In this paper, the experimental contactor is manufactured by a domestic and professional company, Shilin. This device is a tripolar contactor and its type is S-C21L. The coil will be applied an ac voltage source, their nominal power frequency is 60 Hz, and its rated root-mean-square coil voltage is 220 $V_{RMS}$ . Rated contacts' capacity is 5.5 KW, 24 A , the number of coil windings are 3750, the coil resistance is 285 $\Omega$ , and the mass of the movable part is 0.115 Kg.

### 5.1 Establishing simulation model

In general, the dynamic behavior of the contactor can be predicted by using the simulation technique. From the preceding statement in this paper, we know that the governing equations of the contactor are basically composed by the electrical circuit equations and mechanical motion equations. Therefore, five individual simulation sub-modules are firstly established based on the respectively governing equations. At last, a complete contactor simulation model could be built by means of combining the preceding obtained five sub-modules; into a resulting model. The completed simulation model of contactor is shown in Fig. 6.

In order to verify the correctness of the simulation model of the contactor, further to compare of the concerning parameters between the experimental results and the simulation results are essential and necessary work. Hence, the instantaneous coil current, electromagnetic force, counter force and movable-part position, are all used as the compared parameter items. In Fig. 6, it is shown that the simulation results using contactor model are basically in agreement with well the experimental results. To a word, the validation of the correctness and precision of the simulation model of the contactor are successfully done. This simulation model can then be used to simulate and predict the performance of contactor under different operating assumed working status.

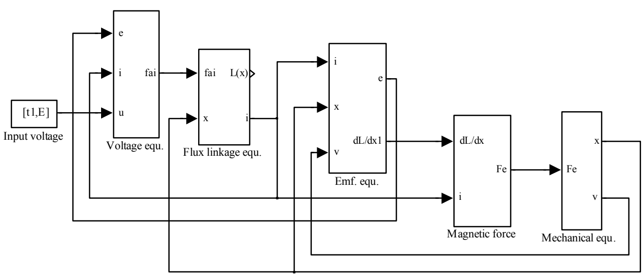
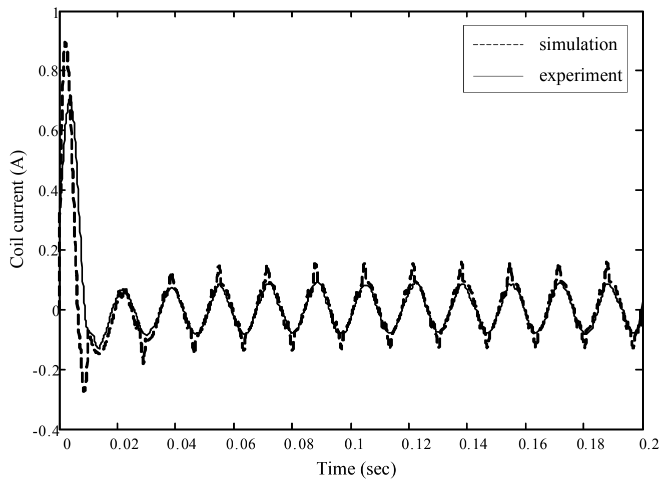



Fig. 6. Completed simulation model of the electromagnetic contactor.

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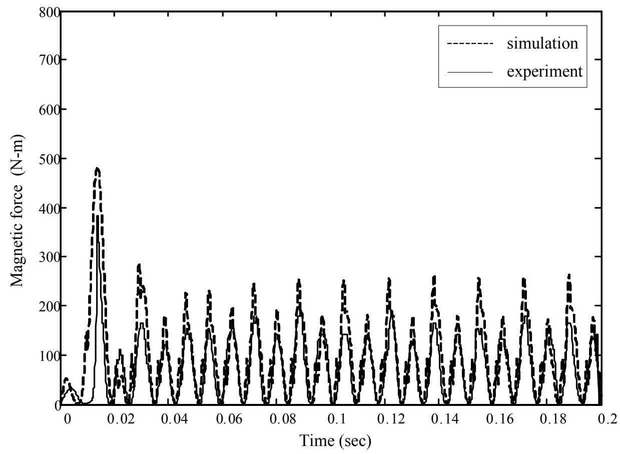


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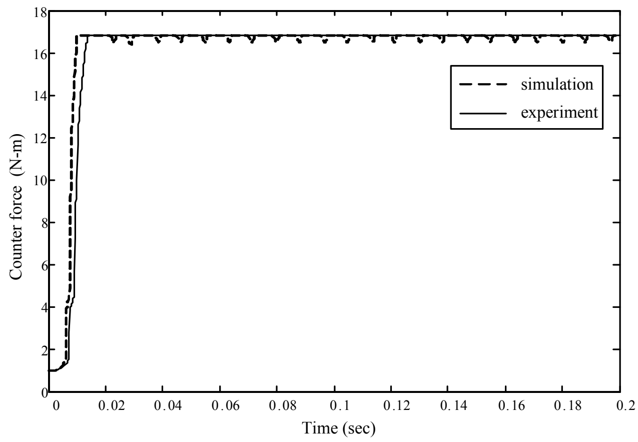


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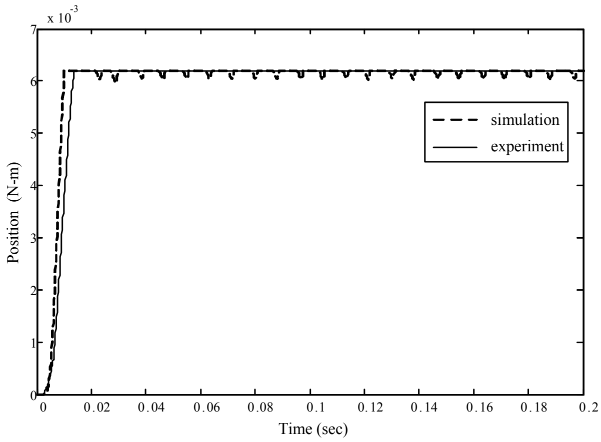
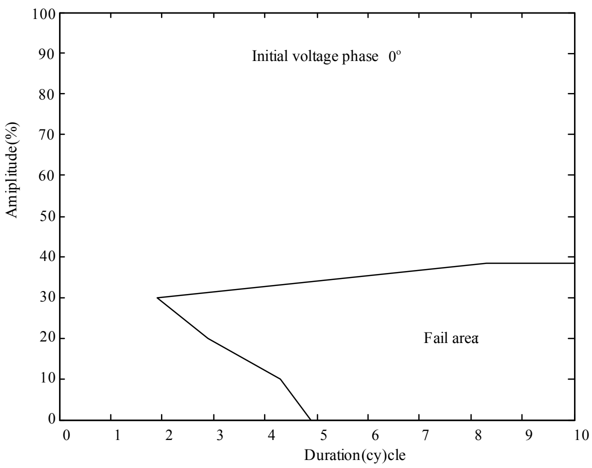



(d)

Fig. 7. Simulated parameter waveforms by model compared with those measured by experimental contactor.

## 5.2 CBEMA curves analysis

The dynamic performance of contactor is to be studied and expressed by using CBEMA curves when it is operated under different voltage-sags conditions like amplitude, duration, and initial voltage sags phase. This kind of curve, CBEMA, was originally introduced to represent the computers voltage-tolerance performance for over-voltage and under-voltage. They show minimum voltage against maximum duration, which ensure the non-stop operation of contactor. Provided that a special point-in-wave where sag occurs, the boundary between succeed and fail to close the electrical contacts are measured and plotted, as shown in Fig. 8. The abscissa of Fig. 8 is voltage-sags duration in cycle, while the ordinate is voltage-sags amplitude in percentage. CBEMA curves of contactor in terms of initial voltage sags phase $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$ are respectively obtained, notice that the border of the $45^\circ$ initial voltage phase is similar to one of the $135^\circ$, but there are not completely identical.

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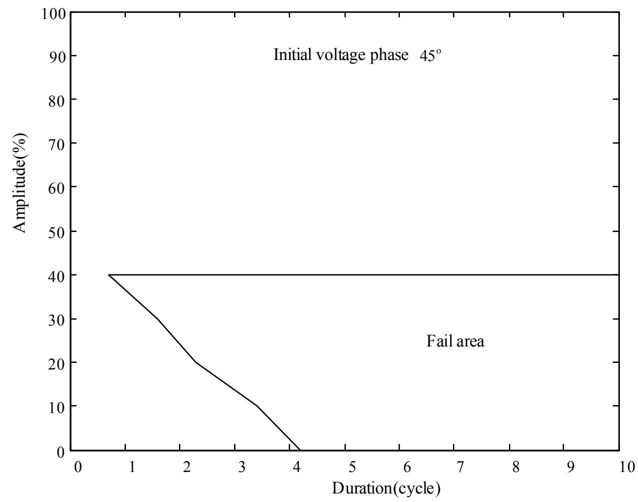


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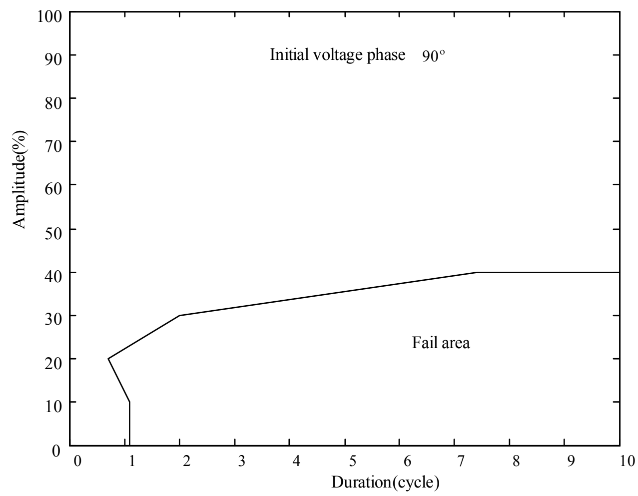


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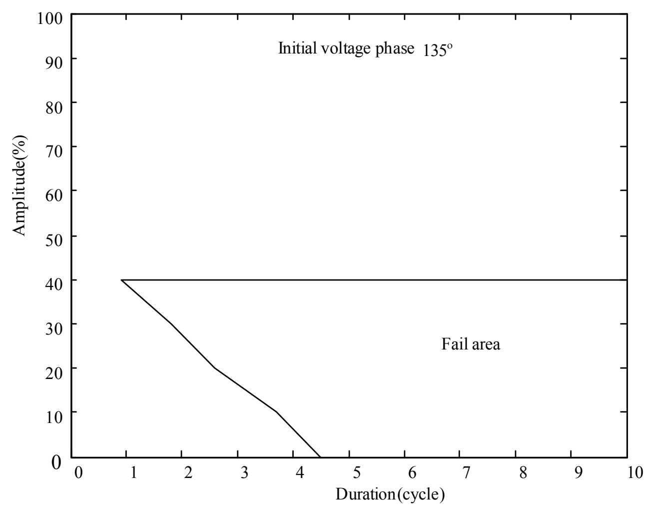
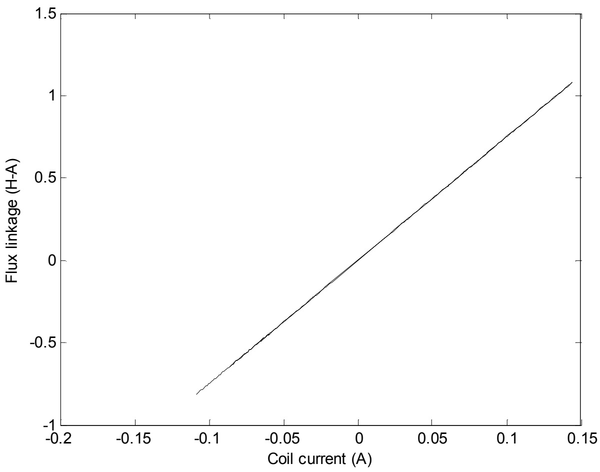



(d)

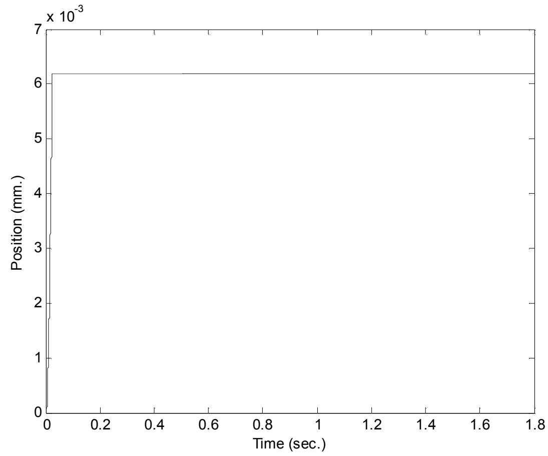
Fig. 8. CBEMA curves of the contactor tolerance under phase angle $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$ where sag occurs.

### 5.3 Flux linkage versus coil current varying curves

From the characteristic of the contactor in terms of input driving impedance, it is indeed an inductor element. As mentioned above, if the inductive one-port is passive, the instantaneous power entering it is nonnegative. Thus, the energy stored in the network is going to be a nonincreasing function of time, as seen in (21). However, any nonlinear passive time-varying network made of flux-controlled inductors is a stable network. We can say that a network is passive if all the elements of the network are passive. Therefore, we say that the dynamic behavior of contactors is either stable or unstable can be completely decided by the net energy stored in the contactor during the dynamical period. If the net energy stored is nonincreasing, the dynamic stability of contactor will be situated at stable state. As a matter of fact, in many practical applications, most the characteristic of the contactor is passive, but locally active at some operating points occur because the slope of the characteristic in the $i\lambda$ plane is negative. So that the electrical contacts is whether remain closed or dropped out, completely relies on the energy delivered by the circuit to the agent $\int_{t_0}^{t} \frac{1}{2}\dot{L}(t')i^2(t')dt'$ during the dynamical period. If the stored energy within this period is negative, the electrical contacts are anticipated to be dropped out, as shown in Fig. 9; contrarily, if the stored energy within this period is nonnegative, the electrical contacts will therefore remain closed or disengagement and re-engagement, as shown in Fig. 10 and 11. In one word, the electrical contacts are either remain closed or dropped out after the considered dynamical period past depends on the value of the net stored energy is negative or nonnegative within the dynamical period.

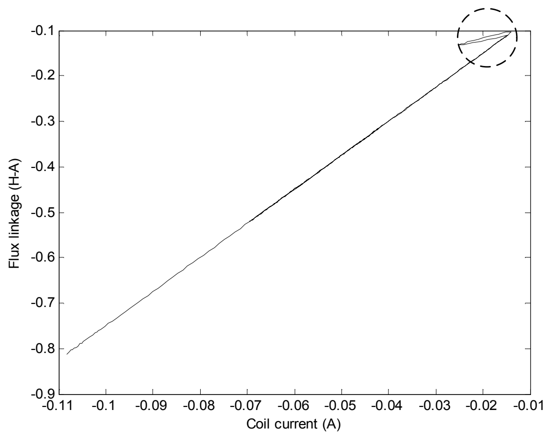



(a)




(b)

Fig. 9. Coil inductance $\dot{L}(t)$ and position varying curves when the voltage sag whose amplitude is 10%, duration is one cycles, and point-in-wave $0^o$ where sag occur.

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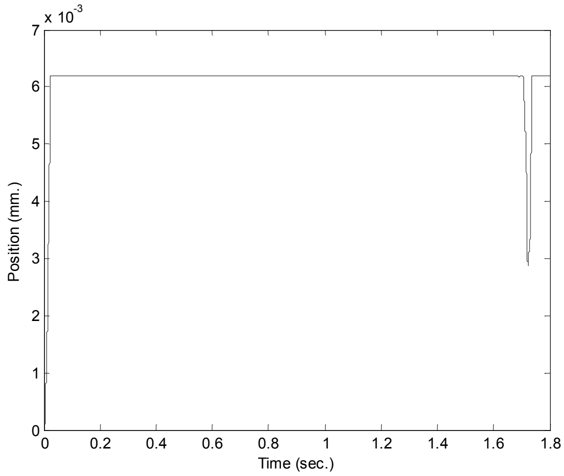
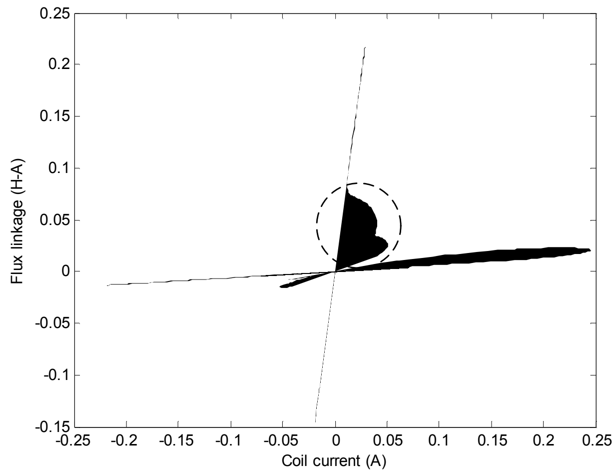


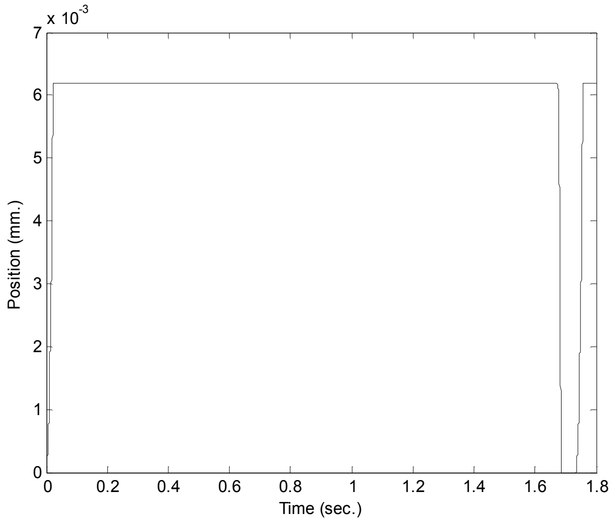

(b)

Fig. 10. Coil inductance $\dot{L}(t)$ and position varying curves when the voltage sag whose amplitude is

20%, duration is three cycles, and point-in-wave $0^{\circ}$ where sag occur.




(a)




(b)

Fig. 11. Coil inductance $\dot{L}(t)$ and position varying curves when the voltage sag whose amplitude is 20%, duration is two cycles, and point-in-wave $90^{\circ}$ where sag occur.

As commented earlier, the dynamic characteristic of the contactor is like a nonlinear time-varying inductor. Nevertheless, for a nonlinear time-varying inductor to be passive, its characteristic (in the $i\lambda$ plane) must pass through the origin and lie in the first and third quadrants in the neighbourhoods of the origin. Also, if the characteristic of a nonlinear time-varying inductor is monotonically increasing and lies in the first and third quadrants, it is passive.

Fig. 9 shows that the energy stored in the contactor is zero during the voltage sag occurs because the position of the movable part never leaves away the electromagnet. However, the characteristic of a nonlinear time-varying inductor is monotonically increasing and lies in the first and third quadrants, it is passive. Therefore, the electrical contacts is remain closed during the voltage sag occurs.

Fig. 10 shows that the total energy stored within the position increasing part is -0.04368 Joules, while the total energy stored within the position decreasing part is 0.06493 Joules during the voltage sag occurs. The characteristic of a nonlinear time-varying inductor is monotonically increasing and lies in the third quadrants, it is passive. Note that the there is partial characteristic occurs the time rate of the change of coil inductance $\dot{L}(t)$ is negative, as shown in Fig. 10(a), where denoted by a dash circle; namely, the operating feature of these points is locally active. Consequently, the energy stored in the contactor within this dynamic period becomes a negative value and the magnetic circuit produces an interesting result that the movable part disengage and then re-engage without any disengagement of the electrical contacts. In addition, considering the net energy stored in the contactor during voltage sag occurs is still a nonnegative value; hence, the contactor is to be passive and stable.

Fig. 11 shows that the total energy stored within the position increasing part is -0.004604 Joules, while the total energy stored within the position decreasing part is 0.05413 Joules during the voltage sag occurs. Since the characteristic of a nonlinear time-varying inductor is monotonically increasing and lies in the first and the third quadrants, it should be passive. Note that the there are some operating points in the characteristic occurs the time rate of the change of coil inductance $\dot{L}(t)$ is negative, as shown in Fig. 11(a), where is denoted by a dash circle; namely, the operating feature of these points is locally active. The sustaining time of the negative coil inductance $\dot{L}(t)$ is longer than preceding case. As seen in (37), because of the net energy stored in the contactor during voltage sags has become a nonnegative value, and therefore the unintended disengagement of the electrical contacts occurs. For this situation, the characteristic of the contactor can be said to be an active and the action is considered as an unstable operation.

# 6 Conclusion

Up to now, there is nothing works concerning the dynamic stability of the contactor by researching of the characteristic of contactor can be found. In this paper, according to the basic definitions of the stability and passivity condition, we provide a new approach, which can be used to predict the dynamic stability of contactor in terms of its characteristic curve in the $i-\lambda$ plane. We are successful to obtain some valuable results by using the established simulation model of the contactor. The contactor model followed by the electromagnetic circuit analysis approaches is established. In the following the contactor voltage sag sensitivity is also simulated on this model and the simulation results are shown in CBEMA curves. Additionally, as seen in the characteristic of contactor in the $i-\lambda$ plane, provided that there exists locally active point during closing process or where voltage sag occurs, the final state of contacts may be remain closed, disengagement or disengagement and re-engagement, which depends only on the net energy-storing within the dynamic period. From those simulation results, we can ensure the dynamic stability of contactor such as during closing process or where voltage sags occur, can be predicted by using the characteristic of a contactor in the $i-\lambda$ plane.

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