Dynamic Stability Analysis Based on Energy-Passivity Considerations

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Abstract: - This study aims at researching the relations between the stability characteristics of an ac contactor and the passivity conditions during power disturbances such as voltage sag. Based on the basic definitions of energy passivity, the stability performance of contactor can be determined by employing the flux linkage versus coil current curve of contactor. On the basis of the governing equations of ac contactor, a digital simulation model is first established. The correctness of the contactor model is verified by comparing the difference of the coil current and the armature displacement between model and contactor. The dynamic stability of contactor can be determined by the energy transferred direction in the electric part or the polarity of the time rate of the change of coil inductance. There are three types of voltage sag are respectively assumed to be the experimental case. Finally, we found that the results which were obtained from simulation tests agree well with those of the theoretical inferences. The identifying rules of the stability of contactor during voltage sag are presented here is valuable for the contactor designer to draft an effective compensation strategy in future so as to improve the momentary performance of contactor.

Key-Words: - Dynamic stability, contactor, passivity, energy, voltage sag, model

1 Introduction

Contactors are devices that have been widely used in all low voltage apparatus. The number of contactors in use is increasing positively proportional to the development of the industrial control. However, they have been identified as a weak link in many processes during power disturbances such as voltage sags. In other words, they are very sensitive to power disturbances [1], [2]. In case of the short-circuit faults of power system and motor reacceleration, the power disturbances will be produced in power system. Unfortunately, the arising positions of these accidental events are often produced outside the controllable area of system [3].

Voltage Sags have been extensively reported as being one of the worst power quality problems. In particular, they are common in rural areas. The voltage sag is defined as the voltage decreases between 0.1 and 0.9 per unit at the power frequency for duration from half a cycle to 1 minute [4]. In many cases, contactors are operated as a switch in a variety of electrical systems for the purpose of power distribution and control. Let an independent system be equipped with contactor, when the contactor face voltage sag, it may be disconnected due to the magnitude of remaining voltage source is insufficient. Consequently, this phenomenon can lead to costly shutdowns in industrial processes [5].

Influencing factors are relevant to the dynamic behaviour of contactor, Collins and Bridgwood showed that contactor drop out and recovery depends upon the point-on-wave occurrence of the voltage sag as well as duration by using experimental approaches. The contactor transient performance caused by shading rings is also studied as in [3], [5]. As for the effects of power disturbances such as voltage sags on the dynamic behaviours of contactor have also been investigated by several authors [6]-[8]. For example, Pedra *et al.* presented a contactor model to analyze the dynamic behaviors in terms of the sensitivity CBEMA curves. These curves were obtained by different initial phase angles in which voltage sag occurs. Later, Mohamad *et al*. aimed at studying the dynamic performance of an ac contactor during voltage sag by merely using their self-defined susceptibility level. They also found the ridethrough capability of the contactor when it was subjected to voltage sags. The characteristic for any type of configuration can be simulated through their self-established contactor model without having to perform laboratory experiments. Furthermore, Isao *et al.* investigated that the sensitivity of the electro-magnetic of contactor during voltage sags by means of experimental approach. At last, they found that shallow sags may cause faster trip of contactor comparing to deep sags in some cases. Additionally, several researchers have also reported that the quantities of sags are produced in the equipment such as induction motor and special designed machines may be measured [9]-[11]. In the last decade, the ridethrough methods of contactor during voltage sags have attracted more and more attention [12], [13], [14].

Although much work is related to contactor has been done, for example, the impact between movable contact and fixed contact during closing process, the measurement of voltage sag and coil current, and the ridethrough of contactor during voltage sags, however, little attention has been paid to study the dynamic stability analysis. The objective of this research was to examine the effects of the voltage sags on the dynamic stability of an AC contactor based on the energy passivity theory. Theoretically, the characteristic of singly excited contactor is linear and time-varying device; it will be viewed as inductor too. Based on a general fact that describes any linear passive time-varying RLC system which is made of flux-controlled inductors is always a stable system [15]. For the purpose of realizing that the dynamic stability property of contactor, especially voltage sag event occurs, the dynamic stability of contactor is identified in terms of the change of energy in the electrical terminal of contactor. The methods reported here could be beneficial to research attempting to increase the dynamic performance of contactor during power disturbances.

2 Operation Principle of Contactor

The basic mechanism of a typical ac contactor, as shown in Fig. 1, is composed of an electro-magnet part and a mechanical part. The electro-magnet part is composed of an exciting coil, air gap, a movable core (armature) and a fixed core (electromagnet). It is responsible to provide a sufficient magnetic force or energy for attracting the movable part when the coil is energized. In the other hand, the mechanical part consists of movable part, fixed part, a set of return springs and one, or triple pairs of the contacts. Electrical contacts are mechanically linked with armature by using a contact holder.

For convenience, one complete working process of a contactor is generally divided into three sub-phases such as closing process, closed process, and opening process. The detailed transitions of these sub-phases are represented by the state machine of contactor in terms of the change of the armature displacement [16], [17].

The main researching purpose of this paper focuses on the dynamic stability of contactor during voltage sags, so that the transient events such as closing process and power disturbances will be considered. In Fig. 2, providing that initiating state S_0 represents that the contactor is not triggered by any voltage source, hence, the electrical contacts are disengagement. As the contactor is energized by an external voltage source, the present state S_0 is immediately shifted to the next state S_s. In this state, as a result of the value of magnetic force is lower than that of spring tension force, therefore, the armature will be kept at stationary status. As the value of voltage source increases, the coil current varies exponentially proportional to the increasing of voltage source. Since the strength of magnetic force is square function of the coil current, then the final strength of magnetic force will be sufficient to overcome the spring tension force. The armature moves toward the fixed part of magnetic circuit. The present state S_s is shifted to the next closed state S_2, through the immediate state S_t.

As denoted in Fig. 2, although power disturbances or switching off operation occurs, if the value of magnetic force is still below the value of the spring tension force, the contactor must be kept on the closed state S_2, which means the normal opening electrical contact will remain closed. The state S_2 will be tentatively shifted to the next state S_d. Through a short time delay S_d, if the magnetic force is being sustained below the spring tension force, the electrical contacts will be dropped out and present state returns to the initial state S_0, otherwise moved back to the closed state S_2.

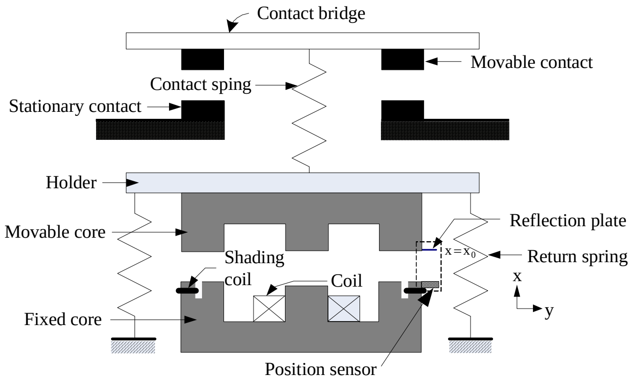


Fig. 1. Basic structure of contactor.

where the states and relevant symbols as shown in Fig. 2 are defined as follows:

S_0 : initial state, generally indicates the contact is open,

S_s : triggering state; as the coil is energized, and the magnetic force is lower than the spring tension force,

S_t : attracting state; since the strength of magnetic force is beyond the spring tension force, the armature moves toward fixed part,

S_2 : closed state; the cores is maintain in pick-up state,

S_d : suspending state; if the voltage sags or power off occurs, the contactor may need responding time,

F_e : magnetic force,

F_f : spring tension force.

In a closed state S_2, if voltage sags or opening process occurs, the magnetic force will be reduced greatly caused by the input electrical energy is lost. The state will be tentatively shifted to the immediate state S_d and even moved back to the initial state if there is no additional electrical energy is supplied; otherwise recovers to the closed state, S_2.

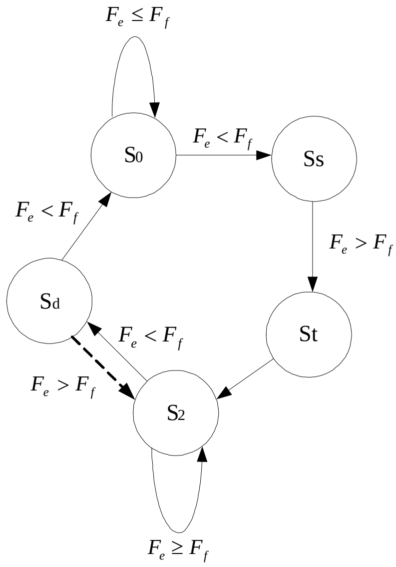


Fig. 2. The dynamic behaviour of contactor is shown as dynamic state machine.

3 Dynamic Characteristics Analysis

In fact, the dynamic behaviors of contactor are an energy transfer from electrical system to mechanical system. Most of the closure process of contactor; its properties are belonging to a linear and time-varying operation [18]. The behaviour of contactor can be accounted for the energy transfer. If it is mathematically to separate those loss mechanisms from the magnetic energy-storage mechanism, the contactor coupling field can be represented as a lossless and conservative magnetic energy-conversion system with the electrical and mechanical terminals, as shown in Fig. 3. In a contactor, this type of system the magnetic energy-conversion system serves as the coupling medium between the electric and mechanical terminals.

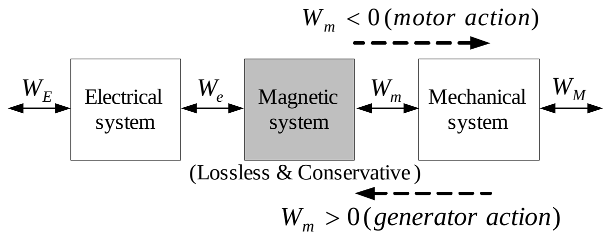


Fig. 3. Energy balance relationship of contactor.

According to the principle of conservative of energy, the stored energy in the lossless magnetic energy-conversion system is neither created nor destroyed; it is merely changed in form. Therefore, in a contactor system, the energy transfers between electrical system and mechanical system can simply be described as follows:

$$dW_f = dW_e - dW_m \tag{1}$$

dW_e : differential electrical-energy input

dW_f : differential change in magnetic stored energy

dW_m : differential mechanical-energy output

If the net mechanical energy or electrical energy is negative, the behaviour of contactor performs a generator action; on the contrarily, if the net mechanical energy or electrical energy is positive, the behaviour of contactor performs a motor action.

The total energy transferred to the magnetic field from electrical system may be expressed as:

$$dW_e = e\,i\,dt \tag{2}$$

where i is the coil current. By the application of Faraday's law, the induced voltage across the coil of contactor can be represented in terms of the change of flux linkage λ with respect to time.

$$e = \frac{d\lambda}{dt} \tag{3}$$

Substituting (3) into (2), we obtain

$$dW_e = i\,d\lambda \tag{4}$$

By employing the Newton's law of motion, the energy output from mechanical system can be expressed in a differential form as

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

Substituting (4) and (5) into (1), the final representation of differential change in magnetic stored energy then becomes

$$dW_f = id\lambda - F_e dx \tag{6}$$

Since the magnetic energy-conversion system is lossless, it is a conservative system and the value of W_f is uniquely specified by the values of λ and x. Thus, W_f is the same independent of how λ and x are brought to their final values. It is convenient to fix mathematically the position of the mechanical system associated with the coupling field and then excite the electrical system with the displacement of the mechanical system held fixed. Equation (1) becomes

$$dW_f = id\lambda \tag{7}$$

As shown in Fig. 4, the area to the right of the $\lambda - i$ curve is called the coenergy and it is expressed

$$W_c = \lambda i - W_f \tag{8}$$

Taking the differentiation of (8) with respect to both sides, yields

$$\begin{aligned} dW_c &= d(\lambda i) - id\lambda \\ &= \lambda\, di \end{aligned} \tag{9}$$

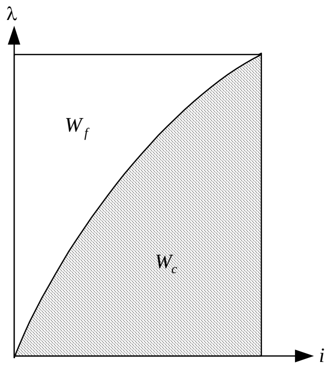


Fig. 4. Stored energy and coenergy in the coupling field of contactor.

In a closure process of contactor, refer to the basic contactor structure in the Fig. 1, let us assume that as the movable part moves from $x = x_1$ to $x = x_2$, where $x_2 < x_1$, the $\lambda - i$ curve moves from point a to point b. Consequently, the change in the field energy is

$$\Delta W_f = area\,(obdo) - area\,(oado) \tag{10}$$

Similarly, the change in W_e, supposed it is denoted as ΔW_e and given

$$\Delta W_e = area\,(caT_1bdc) \tag{11}$$

Since the energy relationship between electrical system, magnetic energy storage system, and mechanical system has been shown in (1). Hence

$$\begin{aligned} \Delta W_m &= \Delta W_f - \Delta W_e \\ &= -area\,(oaT_1bo) \end{aligned} \tag{12}$$

The change in ΔW_m is negative, which represents the energy is supplied to the mechanical system from the coupling field part of which came from the energy stored in the field and part from the electrical system. The net ΔW_m for the cycle from point a to point b back to point a through T_1' is the shaded area shown in Fig. 5. Since ΔW_f is zero for this cycle

$$\begin{aligned} \Delta W_m &= -\Delta W_e \\ &= area\,(oaT_1'bo) \end{aligned} \tag{13}$$

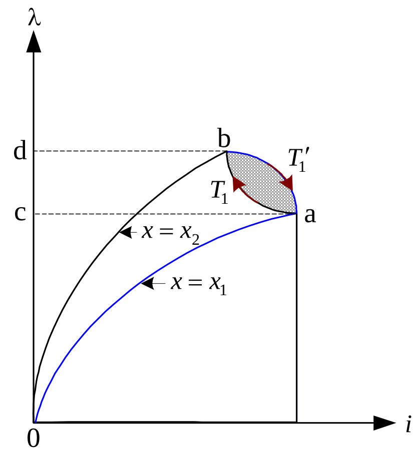


Fig. 5. Energy conversion of contactor for $\lambda - i$ path a to b through T_1 trace, then back to a through T_1' trace (generator action).

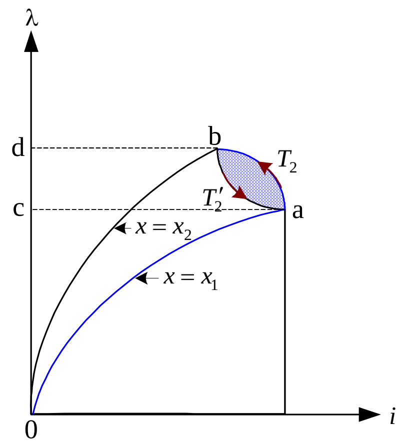


Fig. 6. Energy conversion of contactor for $\lambda - i$ path a to b through T_2 trace, then back to a through T_2' trace (motor action).

For the cycle shown the net ΔW_e is negative, thus ΔW_m is positive; we have generator action. In another special case, as shown in Fig. 6, assume that energy conversion of contactor for $\lambda - i$ path from a to b through T_2 trace, then back to a through T_2' trace. We found that the cycle shown the net ΔW_e is positive, thus ΔW_m is negative; we have motor action.

4. Passivity and Stability

Contactor can be sometimes viewed as a one-port, which includes linear and time-varying elements [14], [19]-[22]. Let us drive this one-port by a voltage source as shown in Fig. 7. According to basic physics theory, we have known that instantaneous power entering the one-port at time t is defined as

$$p(t) = e(t)i(t) \tag{14}$$

The energy transferred to the contactor from time t_0 to t is

$$W(t_0,t) = \int_{t_0}^{t} p(t')dt' = \int_{t_0}^{t} e(t')i(t')dt' \tag{15}$$

Since the dynamic behaviour of contactors in nature are equivalent to a linear and time-varying inductor. The characteristic is given for each t by a curve similar to that shown in Fig. 8, the curves changes as t varies. Supposed those at all times t the characteristic curve goes through the origin; thus, the inductor is in the zero state when the flux is zero. In addition, we also assume that at all times t the inductor is flux-controlled; therefore, we may represent the linear time-varying inductor by

$$i = \hat{i}(\lambda,t) \tag{16}$$

Note that i is an explicit function of both λ and t. The deduced voltage across the coil has been given by Faraday's law as seen in (3). Substitution of (3) and (16) into (15), the energy transferred by the voltage source to the inductor from time t_0 to t can be written as

$$W(t_0,t) = \int_{t_0}^{t} e(t')i(t')dt' = \int_{\lambda(t_0)}^{\lambda(t)} \hat{i}(\lambda',t)d\lambda' \tag{17}$$

Equation (17) shows that $W(t_0,t)$ is a function of the flux at the starting time t_0 and at the observing time t. If we assume that the initiating state of flux is zero, that is, $\lambda(t_0) = 0$, and if we choose the state of zero flux to correspond to zero stored energy, then, recalling that an inductor stores energy but does not dissipate energy, according to the energy conservation, the energy stored ε must be equal to the energy delivered by the voltage source from t_0 to t, that is, $W(t_0,t)$, must be equal to the energy stored

$$\varepsilon[\lambda(t),t] = W(t_0,t) = \int_{0}^{\lambda(t)} \hat{i}(\lambda',t)d\lambda' \tag{18}$$

Note that λ' is only the dummy variable of integration and that t is considered as a fixed parameter during the integration process. Equation (18) can also be rewritten in the following form:

$$W(t_0,t) = \varepsilon[\lambda(t),t] - \varepsilon[\lambda(t_0),t_0] - \int_{t_0}^{t} \frac{\partial}{\partial t'}\varepsilon[\lambda(t'),t']dt' \tag{19}$$

The first two terms give the difference between the energy stored at time t and the energy stored at t_0. The third term is the energy delivered by the circuit to the magnetic field medium which changes the characteristic of the contactor; thus, it is the work done by the electrodynamic for forces during the changes of the configuration of the contactor.

As previously stated, if the input of contactor is assumed as a time-varying inductor, we use a time-varying inductance $L(t)$ to describe its time-varying characteristic. Thus,

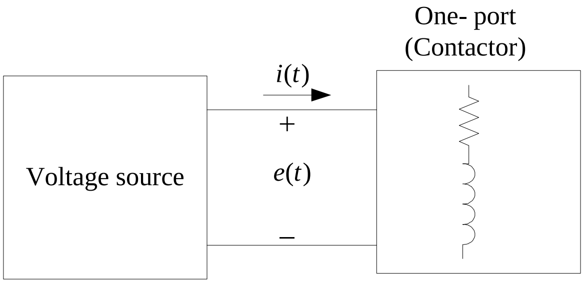


Fig. 7. The contactor is driven by a voltage source.

$$\lambda = L(t)\, i \tag{20}$$

According to the (14), the energy delivered to the time-varying inductor by a voltage source from t_0 to t is

$$W(t_0,t) = \frac{1}{2}L(t)i^2(t) - \frac{1}{2}L(t_0)i^2(t_0) + \int_{t_0}^{t} \frac{1}{2}\dot{L}(t')i^2(t')dt' \tag{21}$$

where the last term in the right-hand side is the energy delivered by the circuit to the magnetic field medium which changes the characteristic of the time-varying inductor. It is important to note that this last term depends both on the waveform $\dot{L}$ and the waveform i.

An inductor or contactor is said to be passive if the energy is

$$W(t_0,t) + \varepsilon(t_0) \geq 0 \tag{22}$$

This is also so-called the passivity condition, for all initial time t_0, for all time $t \geq t_0$, and for all possible input waveforms. From (22), passivity requires that the sum of the stored energy at time t_0 and the energy delivered to the contactor from t_0 to t be nonnegative under all circumstances. So that, the passivity condition for time-varying contactors require that for all time t, and for all possible coil current and coil voltage waveforms. From (21) and (22), the condition for passivity is

$$\frac{1}{2}L(t)i^2(t) + \int_{t_0}^{t} \frac{1}{2}\dot{L}(t')i^2(t')dt' \geq 0 \tag{23}$$

for all time t, for all starting times t_0, and for all possible currents i. Therefore we can assert that a linear time-varying contactor is passive if and only if

$$L(t) \geq 0 \tag{24}$$

and

$$\dot{L}(t) \geq 0 \tag{25}$$

A contactor is said to be locally passive at an operating point if the slope of its characteristic in the $\lambda - i$ plane is nonnegative at the point. In the other hand, a contactor is said to be locally active at an operating point if the slope of its characteristic in the $\lambda - i$ plane is negative at the point. If the contactor is passive, the instantaneous power entering it is nonnegative. Thus, the energy stored in the contactor is a nonincreasing function of time. That is,

$$\varepsilon(t) \leq \varepsilon(t_0) \quad \text{for all } t \geq t_0 \tag{26}$$

We can say that a contactor is passive if all the elements of the contactor are passive. However, any linear passive time-varying contactor made of flux-controlled is a stable system.

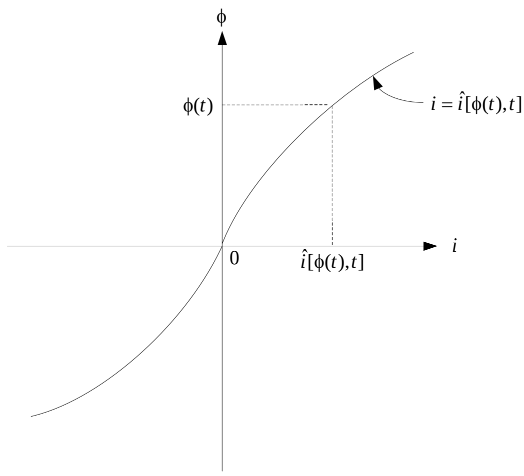


Fig. 8. The characteristic of a typical linear time-varying contactor.

5 Laboratory Tests

In this paper, the experimental contactor is manufactured by a famous company, Shilin. This device is a tri-polar contactor and its type is S-C21L. The coil is applied an ac voltage source, their nominal power frequency is 60 Hz, and its rated rms coil voltage is $220V_{RMS}$. Rated contact capacity is 5.5KW, 24A, the number of windings is 3750 turns, the coil resistance is 285 Ω, and the mass of armature is 0.115Kg.

5.1 Establishing Simulation Model

As previous statement, we have known that the governing equations of contactor are basically composed by the electrical circuit equations and mechanical motion equations. At first, these five individual simulation sub-modules corresponding to each governing equation are established. In addition, a complete contactor simulation model is built by means of combining with five sub-modules. The obtained contactor simulation model is as shown in Fig. 9.

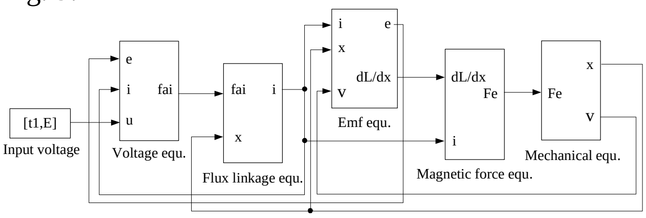
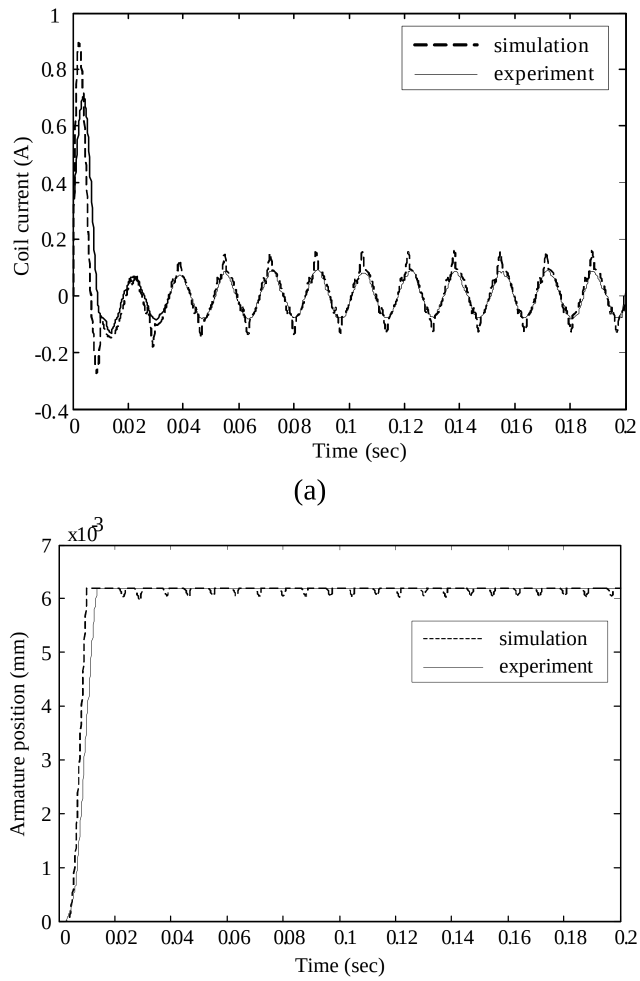


Fig. 9. Simulation model of contactor is established by the Matlab/Simulink software.



(a)

(d)

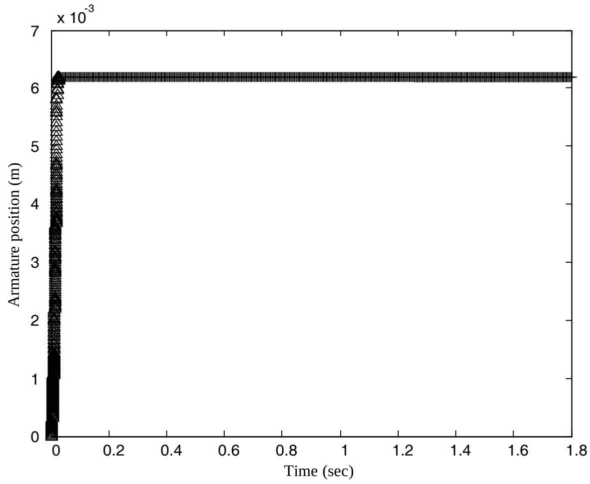
Fig. 10. Parameters comparison between simulation model and real contactor (a) coil current (b) armature displacement.

However, the comparisons of the corresponding parameters between the experimental results and the simulation results are essential to verify the correctness of the developed contactor simulation model. In Fig. 10, it is shown that the simulation results such as coil current and armature displacement using contactor model are basically in agreement with well the experimental results. This result stands for the accuracy of contactor model is acceptable and its behaviour can be equivalent to the behaviour of contactor.

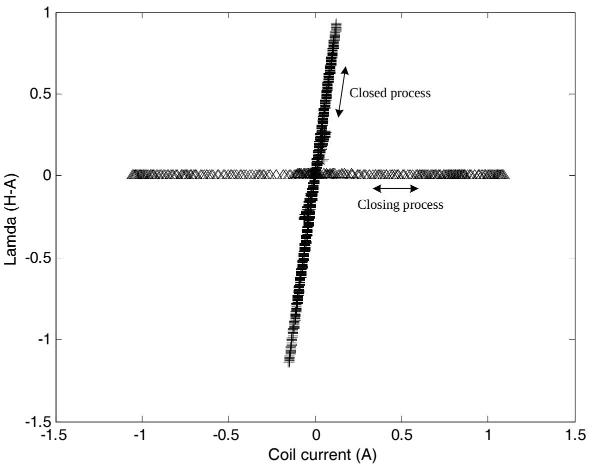
5.2 Flux Linkage versus Coil Current Varying Curves

In theory, the characteristics of the contactor can be featured with its input driving-point impedance. As mentioned above, when the inductive one-port is passive, the instantaneous power entering it is nonnegative. Thus, the energy stored in the system is going to be a nonincreasing function of time, as seen in (26). However, any linear passive time-varying system made of flux-controlled inductors is a stable system. We can say that a system is passive if all the elements of the system are passive. Therefore, we say that the dynamic behaviour of contactors in the period of voltage sags is either stable or unstable can be completely determined by the net energy stored in the contactor. If the net energy stored is nonincreasing, the dynamic stability of contactor will be said at stable state. As shown in Fig. 11(b), the $\lambda - i$ curves in the closing and closed processes are all linear, they agree well with the theoretical analysis.

In many applications, most of the characteristic of contactor is passive, but sometimes exists locally active at some operating points. Some part of the $\lambda - i$ curve, the slope of the characteristic of contactor is negative. This phenomenon represents that the energy transfer is from the mechanical system to electrical system. The dynamic behaviour can appear momentarily unstable. Either engagement or disengagement of the electrical contacts is determined by the energy transferred direction or the polarity of $W(t_0, t) + \varepsilon(t_0)$ from the electrical system to the magnetic energy-conversion system. As mentioned above, the dynamic characteristic of contactor can be viewed as a linear time-varying inductor. However, in case of a linear time-varying inductor to be passive, its characteristic (in the $\lambda - i$ plane) must pass through the origin and lies in the first and third quadrants in the neighbourhood of the origin. Also, if the characteristic of a linear time-varying inductor is monotonically increasing and lies in the first and third quadrants, then it is passive.

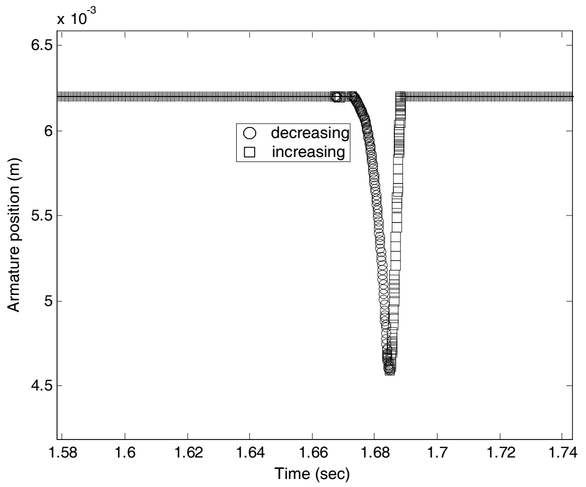


(a)

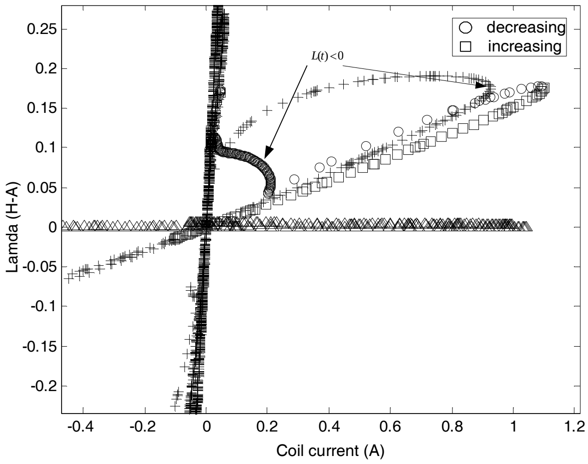


(b)

Fig. 11. When the voltage sag occurs with a magnitude 10%, duration one cycles, and point-in-wave 45^{o}, the varying curves are the coil inductance $L(t)$ and position.

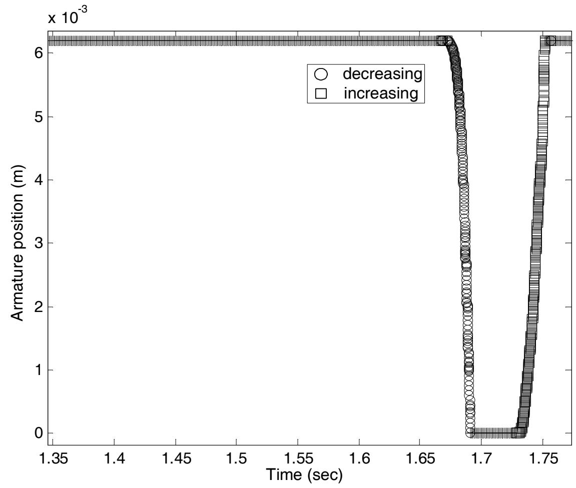


(a)

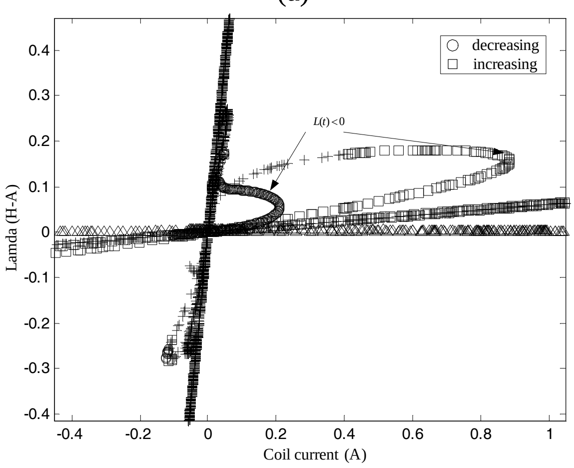


(b)

Fig. 12. When the voltage sag occurs with a magnitude 10%, duration one cycle and point-in-wave 90^{o}, the varying curves are the coil inductance $L(t)$ and position.



(a)



(b)

Fig. 13. When the voltage sag occurs with a magnitude 20%, duration two cycles, and point-in-wave 90^{o}, the varying curves are of the coil inductance $L(t)$ and position.

As shown in Fig. 11 depicts when the operation of contactor is transferred from closing process to closed process, there is no power disturbances occur. Since there is no energy change in the electrical system, we could say no impact of voltage sags upon the contactor. Fig. 11 shows that the energy stored in the contactor is zero due to no voltage sag occurs. The armature never leaves away the electromagnet. Moreover, the $\lambda - i$ curve is monotonically increasing and lies in the first and third quadrants, thus, it is passive. Therefore, the electrical contacts are kept in the closed state.

If the energy transferred direction in electrical terminal has been changed, as denoted in Fig. 12(b) shows $\dot{L} < 0$, but its total energy change is still suffice for the passive condition as shown in (26). Therefore, although the armature has been disengaged and re-engaged with the fixed part of magnetic circuit, the electrical contacts have nothing affected the closed state. Fig. 12 shows the total energy stored within the disengagement process is -0.02547 joules, while the total energy stored within re-engaging process is 0.03644 joules during voltage sags. In addition, the $\lambda - i$ curve is monotonically increasing and lies in the first and third quadrants as well, therefore, it is passive. Note that there is a fraction of the characteristic occurs the coil inductance $L(t)$ is negative, as shown in Fig. 12(a). As the stated passivity conditions, as seen in (23) to (26), the operating features in some special time instants appear locally active. Consequently, the energy stored in the contactor during voltage sags becomes negative and the magnetic circuit disengage and then re-engage without affecting the engagement of electrical contacts. Nevertheless, from the net energy stored in the contactor point of view, the contactor is still to be passive and stable.

However, if the energy polarity in the electrical terminal becomes negative, as the $\lambda - i$ characteristic of contactor illustrated in Fig. 13(a) denotes $\dot{L} < 0$. The passive condition as shown in (26) is not satisfactory again. The total net energy in electrical system over the voltage-sags period reveals a negative value. The disengagement of electrical contacts may be occurred, as demonstrated in Fig. 13(b). Fig. 13 shows that the total energy stored within the disengaging process is -0.09637 joules, while the total energy stored within re-engaging process is 0.017 joules during voltage sags. Although the $\lambda - i$ curve is monotonically increasing and all of curve lies in the first and the third quadrants, some characteristic $L(t)$ appears negative, as shown in Fig. 13(a). As the previous case, if some characteristic of contactor is locally active, the maintaining time of the negative inductance is longer than preceding case. As seen in (24), owing to the net energy stored in the contactor during voltage sags is still a nonnegative value, the undesired disengagement of electrical contacts will not occur.

6 Conclusion

Up to now, only little research has been performed on the dynamic stability of switchgears such as contactor. Based on the definitions of passivity condition, the dynamic stability of contactor after voltage sags was first studied. For convenience, the digital contactor simulation model was built by using its governing equations. Since the characteristics of contactor can only be characterized by the flux linkage and coil current. Hence, during voltage sag, the dynamic behaviour of contactor was determined by the polarity change of inductor on $\lambda - i$ curve or the energy transferred direction in the electrical system. In order to verify the feasibility of proposed method, several experiments were carried out through simulation tests. Experimental results showed that the dynamic stability of contactor could be precisely detected by the developed method. Included conclusions of this paper can be also used to design a voltage compensator for the ridethrough of contactor during voltage sag in future. The electrical contacts of contactor can be prevented from abnormal disengagement.

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References:

[1] M. F. McGranaghan, D. R. Mueller, and M. J. Samotyj, Voltage Sags in Industrial Systems, *IEEE Trans. on Industrial Applications*, Vol.29, No.2, 1993, pp. 397-403.

[2] A. E. Turner and E. R. Collins, The Performance of AC Contactors during Voltage Sags, *7th Int. Conf. on Harmonics and Quality of Power*, 1996, pp. 589-595.

[3] E. R. Collins and M. A. Bridgwood, The Impact of Power System Disturbance on AC-coil Contactors, *IEEE 1997 Annual Textile, Fiber, and Film Industry Technical Conf.*, 1997, pp. 1-6.

[4] R. C. Dugan, M. F. McGranaghan, and H. W. Beaty, *Electrical Power System Quality*, New York, McGraw-Hill, 1996.

[5] E. R. Collins and F. Zapardiel, An Experimental Assessment of AC Contactor Behavior during Voltage Sags, in *Proc. of the IEEE Int. Symposium on Industrial Electronics*, Vol.2, 1997, pp. 439 – 444.

[6] J. Pedra, F. Corcoles, and L. Sainz, Study of AC Contactors during Voltage Sags, *The 10th Int. Conf. on Harmonics and Quality of Power*, Vol.2, 2002, pp. 565 – 570.

[7] H. Mohamad and K. M. Nor, Evaluation on Sensitivity of AC Contactor during Voltage Sag, *TENCON 2004*, 2004, pp. 295 – 298.

[8] I. Isao, H. Masaya, S. Nobuyuki, P. Sompathana, O. Kenji, and I.T oshifumi, Affect of Voltage Sags on Electro-Magnetic Contactor, *The 9th Int. Conf. on Electrical Power Quality and Utilisation*, 2007, pp. 1 – 6.

[9] V. J. Gosbell, V. Smith, D. A. Robinson, B. S. P. Perera, and R. Coulter, Sag Testing of Dairy Farm Milking Equipment, *Int. Conf. on Power System Technology*, Vol.2, 2000, pp. 947 – 952.

[10] J. C. Gomez, M. M. Morcos, C. A. Reineri, and G. N. Campetelli, Behavior of Induction Motor due to Voltage Sags and Short Interruptions, *IEEE Trans. on Power Delivery*, Vol.17, 2002, pp. 434 – 440.

[11] J. Horak, Power Quality: Measurements of Sags and Interruptions, *PES TD 2005/2006*, pp. 733 – 739.

[12] A. Kelley, J. Cavaroc, J. Ledford, and L. Vassalli, Voltage Regulator for Contactor Ridethrough, *IEEE Trans. on Industry Applications*, Vol.36, 2000, pp. 697 – 704.

[13] P. Andrada, G. Navarro, and J. I. Perat, A New Power Supply System for AC Contactor Ride-through, *9th Int. Conf. on Electrical Power Quality and Utilisation*, 2007, pp. 1 – 5.

[14] F. A. Guillermo, A. R. Jose, D. M. Basilio, and F. G. Jose-Job, Preservation of Robustness, non-Fragility and Passivity for Controllers Using Linear Fractional Transformations, *WSEAS Trans. on Circuits and Systems*, Vol.5, May. 2006, pp. 603-610.

[15] A. D. Charles and S. K. Ernest, *Basic Circuit Theory*, Taiwan, Central Book Company, 1979.

[16] S. Fang and H. Y. Lin, Magnetic Field Analysis and Control Circuit Design of Permanent Magnet Actuator for AC Contactor, in *Proc. 8th Int. Conf. on Electrical Machines and Systems*, 2005, pp. 280 – 283.

[17] C. T. Chi, A Study of Closing Adaptive Control in Electronically Controlled Intelligent Contactor, *TENCON 2006, IEEE Region 10 Conf.*, 2006, pp. 1 – 4.

[18] H. Liang, G. C. Ma, L. Cai, X. Yong, and G.. Q. Xie, Research on the Relationship between Contact Breakaway Initial Velocity and Arc Duration, in *Proc. 49th IEEE Holm Conf. on Electrical Contacts*, 2003, pp. 204-210.

[19] S. Washizu, T. Ichikawa, K. Yukita, K. M. Y. Got, and, K. Ichiyanagi, Estimation of ATC from Viewpoint of Voltage Stability in Multi-Machine Power System, *WSEAS Trans. on Power Systems*, Vol.1, 2006, pp. 331-340.

[20] F. A. Guillermo, A. R. Jose, and F. G. Jose-Job, Properties of Fractional-Order Linear Systems: Stability and Passivity, *WSEAS Trans. on Circuits and Systems*, Vol.6, May 2007, pp. 459-464.

[21] Q. Licer, N. E. Alarm, and M. Mrabi, Passivity and Energy based Control for Finding Optimal Compass Gaits, *WSEAS Trans. on Systems*, Vol.5, Sep. 2006, pp. 2061-2067.

[22] T. T. J.C. and D. M. M.A., Equivalence Between Adaptive Passivity Based Control and Model Reference Adaptive Control, *WSEAS Trans. on Circuits and Systems*, Vol.3, Nov. 2004, pp. 1912-1917.