Energy Distribution Analysis in the Closing process of Contactor

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Abstract—This paper aims at studying the energy distribution in each subsystem during the closing process based on the equivalent electrical and mechanical models of contactor. On one hand, the more dynamic behaviors are related to contactor can be obtained; on the other hand, the end result is helpful to improve the performance of contactor. Based on easy modeling and high calculating efficiency, the magnetic circuit analysis method is adopted as the establishing approach of contactor model. The simulation model of contactor is implemented by using Matlab/Simulink software tool. The simulation results showed that the energy distribution in each subsystem critically depends on the initial phase angle of ac voltage source. If the contactor is supplied to some ac voltage source at a specified initial voltage phase angle, the moving velocity or kinetic energy of movable contact prior to collision is allowed to be effectively controlled. Therefore, the rebounding time of contacts after the first time close with fixed contact can then be reduced greatly.

Index Terms—ac contactor, phase angle, ac voltage source, electromagnetic, mechanical, coil, moving velocity, contact bouncing.

I. INTRODUCTION

In the last decade, a growing fields of research in contactor resulting in the development of a variety of prototypes [1]-[6]. In the control engineering and power distribution system, contactors are often used to control the voltage source of load by means of either breaking or making. The application fields and the number of consumers have been increasing. To shorten the closing time, the contactor is usually supplied to a maximum magnitude of voltage source. However, the kinetic energy of armature prior to contacts collision is too large, an uncertain number of contact bounces occur after the impact [6].

On the basis of the starting current of induction motor is about 6-10 times nominal current. The contacts will be damaged by arc due to both the contact bounce and a large number of inrush current occur together. In general, the temperature of arc is high enough to erode the surface of contacts. The lifespan of contacts is significantly decreased.

The contact bounces with erosion have been thoroughly investigated in the past [1]-[3]. Lots of investigators have explored the reduction of contact bounces by using diverse approaches. For example, Nouri et al. [4] reported that contact bounces are produced due to the kinetic energy prior to impact was too much. Therefore, they used power electronic technology and referred to the change of the armature position. The kinetic energy of armature is controlled by timing coil energizing periods. In addition, other similar works were done as well [6], [11]. For an ac electromagnetic contactor, Li et al. [8] showed that the moving velocity of armature is profoundly affected by different initial phase angles during closing process. Hence, the optimizing initial phase angle of ac voltage source was found by taken as the optimization objective [10], taking moving velocities lower than their worst values as restrictions, the optimization model was established. Game theory was adopted to solve this optimization problem. Whereas Xu and Zhang [9] proposed a special contact de-bounce method to solve the bouncing issues. They energized their particular ac contactor at the zero crossing point of the voltage source of load. Theoretically, the end result leads to no arcing due to zero instantaneous power. However, this method may only be achieved in their particular mechanism of contactor. However, it does not fit for the existing products. Moreover, with the help of feedback system, an intelligent contactor with the controlling ability of the kinetic energy of armature was presented [7], [10].

The main objective of this study focuses on two researching aspects, the first is exploring the energy distribution in each subsystem of contactor under closing process and different initial phase angles; the second is hope to optimize the initial phase angle of ac voltage source based on obtaining a minimum kinetic energy associated with the movable contacts prior to collision. The methods reported here could be beneficial to research attempting to reduce the contact bounces during closing process.

II. DESCRIPTION OF CONTACTOR

As shown in Fig. 1, it illustrates a basic mechanical mechanism of an ac contactor. The contactor includes electromagnetic part and mechanical part. The electromagnetic part is responsible for generating a sufficient magnetic force to attract the armature. It is composed of coil, movable core (armature) and fixed core (electromagnet). If the strength of the magnetic force is sufficient to overcome the counter force, the armature begins moving toward the electromagnet. In the opening phase, we hope that armature moved back from fixed part of magnetic circuit as soon as
possible in order to increase voltage gradient between two contacts. At this moment, much more counter force is better. Consequently, there is a tradeoff when designing the tension strength of return spring. One typical working sequences of contactor is denoted in Fig. 2. It is convenient to divide the entire work of contactor into three sub-phases as follows [12]:

A. Closing Phase

The operating time period of this sub-phase is defined as from the coil is initially applied a voltage source to the air gap between armature and fixed part disappear. In general, this sub-phase can be further partitioned into triggering phase and moving phase. In the triggering phase, as shown in Fig. 2(a), the strength of magnetic force is insufficient to attract the armature move toward the electromagnet. In contrast, the moving sub-phase as illustrated in Fig. 2(b), the strength of magnetic force is sufficient to overcome the counter force generated in return springs. Consequently, the armature moves toward the fixed part of magnetic circuit until the closing phase is finished.

B. Closed Phase

When the air gap between two pole pieces disappears, the closed phase begins. The working processes of closed phase are plotted in Fig. 2(c) and Fig. 2(d). In many cases, the armature will proceed an over-distance due to the inertia effect of the mass of armature. In this sub-phase, the coil inductance will significantly increase because the reluctance in the magnetic circuit is reduced greatly. Most of the energy is transferred from the electrical system to mechanical system so as to protect the contacts from disengagement.

C. Opening Phase

In case of breaking the voltage source of contactor, the electromagnetic force will suddenly disappear, and the armature moved back electromagnet immediately. As mentioned earlier, it is necessary to shorten the opening time as possible as in order to reduce an amount of arc or increase the voltage gradient between two contacts. Through these efforts, the using life is prolonged and the operating reliability is improved.

III. ENERGY DISTRIBUTION ANALYSIS IN CLOSING PROCESS

In theory, contactors are singly excited and linear system. The contactor includes three subsystems such as electrical system, magnetic energy-conversion system and mechanical system. Let the energy dissipations in the magnetic energy-conversion system be separated and supposed to be allocate to the electrical and mechanical systems, respectively. Based on the principle of energy conservative must be held in the magnetic energy-conversion system. The energy is transferred from the external voltage source to the mechanical system for the purpose of translational motion of armature. To realize the dynamic behaviors and the energy distribution in each subsystem during the closing process, the transient responses in both the electro-magnet part and the mechanical part are to be explored respectively.
A. Electro-Magnet Part

Fig. 3 demonstrates the equivalent electrical circuit of the electrical system of contactor. By employing the Kirchhoff’s law of voltage, the voltage source of contactor must be dropped down on each load. The first voltage drop term occur due to the coil resistance. The second voltage drop term, \( \frac{d\lambda}{dt} (= f_e(x,i) ) \), which describes the energy transfer between the electrical system and magnetic circuit. Note that the value of latter term depends upon the geometry of the structure of magnetic circuit and the permeability of the magnetic material.

In Fig. 4, the model of electrical system can be represented by the following equation:

\[
\begin{align*}
  u(t) = & \ i(r + e) \\
  \text{where the symbols are defined as follows:} \\
  u & : \text{voltage source} \\
  i & : \text{coil current} \\
  r & : \text{coil resistance}.
\end{align*}
\]  

\[
  e = \frac{d\lambda}{dt} = f_e(x,i)
\]  

From Faraday’s law we can solve for the induced voltage across the coil in terms of the flux linkage \( \lambda \).

\[
  e = \frac{d\lambda}{dt} = f_e(x,i)
\]  

1) Closing phase

The coil inductance \( L \) is a function of the armature position. Since the singly excited device such as contactor, the \( \lambda - i \) characteristic of contactor is linear, the flux linkage can be expressed in terms of coil inductance and coil current as \( \lambda = L(x)i \). Substituting the representation of flux linkage into (2), yields in

\[
  \frac{d\lambda}{dt} = L(x) \frac{di}{dt} + i \frac{dL(x)}{dx}
\]  

where the moving velocity of armature \( v \) in (3) is equivalent to the time rate of the change of the armature position \( dx/dt \).

Substitution of (3) into (1), we obtain

\[
  u(t) = ir + L \frac{di}{dt} + i \frac{dL}{dx}
\]

Since the coil current for an inductive load can not momentarily change, the \( \lambda - i \) characteristic of contactor reveals linear relationship. Equation (4) can then be simplified as a first order differential equation. The solution of (4) or the coil current must be exponentially functioning of the applied voltage source.

2) Closed phase

When the working process of contactor has entered into the closed phase, the reluctance in magnetic circuit becomes a minimum value or the coil inductance becomes a maximum and constant value. The third term of (4) is equal to zero. Hence, (3) can be further simplified as

\[
  \frac{d\lambda}{dt} = L \frac{di}{dt}
\]

The electrical model as shown in (4) is simplified as follows:

\[
  u(t) = ir + L \frac{di}{dt}
\]

Clearly, the solution of coil current in (6) can be written as

\[
  i(t) = \frac{u}{r} (1 - e^{-\frac{t}{\tau}})
\]

Equation (7) means that the coil current will exponentially increase and finally become a constant value by spending about five times time constant, \( \tau (= L/r) \), later.

B. Mechanical Part

Mechanical part of contactor includes of armature, fixed part, return springs, and contacts spring etc. The dynamic behaviors of mechanical system can be described by employing the Newton’s motion law:

\[
  F = m \frac{d^2x}{dt^2} + B \frac{dx}{dt} + kx
\]

Because of the effect of the second term, a damper, on the dynamic behavior of mechanical system is small, it is assumed to be neglected and the approximating accuracy should be acceptable as well. Here, the total counter force acting on the armature is denoted as \( F_i \) when the magnetic force acting on the armature is represented as \( F_e \). Rearrange the force equilibrium as shown in (8) and given as:

\[
  F_e - F_i = m \frac{d^2x}{dt^2} + \Delta F
\]

where \( m \) is the mass of armature. Once the coil is applied to a voltage source, the expression of the generated magnetic force acts to the armature can be described as follows:
\[ F_i = \frac{1}{2} i^2 \frac{dL(x)}{dx} \]  \hspace{1cm} (10)

IV. ENERGY DISTRIBUTION ANALYSES

As mentioned above, the operating processes of contactor can be partitioned into three processes such as closing phase, closed phase, and opening phase. Since the first two terms concerned with the displacement of armature, the contactor should input electrical energy to the device for making the contacts or avoid disengaging the contacts. In fact, the contactors are belonging to the energy converting devices. There are some special features with these devices. In the closing process, the change of dynamic parameters is complex. It is difficult to control the contactor tracing desired action as a result of the total operating time period is too short. Regardless of controlling the contact bouncing problems or predicting the dynamic behaviors, it is very helpful for designer to realize the energy distribution in contactor under different operating phases.

First of all, if (1) is multiplied by the coil current on both sides, and yields in the following expression

\[ ui = i^2 r + i \frac{d\lambda}{dt} \]  \hspace{1cm} (11)

Substitution of (3) and (10) into (11), and results in:

\[ ui = i^2 r + i L \frac{di}{dt} + 2F_v \]  \hspace{1cm} (12)

Equation (12) represents the input electrical energy from the voltage source, should be distributed to respective three parts. In the right side of (12), the first term denotes the energy dissipation of total resistance generated in both current-carrying conductor and coil, the second term is the energy stored in self-inductance voltage term, and the third term is the velocity-voltage term, which depicts the energy transfer between the external electrical system and the magnetic energy-conversion system. Note the last term in (12) is changeable with the variation of working process of contactor. As stated in physics theory, if a body is acted on by a force and doing work, \( W \), within a time period, \( \Delta t \). The average power is the work done divided by the time period and given by [13]:

\[ P = \frac{W}{\Delta t} \]  \hspace{1cm} (13)

where \( P \) is the average power. If the work is done by a very short time period, namely \( \Delta t \rightarrow 0 \), the power value acted on a body become an instantaneous power and the expression is given by the following form:

\[ P = \lim_{\Delta t \rightarrow 0} \frac{W}{\Delta t} \]  \hspace{1cm} (14)

As a result of the definition of the instantaneous power, total input power energy of contactor within a time period, \((t_0 \rightarrow t_1)\), can be computed by the following expression:

\[ E = \sum_{i=0}^{n} u(t_i) i(t_i) \Delta t \]

\[ = E_r + E_s + E_e, \Delta t = t_i - t_{i-1} \]  \hspace{1cm} (15)

where the symbols are respectively defined as:

- \( E_r \) : is the dissipated energy in coil resistance, which is equal to \( \sum_{i=0}^{n} i^2 (t_i) r \Delta t \);
- \( E_s \) : is the stored energy in self-inductance, which is equal to \( \sum_{i=0}^{n} i(t_i)[L(x) \frac{di(t_i)}{dt}] \Delta t \);
- \( E_e \) : is the energy transfer from the electrical to the magnetic energy-conversion system, which is equal to \( \sum_{i=0}^{n} 2F_v(t_i) \Delta t \);

V. LABORATORY TESTS

For convenience, an experimental contactor prototype, which is manufactured by a famous company, Shilin, has been established in our laboratory. Contactor is allowed to be applied with a rated rms voltage 220 \( V_{rms} \) of voltage source. Type of contactor is S-C21L. Contact capacity is 5.5 KW and the nominal value of the coil current is 24 A. Fig. 4 and Table I shows the mechanical sketch of the experimental contactor and size data, respectively. The number of windings is 3750 turns, the coil resistance is 285 \( \Omega \), and the mass of armature is 0.115 Kg.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value (unit: m)</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>0.009</td>
</tr>
<tr>
<td>b</td>
<td>0.013</td>
</tr>
<tr>
<td>c</td>
<td>0.026</td>
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<td>d</td>
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<td>f</td>
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<td>g</td>
<td>0.006</td>
</tr>
<tr>
<td>( e_l )</td>
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</tr>
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A. Establishing Simulation Model

Based on the electrical system and mechanical system model as depicted in (1) and (8), respectively, in compliance with the expressions of magnetic force, as seen in (10), and the moving velocity of armature is defined as $v = \frac{dx}{dt}$. The respective model modules of each subsystem are implemented by using Matlab/Simulink software tool. Furthermore, these five individual simulation modules are combined with each other and become a complete contactor model, as shown in Fig. 5.

In order to demonstrate the input electrical energy of contactor depends upon the initial phase angle of ac voltage source, some simulation tests have been carried out by using developed digital simulation contactor model. From the theoretical analysis result, the electromagnetic force is determined by the coil current. The kinetic energy of armature prior to contacts collision depends on the electromagnetic force. If contactor is to be supplied to a specified initial phase angle, there is a minimum coil current could then be obtained and used to produce the corresponding kinetic energy in armature at a specified armature position. In other words, the desired kinetic energy of armature during closing process could be controlled by carefully selecting the initial phase angle of ac voltage source. In particular, the control of the kinetic energy in armature prior to contacts collision must be implemented, the undesirable contacts bouncing problems is reduced greatly. Improvement of using life and operating reliability of contacts is achieved as well.

B. Effects of the Initial Voltage Phase upon the Energy Distribution in each Subsystem

Obviously, the obtained simulation results in Fig. 6 shows the total input electrical energy of contactor during closing process is a function of the initial phase angle of voltage source. When the contactor runs on the specified initial phase angle, it is supplied to a minimum electrical energy for completing the closing process. Additionally, if we are further hope to analyze how this minimum electrical energy is distributed in each subsystem of electric portion such as coil resistance, self-inductance, and kinetic energy in armature. Fig. 7 presents the energy change of the included subsystems of electrical system. All of the simulated energy data is normalized for the comparisons of distributed energy in each subsystem. As can be seen in Fig. 7, we found the distributed energy of each subsystem that reveals a cyclic function of the initial phase of voltage source as well. Each one changing cycle is 180 degrees. The distributed energy in resistance and transferred to coupling field almost have the same changing trend. When the contactor is powered on under a specified initial phase angle of voltage source, which approximates 90 degrees and 270 degrees as indicated in Fig. 7, there is a maximum value of the distributed energy in resistance and transferred to coupling field almost have the same changing trend. When the contactor is powered on under a specified initial phase angle of voltage source, which approximates 90 degrees and 270 degrees as indicated in Fig. 7, there is a maximum value of the distributed energy in resistance and transferred to coupling field. On the contrarily, the energy stored in the magnetic field depicts a minimum value. In addition, if the changing curve of the energy transferred to the coupling field in Fig. 7(c) is compared with that of the input electrical energy in Fig. 6, it is easy to find them having the same changing trend; only the numerical scale is different. The more input electrical energy will be, the more energy will be dissipated in coil resistance and transferred to coupling field or part of mechanical system. However, we note that less input electrical energy is stored in self-inductance as shown in Fig. 7(b).

Fig. 5. Function block configuration of ac contactor model.

Fig. 6 shows that the simulation results obtained under different initial phase angles of voltage source. There were two important results have been concluded and presented as follows:

1. In case of the initial phase angle of voltage source is selected at near 90 degree and 225 to turn on the contactor, a minimum input electrical energy will be obtained by contactor.

2. Contactor is fed by a minimum input electrical energy every 180 degrees. In other words, the minimum input electrical energy of contactor is a cyclic function of the initial phase angle of voltage source.

Fig. 5. Mechanical sketch of an ac contactor.

Fig. 6. Input electrical energy during closing process varies with initial phase angle of voltage source.

Fig. 7. Energy change of the included subsystems of electrical system.
C. Energy Distribution in Each Subsystem for Different Initial Phase Angles

The input electrical energy of contactor has been demonstrated to repeat every 180 degrees. In order to clearly observe the energy distribution under the same initial phase angle, supposing that some typical initial phase angles of voltage source are taken into accounted such as 0 degree, 45 degree, 95 degree and 135 degree, the energy distributed in each subsystem will be shown by respective bar chart for conveniently, as displayed Fig. 8.

Emphasizing on the demonstrated results in Fig. 8, almost there is approximating beyond ninety percentages of the input electrical energy has been dissipated in the coil resistance; in contrast, only about ten percentage of input electrical energy is converted into the kinetic energy of armature. Furthermore, the energy stored in self-inductance subsystem is always kept on very small percentage during closing process. Therefore, the necessary magnetic force which acts on armature for preventing the contacts from disengagement is generally very small. For taking energy saving into account, the magnitude of applied coil voltage should be switched to smaller one after the closing process is finished.

VI. CONCLUSIONS

Contactors are devices that include electrical system, magnetic energy-conversion system and mechanical system. The contactor is generally excited by a singly source and reveals linear characteristics. If the losses in magnetic field system are separated and subjected into electrical system and mechanical system, respectively, it then becomes a lossless or conservative system. This paper studies the relationship between energy distribution in electrical system and different initial phase angles of voltage source. We have found the input electrical energy and the energy dissipated in each subsystem during closing process are always a period function of the initial phase angle of voltage source. A specified initial phase angle over an angle period may produce a minimum value of electrical energy. Furthermore, the energy dissipated in each subsystem under different initial phase angles of voltage source have been explored through simulation tests and indicated that different percentage of energy distribution
will be dissipated in each subsystem. In addition to dissipate energy in the coil resistance, almost the other input electrical energy is transferred to the mechanical system for doing the translational motion of armature. The more the energy transferred from the voltage source there is, the more the kinetic energy of armature will have. In this paper, by investigating the energy distribution of electrical energy at different initial phase angles of ac voltage source, a desired optimizing initial phase angle of voltage source for the reduction of the number of contact bounces is then obtained.

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VIII. REFERENCES


IX. BIOGRAPHIES

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