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Finite element analysis and efficiency improvement of the Thomson coil actuator

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Abstract

This paper assesses the electrical to mechanical energy conversion efficiency of a Thomson coil, ultra-fast, linear actuator. Using finite element software a sensitivity analysis of the actuator was conducted in order to understand how different design parameters affect actuator performance. By using an iterative approach a high performance design has been realized. Through FE simulation results it is shown that when the actuator coil is correctly dimensioned, a Thomson coil actuator can achieve a considerably higher efficiency than is reported so far in research literature.

1 Introduction

HVDC links allow the transmission of bulk power with reduced losses over long distances compared with conventional AC systems. Multi-terminal HVDC networks will be used in future transmission systems to connect remotely located renewable power generation to main transmission links. Given the low impedance of DC networks a DC link short circuit will result in a high di/dt value. Thus contrary to AC systems, very fast acting HVDC breakers are required to protect HVDC converter stations. HVDC breakers need to operate in a few milliseconds compared with the tens of milliseconds required for AC counterparts; a 2 to 5 milliseconds operating range is often mentioned in the research literature [1, 2]. This time restriction imposes severe challenges on DC protection systems, consequently both solid-state and hybrid (i.e. solid-state plus mechanical) breakers are being developed.

The clear advantage of solid-state circuit breakers is that the switching time is only a few microseconds, compared to the few milliseconds taken by a mechanical switch with separating metal contacts. The main drawbacks of a solid-state switch are cost and conduction loss. The conduction losses of a solid-state circuit breaker are typically between 0.1 and 0.4% of the transmitted power [3, 4]. In addition, a single semiconductor device is not able to withstand the full voltage and current rating required, therefore a series and parallel arrangement of many semiconductor switches is required to achieve HVDC circuit breaker ratings, increasing the DC breaker cost. On the other hand low conduction loss HVDC

breaker alternatives, such as hybrid [2] and mechanical [5] breakers, use mechanically separable contacts to provide voltage isolation while enabling low conduction loss under normal conditions. Unfortunately hybrid and mechanical breakers are slow in comparison to solid-state breakers due to the inertia of the mechanical part.

Present day hybrid and mechanical low loss HVDC breaker implementations mostly rely on Thomson coil (TC) actuators to provide fast electrode separation. In this actuator a radially wound coil, with a low number of turns, is caused to interact with a conductive plate or armature, Fig. 1. A time varying current injected in the coil results in a time varying magnetic field that produces eddy currents in the armature. Due to the direction of the induced currents, a repulsive magnetic force occurs between armature and coil. Using this principle opening speeds in excess of 20m/s achieved over a time of 2 milliseconds have been reported [5, 6, 7, 8], and consequently TC designs are claimed to provide the high acceleration required for HVDC breaker applications. The main drawback of this actuation mechanism is the low efficiency, typically in the 5% range [5, 6], although recent research reports efficiencies as high as 14% for loaded mechanisms [9]. As a consequence of the TC actuator low efficiency, relatively large and expensive ancillary components (such as energy storage capacitors) are required to ensure proper operation of the device, imposing challenges in operation, reliability and maintenance of the system. As result of the TC actuator efficiency limitation an alternative, repulsion-driven design comprised of two opposing coils, which does not rely on eddy currents, has been proposed in [6]. It was shown in [6, 9] that the two coil approach exhibits higher efficiency (23%) than a comparable TC design.

Fig. 1 Thomson coil diagram

The focus on the work described in this paper is to analyse and improve the efficiency of the TC actuator, while retaining the high mechanical performance characteristic of the device. To this end a parametric analysis of the TC actuator has been conducted, using a multi-physics FE model implemented in COMSOL 5.1, to design a high efficiency TC actuator. Key factors that influence the actuator efficiency are discussed and general conclusions are drawn.

2 FE Simulation

Finite element modelling and analysis software has been shown to be able to predict with good accuracy (within 5% error) the performance of the TC actuator and other repulsion-driven based linear actuators [9, 11]. FEA is adopted in this work to assess the efficiency of the TC design. In order to assess the performance of the TC actuator under different operating conditions a numerical model has been implemented using COMSOL multi-physics FEA software. The numerical simulation involves simultaneous solution of solid mechanics, electrical circuits and electromagnetic equations over a total simulation time of 2ms. This time window is comparable with reported HVDC mechanical switch operation times [2]. For simplicity 2D axial symmetry is assumed and aerodynamic effects are neglected in the model. Copper armature is considered in the FE implementation. In the simulations the actuator coil is excited by a capacitor C with an initial voltage $V(0)$. Low values of series resistance and inductance (9.1 m Ω and 3.6 μ H, respectively) between the capacitor and coil are used to emulate connection leads.

The mechanical behaviour of the system is described by equations (1)-(3).

$$F(t) = ma \quad (1)$$

$$a(t) = dv/dt \quad (2)$$

$$v(t) = dx/dt \quad (3)$$

where F is the total force acting over the armature, m is the moving mass, a is the acceleration, v is the velocity and x is the displacement of the moving element, respectively. In the analysis the moving mass represents the armature (m_a) and mechanical load (m_l) masses, see equation (4).

$$m = m_a + m_l \quad (4)$$

The total force acting on the armature is given by the vector sum of the Lorentz force (F_l) and the gravitational force. The electromagnetic force acting over the armature is calculated by integration of Maxwell's stress tensor over the exterior surfaces of the domains using the COMSOL force component. It should be noted that only the vertical components of force, displacement, velocity and acceleration are of interest in this analysis. Consequently all the results reported in this work are related to the vertical direction, unless otherwise stated. In scalar form, the vertical component of force is given by:

$$F = F_{lz} + F_{az} + F_{mz} \quad (5)$$

where F_{lz} , F_{az} and F_{mz} represent the Lorentz, armature and mechanical load force components, respectively, in the vertical (z) direction. Electrical to mechanical energy conversion efficiency is calculated in this assessment as the kinetic energy to electrical energy spent ratio after the 2 milliseconds of interest. The efficiency in percent can be calculated at any instant using (5).

$$Eff(t) = mv(t)^2 / (C[V(0)^2 - V(t)^2]) \times 100 \quad (5)$$

Equations (1)-(3) are implemented in the model solution by using the COMSOL ODEs and DAEs interface and are solved simultaneously with the TC FE model using a fully coupled solver.

In order to verify the correctness of the proposed numerical implementation the case in section V in [11] was simulated, see Fig. 2. The results in Fig. 2 match closely the results presented in Figs. 9-12 of [11], validating the correctness of the FE implementation in this work. Now that confidence in the accuracy of the FE implementation has been established, further analysis of the performance of the TC actuator can be conducted.

Fig. 2 FE simulation results of the test from [11].

2.1 Sensitivity analysis

To better understand how the different design parameters affect the actuator performance a sensitivity analysis is conducted in this section. During the assessment one parameter is varied at a time, from a set of predefined values, whilst the rest are kept at their initial values. Table I lists the TC actuator parameters initial values used in the simulations. Fig. 3 shows simulation results for armature displacement obtained from the sensitivity analysis. From the simulation results a set of rules, related to the TC actuator mechanical and electrical performance, can be established:

- Increasing the input energy by increasing the capacitor voltage results in an increase in actuator displacement. On the other hand an increase in capacitance results in a moderate increase in actuator displacement.
- An increase in the number of coil turns results in an increase in displacement and efficiency.
- An increase in conductor cross section area results in a displacement increase until a critical cross section area is reached.
- An increase in armature thickness is detrimental to actuator displacement.
- Moving mass minimization is critical in order to optimize system performance.

3 TC efficiency improvement

Based on the rules in section 2 an iterative optimization of the TC design was conducted using FEA. An example of the difficulties involved in the optimisation process is as follows. From the rules, increasing the number of turns should result in a higher efficiency. However the useful space to fit the coil is limited by the armature radius. An increase in the armature radius may be used to increase the coil turns number, however this increase will be reflected as an increase in moving mass, which is detrimental for the actuator performance [6, 7]. The challenge is therefore to increase the number of turns in the coil without increasing significantly the armature mass. An alternative to increasing the coil turns is to decrease the conductor cross section thickness. The effects of such approaches are analysed below.

Parameter	Value	Description
V0	80 V	Capacitor voltage
C	30 mF	Capacitance
Cn	10	Number of turns
At	6 mm	Armature thickness
Ar	44 mm	Armature radius
Ch	2.24 mm	Conductor height
Cw	2.24 mm	Conductor width

Table 1: TC base parameters

Fig. 3 TC sensitivity analysis simulation results

From the rules listed in section 2 conductor cross section and geometry plays an important role in TC actuator performance. It should be noted however that the coil cross section area must be sufficient to sustain the currents and temperature levels produced during operation. Therefore the minimum cross section area was defined in terms of these parameters. Further, the cross section area of the coil conductor may be kept constant by decreasing the conductor width and increasing the conductor height, thus allowing a substantial increase in number of coil turns without increasing armature radius. It should be noted, that by doubling the number of turns, halving the conductor width and doubling conductor height the coil resistance remains the same, while its inductance increases. In other words, this simple procedure allows for fine tuning of the circuit R/L characteristic.

A further increase in coil cross section by increasing coil height was investigated as a means to improve TC actuator performance. Fig. 4 shows the geometry of the improved TC actuator, assuming the voltage and capacitance values of Table 1. Table 2 lists the modified parameters of the enhanced design. Compared with the original values in Table I, the most interesting change in the TC actuator parameters is in the conductor height, which is four times greater than the original value. For the capacitance and voltage combination used in the analysis this particular conductor cross section geometry enabled the highest actuator efficiency.

As reported in [9] the manner in which the input energy is shared between capacitor voltage and capacitance has an important effect on actuator efficiency. Thus a series of voltage and capacitance values were used to identify the best combination for a maximum electrical energy allowance of 2640 J. The voltage-capacitance combinations used in this assessment were deliberately chosen to be identical to those reported in [9], in order to enable a meaningful comparison with published results. A 1 kg load, evenly distributed over the armature surface, was considered in the simulations. Fig. 5 shows simulation results for the TC armature displacement, velocity and actuator efficiency obtained using the different Voltage-Capacitor combinations. The used Voltage-Capacitor combinations are listed in the figures for completeness.

As can be seen from the results in Fig. 5, the maximum displacement, velocity and efficiency are achieved, by a considerably margin, with the 2298V-1mF combination. The results illustrate the critical role that the electric circuit variables play on the mechanical performance of the TC system. It is also clear from the results that for high voltage, low capacitance combinations the peak efficiency is achieved at an early stage of actuator operation (400 μ s or less), over a relatively small armature gap of less than 10 mm. This is an expected result since, as the armature moves away from the coil, the coil field-armature interaction weakens. However, for voltage levels below 727 V peak efficiency is achieved at relatively long displacements. Thus clearly system efficiency depends considerably on the discharge rate of the exciting circuit as well. It is important to notice the relatively high efficiency achieved by the improved TC actuator design, 26%. As a comparison, under identical voltage-capacitance combination and similar operating conditions an efficiency of 14.5% is reported in [9] for a TC design. In this respect, the coil geometry and turns play a critical role in the actuator efficiency reported in this research work.

Fig. 4 TC geometry

Parameter	Value	Description
Cn	32	Coil turns
At	3 mm	Armature thickness
Cw	1.12 mm	Conductor width
Ch	8.96 mm	Conductor height

Table 2: High performance TC actuator parameters

Fig. 5. TC armature displacement (top) and actuator efficiency (bottom) for several Voltage-Capacitor combinations.

Fig. 6 shows the investigated TC design current density distribution at $t=70 \mu$ s. It can be observed that most of the current concentrates in a thin layer at the top of the coil (skin effect), and a large portion of the conductor material is unused at an early stage of the actuator operation. This conductor geometry however, was designed based on the analysis at different voltage and capacitance values. Now that the most effective voltage-capacitance combination has been identified the conductor cross section can be optimised. Simulation results for displacement, velocity and efficiency with different conductor heights in steps of 1.2 mm and with the 2298V-1mF capacitor combination are shown in Fig. 7. From the results a conductor height of 3.36 mm allows the highest values of displacement, velocity and efficiency, the maximum efficiency of the device being close to 30%, more than double the efficiency value reported for similar operating conditions. Table 3 summarises the performance figures obtained from the 2 ms FE results. The results in Table 3 show that a TC actuator is capable of operation at a much higher efficiency than is published elsewhere. However the

very high peak force will make it difficult for the armature to remain structurally intact after operation, thus the armature thickness should be dimensioned accordingly. In order to assess how the high-performance actuator efficiency is affected by variations in armature thickness a series of simulations were conducted considering thicknesses varying over the 3-12 mm range. Fig. 8 shows the efficiencies obtained from the simulation for the different thicknesses considered.

As can be seen from the simulation results in Fig. 8, for the thickest armature considered (12 mm) the actuator efficiency decreased only to 25%. Thus even with a significant increase in the armature mass (4 times), the efficiency of the TC actuator remains high, even above that of alternative highly efficient repulsion driven actuators, such as the double sided coil proposed in [6]. It is evident from this set of results that the TC actuator is capable of operation at a relatively high efficiency, if its coil is properly dimensioned. For instance, for a different voltage-capacitance combination the most effective conductor height may be different. For example, for the 726.64V-10mF and 400V-33mF combinations the maximum efficiency was achieved with a conductor height of 5.6 and 6.72 mm, respectively.

The integral design of the mechanical and electrical system of a TC actuator allows operational efficiencies far beyond those reported in the existing research literature. Furthermore, using this approach in combination with more complex current control, such as the current train pulse proposed in [10], may produce additional efficiency gains.

4 Conclusions

The factors that affect the efficiency of the TC actuator were investigated in this paper by means of a sensitivity analysis using finite element software. Based on a series of rules established as a consequence of the sensitivity assessment results, an iterative approach was used to improve the performance of the initial TC design, resulting in a high efficiency TC actuator. The new design was shown to achieve a much higher efficiency than those reported in the open literature for similar operating conditions. It was shown that in addition to excitation values, the coil conductor cross section area can be used as a key element to fine tune actuator performance. It was also shown that a conductor with a low width to height ratio can be used to increase the performance of the TC actuator, without adding unnecessary complexity. Using the approach proposed in this research, in combination with sophisticated current control schemes, further performance gains may possibly be achieved.

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Fig. 6 TC Current density at $t = 70 \mu s$.

Fig. 7 TC armature displacement (top), velocity (middle) and efficiency (bottom) for different coil heights at 2298V with 1mF capacitor.

Parameter	Value	Parameter	Value
Turns	32	Displacement (mm)	69
V0 (V)	2298	Efficiency (%)	29
C (mF)	1	Peak Force (kN)	257
Armature Thickness (mm)	3	Peak current (kA)	13
Cross section (mm ²)	1.12x3.36	Peak velocity (m/s)	36

Table 3: Refined TC design performance numbers.

Fig. 8 TC actuator efficiency for different armature thicknesses at 2298V with 1mF capacitor.

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