Dynamic characteristics of electromagnetic contactor with HTS-2G coil in liquid nitrogen

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Abstract. In this paper is presented experimental investigation of dynamic characteristics of electromagnetic contactor with High-temperature superconductive (HTS) coil in liquid nitrogen. Transient characteristics of armature dynamics and current during electromagnet switching are presented and analysed. HTS coil could provide reduced electric energy consumption in long term operation by active coil resistance reduction, improving this way electromagnetic contactor energy efficiency. Estimation of electromagnetic contactor with HTS-2G coil energy consumption is also presented.

1 Introduction

Electromagnetic contactor is widely used switchgear device optimized for frequent operational switching. It is powered by an electromagnetic actuator that provide the switching transient function and static holding function. Energy consumption is mainly related with continuous holding function where electric current of the actuator coil must provide holding electromagnetic force for a long period of time. Actuator coil takes resistive losses that can be significant in some applications. Reducing or eliminating resistive loss is of great importance for improving power consumption and increasing energy efficiency. Superconductivity wires provides such resistive loss elimination. New generation of HTS-2G wires are becoming more accessible and easy to implement in various applications. High-temperature superconductors (HTS) are defined as materials with critical temperature above 77 K (• 196.2 °C). They are falling in liquid nitrogen temperature range, used for cooling these wires. Efficiency of electromagnetic contactors is related with the power supply of main coil during time of operation. It is providing holding current which supports the contact holding force in switched-on contactor. Interesting new direction is so called hybrid superconducting mode, where HTS coil is connected with non-superconducting circuit and terminals [1, 2]. This way ordinary power supply could be used and coil resistance is eliminated without eliminating source, terminals and non-superconducting parts of electric circuit loop. Hybrid superconducting systems still needs nitrogen cooling of superconducting coil [3, 4].

In this paper is presented experimental investigation of dynamic characteristics of electromagnetic contactor with High-temperature super-conductive (HTS) coil in liquid nitrogen. Transient characteristics of armature dynamics and current during electromagnet

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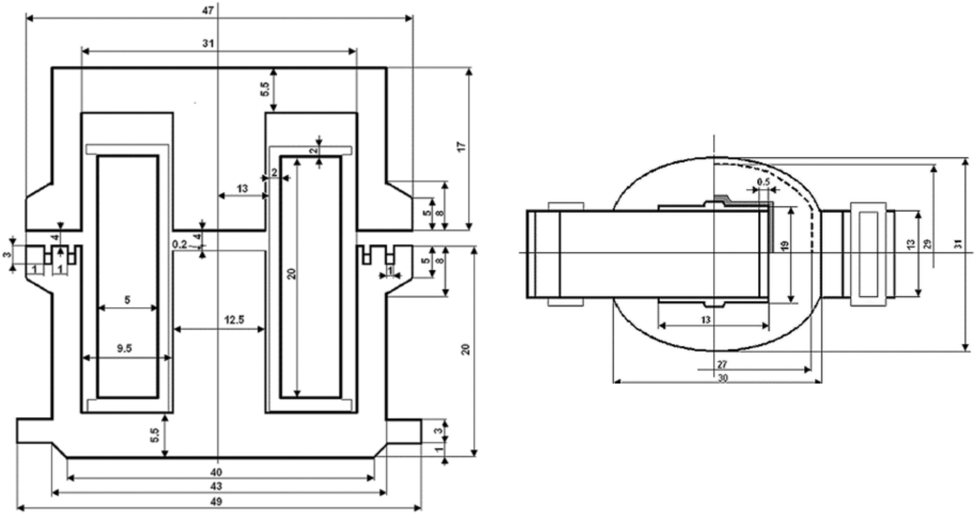
switching are presented and analysed. HTS coil could provide reduced electric energy consumption in long term operation, improving electromagnetic contactor energy efficiency. On second place, transient time-constant in *R-L* series circuit become large, providing electrical stability in the contactor switching process.

2 Electromagnetic actuator

Electromagnetic actuator for AC contactor K10 is considered here for HTS hybrid mode prove of concept [4-6]. The electromagnetic actuator system is a double E-shaped core, with initial working air-gap $\delta = 5$ mm. There are two secondary windings on outer poles for providing additional electromagnetic force. The coil is prismatic, with skeletal spool made of polymer. Figure 1 shows the main dimensions, in mm, of the actuator core and coil.



(a) (b)

Fig. 1. K10 electromagnetic contactor actuator drawing. Side view (a) and top view (b). Coil is replaced with HTS-2G wire. Sizes are in mm.

Original K10 coil magneto motive force (MMF) is estimated of 2160 At, produce by 4800 turns and 450 mA starting current. Original coil is completely removed and replaced with HTS-2G flat wire, with 20 turns with max current of 110 A per turn. This way original MMF is created by this new HTS-2G coil. New coil a has smaller volume than original and fits well in the existing magnetic core. Coil space in the window is significantly reduced.

For the AC contactor prototype is used HTS-2G flat wire with superconducting layer made of GdBCO and critical transition temperature at $T_c = 77$ K. Figure 2 shows the architecture and dimensions of used HTS-2G flat wire. Figure 2 shows the architecture and dimensions of used HTS-2G flat wire [1]-[2].

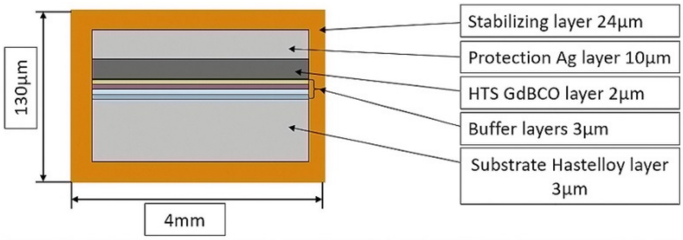


Fig. 2. HTS-2G FESC-SCHO4-50 flat wire architecture and dimensions.

Data for used HTS-2G flat wire, number of electrical turns and dimensions of the contactor main coil are given in Table 1.

Table 1. HTS-2G flat wire FESC-SCH04-50 material properties.

Wire type	**Data**			
	Turns	Wire dimension	Inside d, [mm]	HTS layer
FESC-SCH04-50	20	4 [mm] x130 [μm]	45	GdBCO

2.1 Prototype characteristics testing

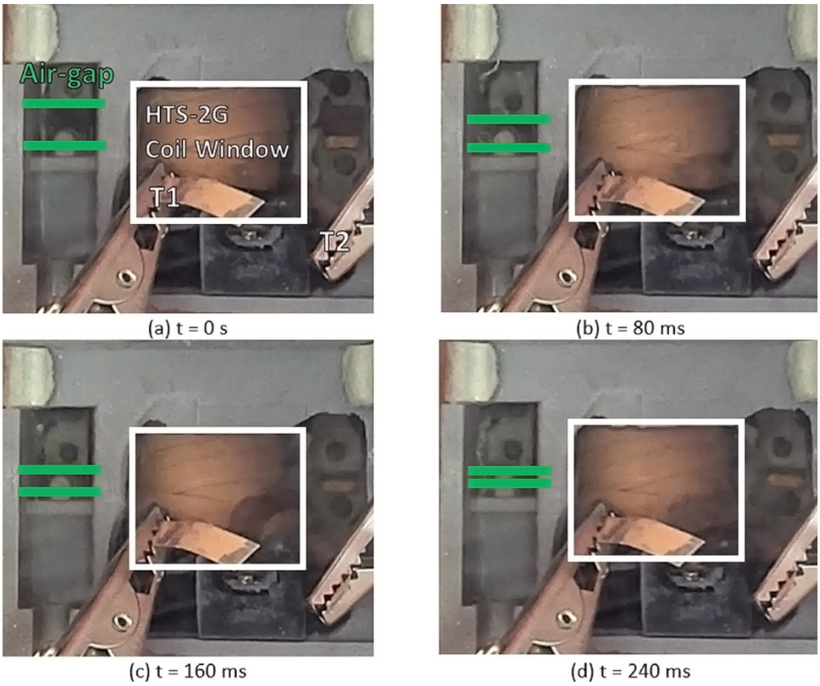
Produced AC contactor prototype with HTS-2G coil is first tested on static inductance and coil quality factor Q. Two static positions are estimated and shown in Table 2. Testing method is described in details in [5-7].

Coil parameters L_1-Q are measured in 100 Hz frequency mode. Further operational transient switching's are tested in 50 Hz AC power supply. Coil, core and contactor enclosure are completely covered with liquid nitrogen.

Table 2. Coil static inductance data.

	Closed air-gap δ = 0	**Opened air-gap δ = 5 mm**
L_1 (μH)	25	21
Q (-)	7.79	1.42

Frames of contactor electromagnetic actuator switching cycle are presented in Figure 3. It contains four main frames with 80 ms time steps showing core armature movement – marked in green lines. For the time interval of 240 ms armature is closing completely. Initial distance is 5 mm, after 80 ms it is 3 mm, at 160 ms 1.5 mm and finally at 240 ms 0 mm. Air-gap closing is indicated in green in the left side of shown frames.



(a) t = 0 s
(b) t = 80 ms
(c) t = 160 ms
(d) t = 240 ms

Fig. 3. Contactor electromagnetic actuator switching cycle. Air-gap closing is indicated in green.

For the time interval of 240 ms armature is closing completely. This is longer duration compared with the dry design without the liquid nitrogen bath. This is because of the moving armature drag force against liquid nitrogen. Also elasticity constant of frozen springs is increased. Additionally, very low loop electric resistivity provides huge response time of electric transients. This is further discussed after the measurement results presented in the next sub-section.

3 Dynamic characteristics

Results for coil current during dynamic switching are experimentally acquired and presented in Figure 4. Initial higher current is due inductance change $L_1(\delta)$ during armature reposition are presented in Figure 3. Dynamic electromagnetic force progress on contactor armature in transient switching is presented in Figure 5.

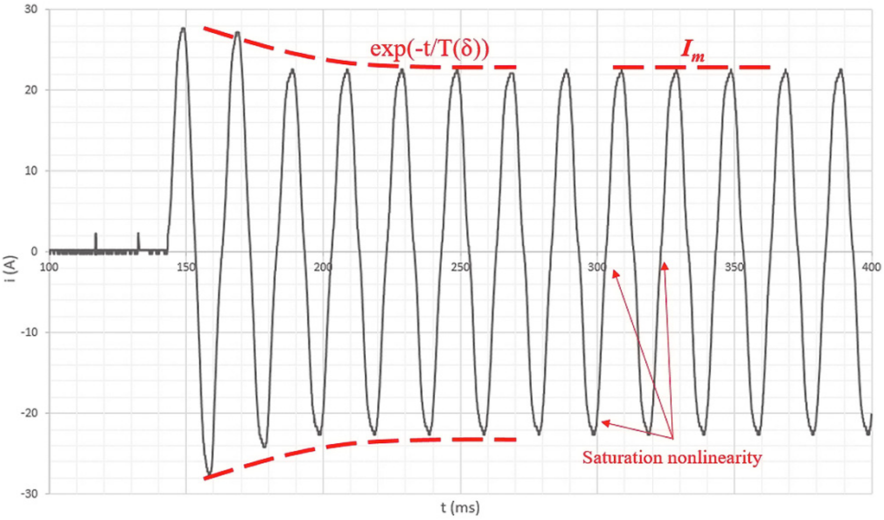


Fig. 4. Coil current during dynamic switching. Initial higher current is due inductance change during armature reposition.

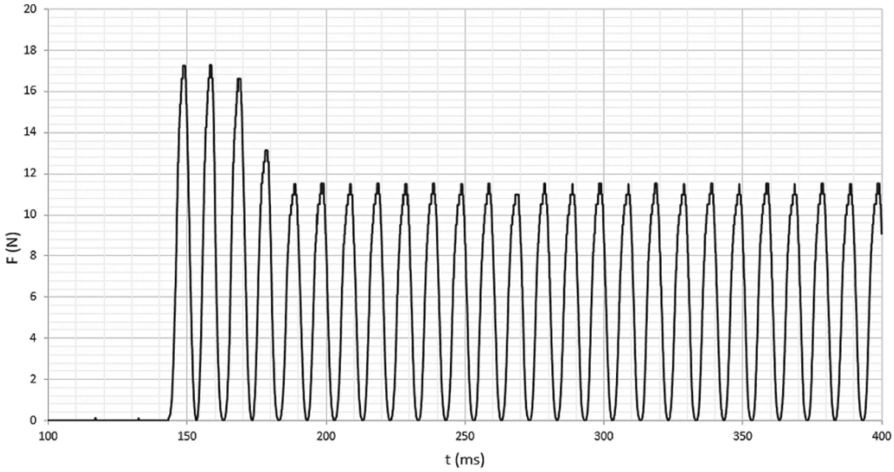


Fig. 5. Dynamic electromagnetic force on contactor armature during transient switching.

The main advantage of superconducting flat wires (HTS-2G) is that they can be used to make devices for wireless power transmission without loss. In addition, the current density in them is extremely high, which means that these devices will be for high power in relatively small dimensions. The quality factor Q of HTS-2G can be calculated using the following equation

$$Q = \frac{2\pi f L_1}{R} \tag{1}$$

where *f* is the frequency in Hz, L_1 is inductance of the HTS conducting layer and *R* is the active resistance of the wires, here active resistance comes from contact resistance and power supply internal resistance in the circuit loop.

The transient switching time constant in a series *R-L* circuit is equal to

$$T(\delta) = \frac{L_1(\delta)}{R} \tag{2}$$

where *R* is the circuit loop of non-superconducting parts of the coil power circuit. Equation (2) explains the long-time constant of the transient switching. It limits the aperiodic change of initial current of HTS-2G coil. In superconducting state, inductance L_1 is defined by geometry of the HTS layer.

Transient coil current *i(t)* during the switching process is modelled by equation (3), coefficients are fitted by measured current data set in Fig.4,

$$i(t) = I_m \, exp\left(-\frac{t}{T(\delta)}\right) sin(\,\omega t + \varphi) \tag{3}$$

where I_m is the amplitude value of coil continuous alternating current, defined as $I_m = U/R$, and angular frequency $\omega = 2\pi f$ for AC frequency $f = 50\ Hz$.

Energy consumption of the contactor coil is calculated by active power during time of operation *t* [5]-[7], or

$$E_{coil} = \int_0^t Ri(t)^2 dt. \tag{4}$$

Transient switching process is modelled by equation (3), where a minimization criterion $\min \|i(t)_{measured} - i(t)_{calculated}\|^2$ is used. Least square method is used for the minimization procedure. Final fitting accuracy is less than 0.02.

Modelled results for transient current and force during switching are presented in Figure 6.

Model parameters fitting results for L_1 and *R* are summarized in Table 3. These results are corresponding very well with directly measured results in Table 2.

Table 3. Model parameters.

	L **(μH)**	***R*** **(Ω)**
Measured	21 → 25	0.6
Modeled	21 → 26.7	0.6

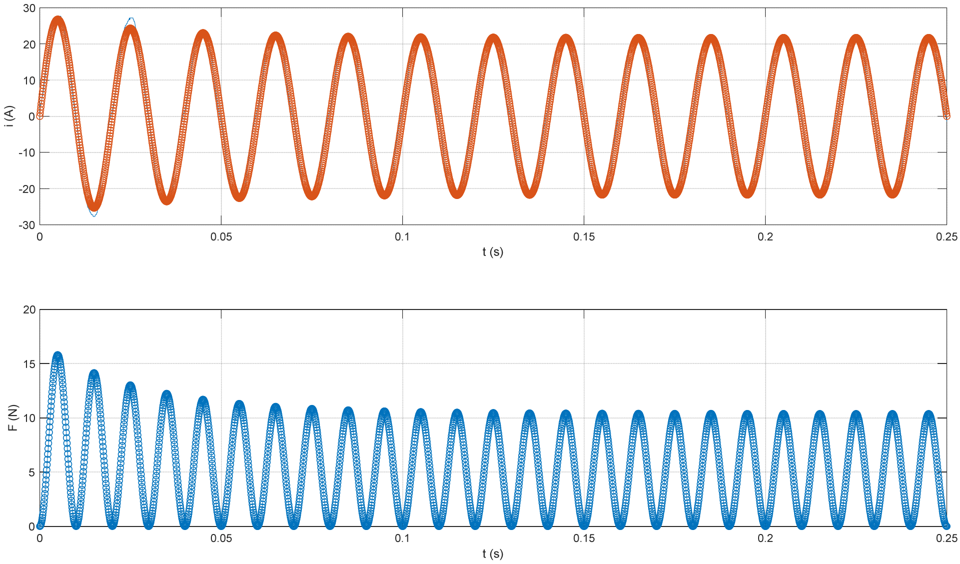


Fig. 6. Modelled results for transient current and force during switching. Circles are representing modelled results over measured with solid line.

Energy consumption can be divided into two components, first is the coil electric consumption and second the energy for keeping 77K for HTC-2G coil. Electric energy during contactor switching, calculated by (4), is 10.8 Ws, which is huge compared with non-superconducting K10 contactor where switching electric energy is 1.2 Ws. This is mainly influenced by switching duration, where in the first case it is t = 240 ms and for non-superconducting case t = 10 ms. As it was explained previously liquid nitrogen provides fluid drag force witch slows armature movement. One of the main recommendations made here is that the contactor armature must be kept out from the liquid nitrogen. Only coil must be submersed in the liquid nitrogen environment. This will provide fast armature movement in the 5-10 ms time range. Also HTC-2G coil does not provide optimal MMF ratio and we believe that better number of coil turns could be defined. Last but not least HTC-2G wire contact improvement can reduce equivalent loop resistance, composed by all non-superconducting parts of the loop, significantly in the mΩ range.

4 Conclusion

In this paper is presented experimental investigation of dynamic characteristics of electromagnetic contactor with High-temperature superconductive coil in liquid nitrogen. Transient characteristics of armature dynamics and current during electromagnet switching are presented and analysed. HTS coil could provide reduced electric energy consumption in long term operation, improving electromagnetic contactor energy efficiency.

HTS design is more compact on size, so magnetic core sizes can be reduced. The obvious problem is the continuous cooling of the HTC coil and design requirements to provide a volume of liquid nitrogen under required thermal insulation for a long operational time. Additionally, very low loop electric resistivity provides huge response time of electric transients. Also elasticity constant of frozen springs is increased so armature and supported kinematics must be kept in room temperature environment.

Cooling requirements limits the application of such systems in large scale. However, it demonstrates some new and interesting opportunities for innovations in electromagnetic actuators with HTS-2G coils.

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