Performance of high-power thomson coil actuator excited by a current pulse train

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Abstract: This paper uses FEA simulations to investigate the behaviour of a high-speed, high-power Thomson coil (TC) actuator suitable for HVDC protection applications, when excited by a double discharge. The influence of the resulting pulse train on the amplitude of observed armature vibration is investigated. The significance of the pulse train on the device electrical to mechanical energy conversion efficiency is assessed and compared with the efficiency obtained using the conventional single discharge approach.

1 Introduction
Thomson Coil (TC)-based actuators are commonly used in applications such as arc eliminators [1], high-speed mechanical switches [2], and hybrid DC breakers [3], where very fast operation times are required. The TC, Fig. 1, relies on magnetic repulsion to achieve fast reaction time and high-speed operation, while typically exhibiting low electrical to mechanical energy conversion efficiency (around 5%) [4]. For TC operation, the actuator spiral coil is excited by a time varying current, hence producing a time varying magnetic field. The magnetic field interacts with the metallic armature, inducing eddy currents on the armature surface. Due to the direction of the induced currents, and the ensuing magnetic field, a strong repulsive force between coil and armature is developed.

Given the low energy conversion efficiency of the TC, several strategies aimed to improve it have been proposed. For instance moving mass minimisation is one of the most commonly sought strategies [5]. The moving mass in a TC is essentially the armature mass; however, a transmission rod is generally used to couple the actuator to an external device and a latching mechanism is normally required to make the TC useable in practice, adding to the total moving mass. For instance, for HVDC breaker applications, the moving mass may be several kg [6]. Ignoring ancillary components, armature geometry, and mass have a direct impact on actuator speed. A thicker armature allows better current distribution, which improves actuator efficiency; however, a large mass is detrimental for armature speed. On the other hand, if a very thin armature is employed, excessive bending may occur, resulting in permanent physical damage to the armature and poor efficiency. Thus, a fine balance between these seemingly contradictory propositions must be found to maximise actuator performance, without compromising the device physical integrity. The TC is normally excited by discharging a capacitor bank into the coil terminals, resulting in a single current pulse. An alternative technique proposed to improve actuator performance relies on exciting the coil using a train of current pulses [7]. This principle is illustrated in Fig. 2. Given that the typical operation time of a TC actuator is only a few ms, the frequency of the train of pulses lies necessarily in the range of several kHz. Depending on armature geometry, this frequency could excite one of the armature natural vibration modes. In such a case, additional armature bending may occur, thus incurring larger losses, therefore, reducing actuator efficiency and risking the physical integrity of the armature. Thus, this approach may produce unwanted effects that need to be investigated.

For HVDC breaker applications, a mass of several kilograms needs to be displaced tens of mm in a few ms; operation times of around 2 ms are often mentioned [8, 9]. Thus, any technique that may improve the speed and efficiency of operation of this high-power, high performance device ought to be investigated. Here, the convenience of using a two stage discharge for the fast operation of high-speed, high-power TC actuator suitable for use in hybrid HVDC breakers is investigated with the help of FE simulations. Mechanical effects in the armature are considered and energy conversion efficiency quantified, and the performance compared with that achievable using a finely tuned TC excited by a single current pulse.

2 FEA simulation
In order to assess the effects that a double discharge may induce in the operation of the TC, an axis-symmetric, 2D FE model of the device is employed. It has been demonstrated that a properly compensated 2D axis-symmetric FE TC model is able to reproduce with high fidelity the physical behaviour of the device [10].
Table 1  FEA software equations variables

| Variable | Description |
|----------|-------------|
| B | magnetic flux density |
| H | magnetic field intensity |
| J | current density |
| J_e | external current density |
| A | magnetic vector potential |
| F_i | lorentz force |
| v | velocity |
| S | stress tensor |
| σ | electric conductivity |
| σ_e0 | reference electric conductivity |
| T | temperature |
| Τ_0 | reference temperature |
| α | temperature coefficient |
| ρ | density of the material |
| u | displacement |
| F | force acting over the solid |
| C_p | heat capacity |
| K | thermal conductivity |
| Q | resistive losses |

Table 2  TC parameters

| Parameter       | Value       | Parameter       | Value       |
|-----------------|-------------|-----------------|-------------|
| capacitor bank  | 2 μF        | armature thickness | 15 mm       |
| bank voltage    | 2400 V      | armature material | Cu (100% IACS) |
| turn number     | 32          | conductor cross-section | 1.12 × 3.36 mm |
| armature radius | 50 mm       | turn gap        | 0.1 mm      |

Fig. 3  TC FE simulation stress

As a result of the uneven distribution of the mechanical load, the armature bends considerably in Fig. 3, with the largest armature mechanical stress exhibited in the corner between the main plate and the armature neck. This mechanical bending results in unwanted energy losses that affect the actuator overall electrical to mechanical energy conversion efficiency. This loss of efficiency is illustrated in Fig. 4, where the FE model that considers material bending is compared with one that assumes an infinitely rigid material.

As can be seen in Fig. 4, the average energy conversion efficiency of the TC FE model that considers material bending is lower than the efficiency obtained from the model that assumes an infinitely rigid material. Similarly, the armature displacement of the flexible model falls below that of the rigid model for most of the simulation time. This comparison shows that excessive armature flexing is detrimental to the actuator performance. Thus, techniques that could exacerbate armature bending should be avoided.

\[
\sigma_e \frac{\partial A}{\partial t} - \sigma_e \nabla \times B + J = f_e
\]  (1)

\[
\nabla \times A = B
\]  (2)

\[
\nabla \times H = J
\]  (3)

\[
J \times B = F_i
\]  (4)

\[
\rho \frac{\partial^2 u}{\partial t^2} - \nabla \cdot S = F
\]  (5)

\[
\sigma_e [1 + \alpha(T - T_0)] = \sigma_e
\]  (6)

\[
\rho C_p \left( \frac{\partial T}{\partial t} + \nabla \cdot (\nabla T) \right) = \nabla \cdot (\nabla T) + Q
\]  (7)

3  Induced TC force with air-gap distance

In [7], the use of a current pulse train, resulting from a double discharge, is suggested to excite a TC. The rationale behind the suggestion is that a time varying magnetic field is required for TC operation, thus supplying a fast varying current for a longer time would be beneficial for actuator operation. For validation, a relatively low mass low-speed TC is employed in [7]. Although technically correct, this line of thought fails to take into consideration the time varying air-gap distance during TC operation. For instance, depending on the distance from the source, the magnetic field intensity varies inversely with distance. Thus, for a given current pulse, the repulsive force produced between armature and coil will also decrease with distance. Therefore, the closer the armature and coil are, the greater the electromagnetic force and hence the expected efficiency. The effect of air-gap distance over the electromagnetic force produced in a TC is illustrated in Fig. 5. The figure shows FE results for the electromagnetic force developed in the TC armature as a capacitor is discharged into the coil for different armature-coil distances. In each simulation, the armature is assumed to be built of an infinitely rigid material and its position is kept fixed. As expected, the armature force decreases as the air-gap distance increases, raising questions about the advantage of a double discharge excitation.

In [7], the use of two differently sized capacitors is suggested to produce a double-pulsed current in a TC. A 6.8 μF capacitor charged at 280 V is used to initiate armature displacement, and a 10 μF capacitor charged at 180 V is used to produce a long-lasting varying current. The larger capacitor is discharged 1 ms later than the smaller one; at 1 ms, a relatively short air gap of around 1 mm exists between armature and coil. It should be noted that for HVDC breaker applications 1 ms generally implies an armature displacement of several mm, thus for this kind of application, the delay between pulses should be adjusted accordingly.

The performance of the double pulse setup is compared in [7] with arrangements that rely on a single capacitor to provide excitation. The fastest single-pulsed experiment in [7] (10 μF at 210 V) takes 3.25 ms to complete the full stroke travel of 6 mm, while the double pulse setup takes only 2.75 ms. Therefore, it is concluded in [7] that the two stage continuous discharge enhances the actuator performance. However, no electrical energy quantification is performed; furthermore the total electrical energy used by the two setups is quite dissimilar. For instance, assuming total capacitor discharge, the two-stage discharge experiment uses
94% more energy than the fastest single-pulse experiment, (429J against 221J) while the traveling time only decreases 18%. Thus, the convenience of the two capacitor arrangement is debatable.

4 Single-pulse analysis

In [4], it was shown that the efficiency of a TC depends on the capacitor size and charging voltage and that there is an optimal capacitor-voltage combination for a given TC design. To investigate the convenience of the two pulse approach over the conventional single discharge operation first, the most convenient capacitor size and voltage combination is obtained for the TC design considered here. FE simulations that consider material flexibility are used for this assessment. The electrical energy used in the simulations corresponds to that calculated from the values in Table 2, equivalent to 5760J. Table 3 lists the capacitor size-charging voltage combinations used during the simulations. Simulation results are shown in Fig. 6 for several mechanical quantities. Using the system kinetic energy reported by the FE software, the energy conversion efficiency in Fig. 6 is calculated with (8).

\[ n = \frac{W_k}{W_e} \times 100 \]  

where \( W_k \) is the system kinetic energy and \( W_e \) is the electric energy consumed. Since the TC armature bends during operation, the armature's point velocity and displacement are shown in Fig. 6. The lowest armature main plate external edge is selected for this purpose, signalled with a red circle in Fig. 7. This armature point was deliberately chosen to better illustrate the deflexion that the armature experiences during operation and clearly illustrates the mechanical effects that the electrical excitation induces in the armature. For comparison, Fig. 8 shows the armature mean velocity derived from the system kinetic energy [10], where the velocity signal is considerably smoother than that shown in Fig. 6.

As can be seen in the results of Fig. 6, as the capacitance decreases and the charging voltage increases the armature reaction time decreases, while the efficiency of the actuator improves progressively, until a small decline occurs with the 0.5 mF capacitor. However, these increases in speed and efficiency are at the expense of pronounced armature flexing. This flexing is responsible for the pronounced oscillations in the armature signals, which are reflected in a particularly violent form in the armature's point velocity signal.

If the armature bending becomes excessive, a thicker armature would be needed, thus increasing moving mass and affecting negatively on actuator performance. It is also observed in the results that at 1 ms, an armature displacement in excess of 5 mm has occurred. Thus, if a double discharge strategy is adopted, the discharge of the second capacitor must start sooner than the 1 ms mentioned in [7]. Otherwise, the magnitude of the electromagnetic force induced in the armature by the second discharge will be severely limited, as shown by the simulation results in Fig. 5. From the previous analysis, it is clear that for better actuator performance, a smaller capacitor at a higher charging voltage is preferable for this high-speed, high-power system. The question is if any benefit is gained from the use of the two discharge approach. This scenario is investigated in the next section.

5 Two-pulse analysis

In Section 4, it was shown that a small size capacitor at a high voltage is preferable to achieve the fastest armature reaction and
efficiency, while a large capacitor at a low voltage is convenient to minimise armature vibration. Thus to assess the convenience of the double discharge configuration, the capacitor that enabled the higher efficiency and longer displacement for the 2 ms simulation considered in Section 4, is paired with the capacitor that produced the smallest armature vibration. For the 2 ms simulation in Section 4, a maximum armature displacement of 19 mm is achieved with both the 1 and 2 mF capacitors. However with the 1 mF capacitor, the actuator exhibits a slightly shorter response time and higher efficiency. Therefore, the 1 mF capacitor is selected as the small size, fast discharging capacitor, while the 10 mF capacitor is selected to enable a longer discharging time in the double discharge setup. Fig. 9 shows a schematic representation of the discharge circuit used in the simulations. In Fig. 9, diodes are connected in antiparallel to the capacitors to protect them against inverted voltage, $R_{\text{stray}}$ and $L_{\text{stray}}$ represent the stray resistance and inductance of the circuit connection leads. Values of 3 mΩ and 9 mH for $R_{\text{stray}}$ and $L_{\text{stray}}$, respectively, are used in the FE simulations. In order to enable a fair comparison with the single discharge configuration, the combined stored energy of these two capacitors should be identical to the total energy used by the single capacitor setup. Thus, the 5760 J of stored electrical energy should be shared between the two capacitors. However, how to establish the energy shared ratio and time delay between discharges offers an infinite number of possible combinations. Hence, certain criteria to define these parameters values must be established.

According to the analysis performed in Section 3, the second capacitor must be discharged when an air gap of around 1 mm exists, otherwise the magnetic force acting over the armature diminishes considerably. Thus, the discharge of the second capacitor will be initiated once the armature displacement reaches 1 mm. Coincidentally, this air-gap distance is in line with that used to trigger the second capacitor in the experiments performed in [7]. To decide the capacitors charging voltage, the only restriction is that the combined energy does not exceed the established 5760 J. For brevity, only a reduced set of combinations is considered here. The chosen voltage combinations and corresponding energy share are listed in Table 4. Fig. 10 shows the current profile obtained from the simulation results for the double discharge setup for the selected voltage combinations, with Fig. 11 showing some performance quantities. As can be seen in Fig. 1, no perceptible gain in efficiency or displacement is obtained from the double discharge configuration, when compared with the best-performing case evaluated in Section 4. Furthermore, only the 80-20% combination produce figures that are close to those obtained from a single discharge setup. However, even in this case the actuator performance falls below that obtained with a comparable single pulse setup. This is illustrated in Fig. 12, where the efficiency obtained with a single discharge and a 1 mF capacitor is compared

![Fig. 7](image) Armature corner used for point velocity and displacement calculation

![Fig. 8](image) TC armature's mean velocity

![Fig. 9](image) Two discharge stages circuit, schematic representation

![Fig. 10](image) Coil current traces from the double-pulse setup cases

![Fig. 11](image) Displacement (top) and energy conversion efficiency (bottom) from the double-pulse setup

![Fig. 12](image) Single-pulse, double-pulse energy conversion efficiency comparison

**Table 4** Charging voltage-energy share combinations used to evaluate the TC performance for an input electrical energy of 5760 J in a double-pulse configuration

| 1 mF Capacitor | 10 mF Capacitor |
|----------------|-----------------|
| Energy share [%] | Voltage [V] | Energy share [%] | Voltage [V] |
| 10 | 1073.30 | 90 | 1018.20 |
| 20 | 1517.90 | 80 | 960.00 |
| 50 | 2400 | 50 | 758.95 |
| 80 | 3035.80 | 20 | 480.00 |
with the 80-20% configuration. Furthermore, for the 80-20% case, the current trace in Fig. 10 does not show a current increase due to the second pulse, and in practical terms, it may be considered equivalent to a single discharge case. As noted before, these oscillations are a direct manifestation of armature bending. It may be argued that this perceived reduction in armature bending is an advantage of the two discharge configuration; however, this reduction in the oscillation magnitude seems to stem from a slower (less effective) armature reaction, rather than from any damping mechanism provided by using the double discharge technique. The TC performance was assessed with several other capacitor size combinations, energy share ratios, and discharge delays (not shown) with none of them exhibiting a performance superior to that achievable with the conventional single discharge approach. Thus, no evidence of any advantage in the application of a two-stage continuous discharge to excite a high-speed, high-power TC actuator was found in this research.

6 Conclusions

Here, the use of a two-stage discharge setup to improve the performance of a high-speed, high-power TC actuator was investigated by using FE simulations. It was found that for identical energy consumption, the performance obtained from the double discharge approach lags behind that of a comparable setup that uses the conventional single discharge approach. It was also found that the main reason behind the lack of performance of the double discharge approach is the time varying air-gap distance intrinsic to TC operation. As the separation between coil and armature grows with time, the electromagnetic force that can be induced by the time varying magnetic field that interacts with the TC armature diminishes. Thus, any delay to provide excitation to the coil once the armature starts to move is expected to result in reduced actuator performance. No benefit for the operation of the investigated high performance TC design was found from the use of a double discharge approach. The conventional single discharge method seems to be the most convenient excitation mechanism for a high-power, high-speed TC actuator.

7 Acknowledgments

This work was funded as part of the UK EPSRC, FCL/B: An Integrated VSC-HVDC Fault Current Limiter/Breaker project, EP/L021552/1.

8 References

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