movable contact first touches the fixed contact until a permanent and stable closing state. This control strategy is to integrate the fuzzy inference machine characterized by experienced rules with the hysteresis comparator in terms of its simple structure. By taking the dynamic armature displacement and coil current as the inputs variables of the fuzzy inference machine, the output is fed to the hysteresis comparator is served as its dynamic upper and lower force-error limitations. As a result of the minimization of the kinetic energy attached on armature, the total transition time from opening position to holding stage is apparently shorter than that in without control case. Tests on experimental prototype have also shown that the proposed control strategy could lead to the minimization of bounce duration after contacts closing. The percentage of the bounce-duration reduction rate is above 90%.



Fig. 15. Sketches the testing rig of the contact bounce.

Table 3. Averaging bounce times.								
Voltage	Averaging Bounce Times (ms)							
source	DC voltage		AC voltage					
• Avg. V	source		source					
for DC	Without	With	Without	With				
● Rms. V	control	control	control	control				
for AC								
(60Hz)								
85%	1.856	0.0396	1.732	0.0948				
90%	1.768	0.0476	1.796	0.0392				
95%	1.878	0.1232	1.996	0.0316				
100%	1.826	0.1872	1.864	0.1372				
105%	1.728	0.0592	1.956	0.1112				
110%	2.032	0.1864	1.854	0.1032				
Avg. value	1.848	0.1072	1.8663	0.0862				
Bounce reduction	94.19%		95.33%					

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