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Mechanical Analysis of Power Electromagnetic Contactors

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Abstract

This paper presents an analysis of the drive mechanism of an AC three-phase electromagnetic contactor. One of the key-feature of the drive mechanism is the strength characteristic, which has been established from experimental tests. A good correlation between strength torque characteristic and the mechanical characteristics of the drive coil for different voltage supply (from 1.1 to 0.7 of rated voltage) has been observed. The recorded oscillograms of the time evolution of the trip of the movable armature, allow to obtain the connection time and the disconnection time of the contactor. Also, the drive coil has been supplied with variable voltage (from 1.1 to 0.7 of rated voltage). The connection and disconnection times are important parameters related to the contactor behaviour from mechanical point of view.

Keywords: Electromagnetic Contactor, Drive Mechanism, Trip Characteristic.

1. Introduction

Contactors with AC coils are among the most widely utilized electromechanical devices in industry. However, since this kind of equipment is usually very sensitive to disturbances in the utility voltages, they can be responsible for load misoperation and loss of production, [1–3]. An electronic device to protect AC contactors from power disturbances, such as voltage sags, is presented in [4]. The use of a square-wave series voltage compensator in the protection of control panels against voltage sags is discussed in [5]. Contactors are designed to disconnect the load or circuit they control when the main power supply is intentionally interrupted. The sensitivity of ac coil contactors to the applied voltage is thus a potentially weak link in industrial processes. An analysis of extensive laboratory testing carried out on ac coil contactors and switch-mode power supply of a PC system to voltage sags with variation in value of point on wave angle of voltage sags, is presented in [6]. Copper-tungsten contacts are frequently used in high power circuit breakers and contactors in air, oil, SF_6, or vacuum. Arc interruption and anti-welding properties are important design parameters. In [7], the effects of tungsten particle size on reignition and weld resistance in air have been examined. Higher power density and longer electrical lifetime at the same time are the main technical targets in development of contactors. Therefore, a close matching of contact material and switching device as well as the understanding of the material-device-interactions is necessary to achieve those demands. The general influence of different material parameters based on Ag/SnO_2 in model switch tests and off-the-shelf contactors under various load conditions, is demonstrated in [8, 9]. The fight for ecological solutions is lead in every technical field. Until 30 years ago, the challenge in the field of power switching apparatus was the interrupting currents and voltages increasing. Nowadays it is important to maintain the same technical performances but to use ecological constructive solutions. In low and medium voltage (up to 36 kV) the switching in vacuum is an ecological very

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good solution, but it raises technical and technological difficulties. For the low voltage contactors the replacement of the Ag-CdO contact material with Ag-SnO_2 is the recommended ecological solution [10, 11]. AC-powered contactors are extensively used in industry in applications such as automatic electrical devices, motor starters, and heaters. In [12], a practical model and simulation of the dynamic behaviour of ac-powered electromechanical contactors is presented. A dynamic simulator for analyzing various behaviours of electromagnetic contactors with AC solenoids, is presented in [13]. The simulator enables short-time analysis of dynamic motions of contactors compared with conventional simulation methods such as finite element method. The study of current and voltage waveforms while controlling relays and low-voltage contactors using a LabVIEW environment, is described in [14, 15]. A fast and effective method for detecting and isolating faults in multi-terminal medium voltage dc shipboard power distribution systems is presented in [16, 17]. This method allows converters and contactors to use only local measurements when deciding whether or not to trip in order to isolate the faulted section. One of the trends in telecommunications power is towards small and compact power systems, [18]. The compact power system needs to be redefined and re-engineered because of the trend of electronics to move from the central office to the loop. To achieve this goal, the system concept has to be optimized, including all the range of contactors, [19, 20]. In an induction-motor-based spindle drive for machine-tool applications, the wye/delta switchover method remains popular for extending the constant-power range without sacrificing the torque capability at higher speeds, [21, 22]. A new generation of medium voltage vacuum circuit breakers can be used to replace sealed SF_6 contactors which experience difficulty in disconnecting the loads safely after 15 years of service, [23].

This paper presents a study related to the drive mechanical system of a power AC three-phase contactor. The connecting and disconnection trip characteristics under various voltage supply values of the drive coil, have been investigated.

2. Theoretical Aspects

The kinematics' analysis of drive mechanism means to establish the kinematics' diagram, the energy sources and the position of the component parts, experimental validation and the motion diagrams. To analyze the mechanism behaviour during transient conditions means to establish the reduction of the masses, of inertia moments, of forces and their moments to a reference element considering the conservation of kinetic energy. Hence, the kinetic energy for a single element "i" is:

$$E_i = \frac{m_i v^2_i}{2} + \frac{J_i \omega_i^2}{2}, \tag{1}$$

where: $\frac{m_i v^2_i}{2}$ is the kinetic energy of the translation with the speed v_i;

$\frac{J_i \omega_i^2}{2}$ – kinetic energy of the rotation of the element;

m_i – mass of the element;

J_i – inertia moment of the element.

Considering the reference point "k" with the known speed v_k, where is concentrated the reduced mass M_{red}, in concordance with the law of the conservation of kinetic energy, the following equation can be written:

$$\frac{M_{red} v_k^2}{2} = \sum_{i=1}^{n} \left(\frac{m_i v_i^2}{2} + \frac{J_i \omega_i^2}{2} \right), \tag{2}$$

hence, it results:

$$M_{red} = \sum_{i=1}^{n} \left[m_i \left(\frac{v_i}{v_k} \right)^2 + J_i \left(\frac{\omega_i}{\omega_k} \right)^2 \right]. \tag{3}$$

Similarly, the next expression for the reference point "k" with rotational motion, can be obtained:

$$\frac{J_{red} \omega_k^2}{2} = \sum_{i=1}^{n} \left(\frac{m_i v_i^2}{2} + J_i \frac{\omega_i^2}{2} \right) \tag{4}$$

hence, the reduced moment becomes:

$$J_{red} = \sum_{i=1}^{n} \left[m_i \left(\frac{v_i}{\omega_k} \right)^2 + J_i \left(\frac{\omega_i}{\omega_k} \right)^2 \right]. \tag{5}$$

The reduced moment of the active forces can be defined considering the balance between its elementary mechanical work and elementary mechanical work of the component parts of the drive mechanism,

$$F_{red} dx_k \cos\alpha_k = \sum_{1}^{n} \left(F_i dx_i \cos\alpha_i + M_i d\alpha_i \right), \tag{6}$$

If the above expression is derived with respect to time, it becomes:

$$F_{red} v_k \cos\alpha_k = \sum_{1}^{n} \left(F_i v_i \cos\alpha_i + M_i \omega_i \right) \tag{7}$$

or:

$$F_{red} = \frac{1}{\cos\alpha}\sum_{1}^{n}\left(F_i\frac{v_i}{v_k}\cos\alpha_i + M_i\frac{\omega_i}{\omega_k}\right), \qquad (8)$$

where:

F_i, M_i are the force and the moment applied to the element "i";
v_i – the speed of the application point of the force F_i;
α_i – the angle between the vectors $\overline{v_i}$ and $\overline{F_i}$;
v_k – the speed of the application point of the force F_k;
α_k – the angle between the vectors $\overline{v_k}$ and $\overline{F_k}$.

In order to establish the reduced moment, the method is the same as previously. Hence, the expression of the reduced moment is:

$$M_{red}\omega_k = \sum_{1}^{n}\left(F_i\cos\alpha_i + M_i\omega_i\right) \qquad (9)$$

or,

$$M_{red} = \sum_{1}^{n}\left(F_i\frac{v_i}{\omega_k}\cos\alpha_i + M_i\frac{\omega_i}{\omega_k}\right) \qquad (10)$$

The analytical study of the behaviour of the power contactors drive mechanism during dynamic switching conditions, requires a mathematical model and also an experimental model in order to validate the proposed mathematical ones.

The strength characteristic of the drive mechanism, in the case of a power contactor means the variation of the resultant strength force F_R vs. the air gap δ. This characteristic has discontinuities because of the prestressed springs of the main contacts and auxiliary contacts, Figure 1.

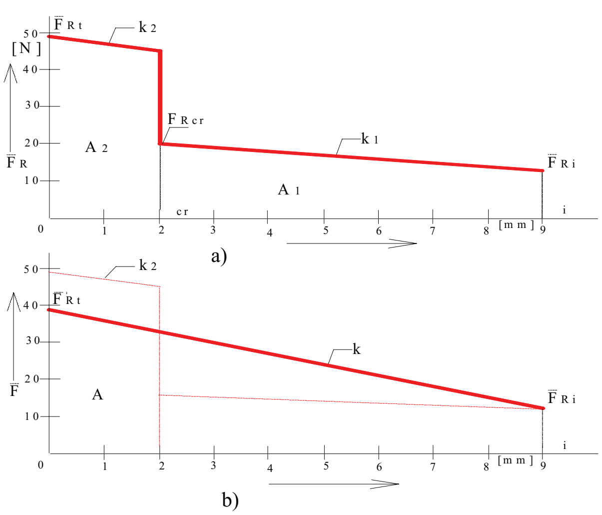

Figure 1. The strength characteristic of the contactor: a) with one single jump; b) without any jump.

This type of characteristic can be idealized with a single jump, Figure 1a, at critical air gap, δ_{cr}, when the prestressed springs of the main contacts start to act. The trapeze areas A_1 and A_2 ($A_1 = \frac{F_{Rcr}+F_{Ri}}{2}(\delta_i - \delta_{cr})$; $A_2 = \frac{F_{Rcr}+F_{Rt}}{2}\delta_{cr}$), are direct proportional with the required energy of the open spring and other prestressed springs. Also, the characteristic can be idealized with a single line, without any jump, Figure 1b, where the effect of all springs can be considered equal with an equivalent spring. The area A is equal with the sum of the above areas, $A = A_1 + A_2$, $A = \frac{F_{Rcr}+F_{Ri}}{2}\delta_i$. This characteristic can be used with the aim to optimize the response time of the drive mechanism.

The mathematical model of the drive mechanism allow to make analysis about the behaviour of the mechanical system of the power contactors during transient conditions of the dynamic switching, as connection and disconnection. A solution may consider the idealized strength characteristic as presented in Figure 1a, which includes two equivalent springs with the elastic constants, k_1 and k_2. At the first spring, the mechanical tension begins at the air gap value of $\delta = \delta_i = \delta_0$, and the second spring, the mechanical tension begins from the critical air gap $\delta = \delta_{cr}$, which because of the pretension energy there is the jump from the characteristic. Other solution, may takes into consideration only one equivalent spring, as presented in Figure 1b.

In order to analyse the behaviour of the drive mechanism of the power contactor during transient conditions (connection/disconnection), it has to investigate the following aspects:

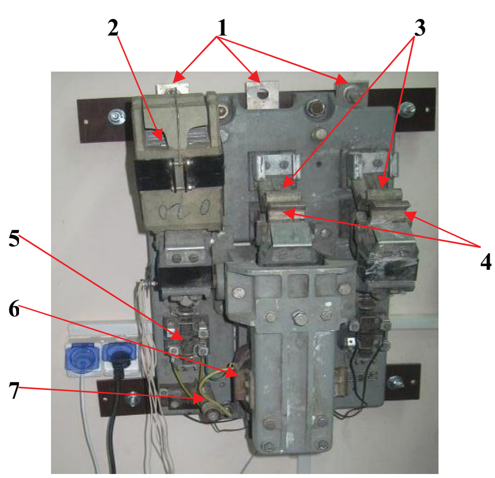

Figure 2. Main component parts of the AC three-phase contactor.

- time evolution of the trip of the movable armature;
- time evolution of the force/torque of the movable armature;
- connection time and disconnection time.

3. Experimental Tests

The analyzed power AC three-phase contactor has the following rated data: rated voltage of 500V, rated current of 600A and the rated frequency of 50Hz. The drive coil has the rated voltage of 220V and the rated frequency of 50Hz. The main component parts of the power contactor, as presented in Figure 2, are: 1 – three-phase terminals, 2 – extinguish chamber for the electric arc, 3 – fixed power contacts, 4 – movable power contacts, 5 – auxiliary contacts, 6 – drive coil, 7 – limiting resistor.

This type of power contactor has the movable armature with the rotational motion. Hence, the strength characteristic will be the variation of the strength torque vs. angle of the rotation of the shaft where is placed the movable armature of the power contactor. Using a digital dynamometer, the strength characteristic has been obtained, Figure 3. It can be observed that the contribution to the total strength torque of the auxiliary contacts on this characteristic is negligible.

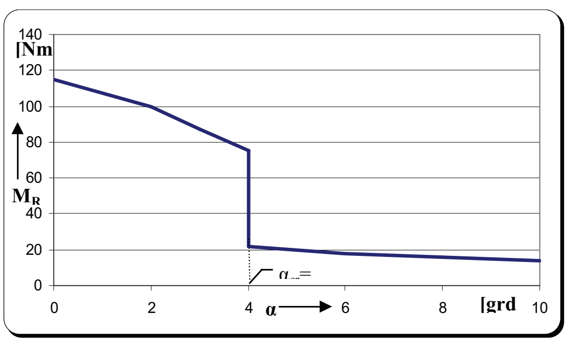

Figure 3. The strength characteristic of the analyzed contactor.

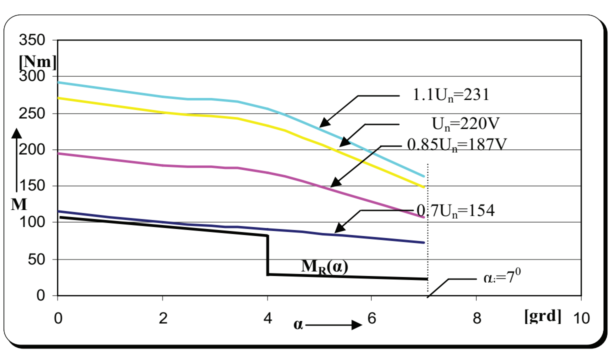

Figure 4. The comparison between the strength characteristic and the mechanical characteristics of the drive coil at different voltage supply.

The comparison between strength torque characteristic and the mechanical characteristics of the drive coil at different voltage supply, is shown in Figure 4. It can be noticed a good correlation between strength and mechanical characteristics and the power contactor can work till the minimum voltage supply of 154V ($0.7U_n$) for the drive coil. At this voltage supply, the strength characteristic is still under the mechanical characteristic of the drive coil.

In order to get the time evolution characteristics of the trip of the movable armature, an experimental set-up has been achieved, as presented in Figure 5.

A potentiometer of 1kΩ value has been mounted with the adjustable part in the shaft of the power contactor where are mounted the movable armature and the power movable contacts. This potentiometer is supplied with dc voltage about 30Vdc, using a single-phase transformer Tr, a rectifier bridge and a filter capacitor of 470uF/40V with the aim to obtain a smooth rectified dc voltage. When the shaft begins to rotate, in the same time, the adjustable part

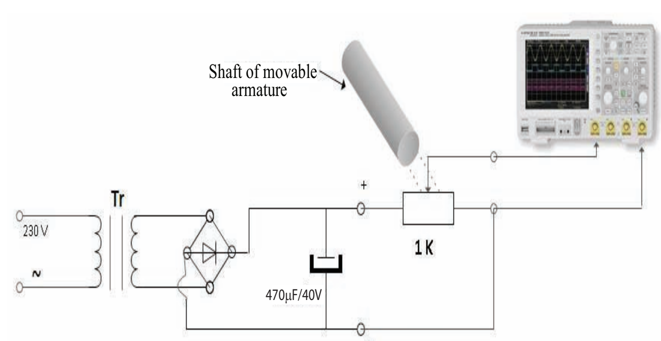

Figure 5. Experimental set-up.

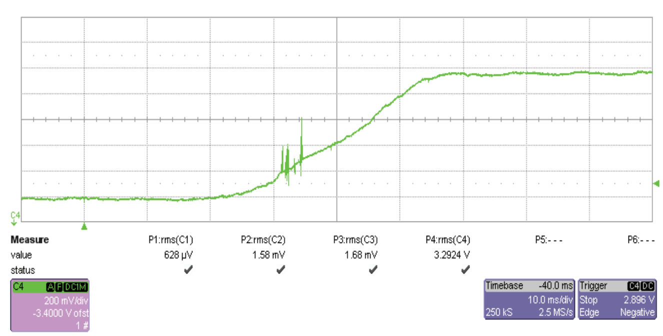

Figure 6. Trip characteristic of the contactor during connection when the voltage supply of the drive coil is 220V.

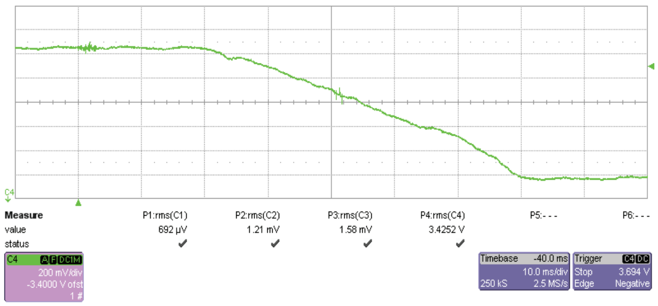

Figure 7. Trip characteristic of the contactor during disconnection when the voltage supply of the drive coil is 220V.

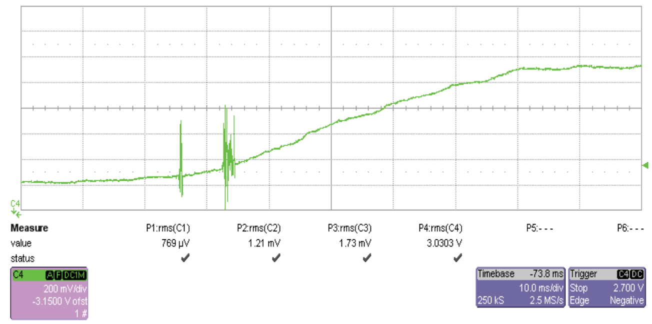

Figure 8. Trip characteristic of the contactor during connection when the voltage supply of the drive coil is 154V.

Table 1. Connection and disconnection time at different voltage supply of the drive coil

U_{coil} [V]	t_{con} [ms]	t_{discon} [ms]
242	22	50
231	24	50
220	30	50
187	35	48
154	50	45
125	100	67

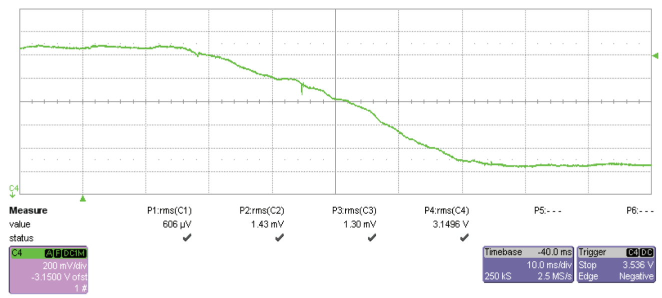

Figure 9. Trip characteristic of the contactor during disconnection when the voltage supply of the drive coil is 154V.

of the potentiometer starts to rotate, and the resistance of the potentiometer will vary direct proportional with the main shaft rotation. It results that the voltage variation across the potentiometer is direct proportional with the rotation of the shaft of the power contactor. This voltage is recorded using a digital oscilloscope, Figure 5. The recorded oscillograms for both connection and disconnection cases of the power contactor at different voltage supply of the drive coil, are presented below, from Figure 6 to Figure 9.

The first two oscillograms, Figure 6 and Figure 7, means the time evolution of the trip in the case of connection and disconnection of the power contactor, when the voltage supply of the drive coil was the rated value of 220V. It can be noticed the connection time of 30ms and the disconnection time of 50ms.

The last two oscillograms, Figure 8 and Figure 9, show the same time evolutions of the trip but in the situation when the drive coil of the power contactor has been supplied with the minimum voltage of 154V ($0.7U_n$). It can be noticed a value of 45ms for the connection time, so an increased value respect to the case when the drive voltage has been supplied with the rated value of 220V. The other values for the connection and disconnection time, are synthesized in the Table 1 below.

It can be observed an increasing of the connection time when the voltage supply of the drive coil is decreased, because the trip force of the coil depends proportional on this voltage supply, and the higher the value of the trip force, the less the value of the connection time.

4. Conclusions

Contactors with AC coils are among the most widely utilized electromechanical devices in industry, especially for motor starting operation. One of the important key-feature for contactors, is represented by its drive mechanism. The behaviour of its drive mechanism during transient conditions, such as connection or disconnection of the main electric circuit, affects the electric drive system from an entire automation process. Hence, it is of major importance to study the drive mechanism of the contactors, especially the correlation between strength characteristic and electromagnetic drive characteristics. Another important parameters which depend on the drive mechanism, are the connection and disconnection times during switching operations of the contactor. At a certain voltage supply of the drive coil, an optimum connection time has to be established.

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6. References

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