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Abstract

This paper uses FEA simulations to investigate the behaviour of a high speed, high power Thomson coil 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 minimization 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 maximize 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 2ms 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. In this paper 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.

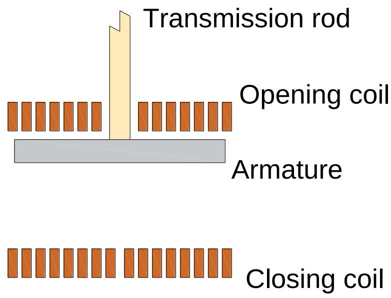

Fig. 1: Thomson coil

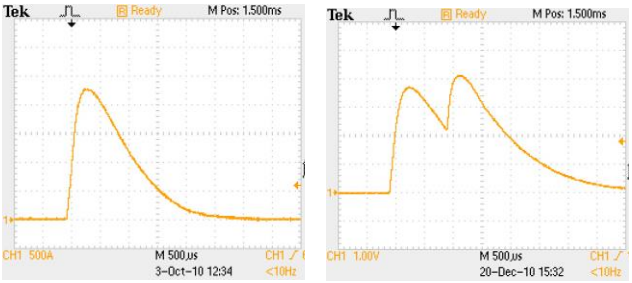

Fig. 2: Example coil excitation current, single discharge (left) and two stage discharge (right) [7].

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 FEA 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]. COMSOL multi-physics 5.3 software is used for the FE simulations in this research and a deformable moving mesh is employed to accurately account for armature displacement and bending. For simplicity aerodynamic effects were neglected in the simulations. Equations (1)-(7) are used by the FEA software for the model solution, the corresponding variables are listed in Table 1, where vector quantities are identified with the symbol →. The ensuing numerical model uses a fully coupled solver for the simultaneous solution of electrical, thermal and mechanical equations. The design parameters of the TC used in this assessment are listed in Table 2. A moveable mass of 8kg, coupled to the armature by the transmission bar, is considered in the simulations and an initial air-gap of 0.5 mm is used between coil and armature. Fig. 3 shows FE simulation results for the mechanical stress obtained for the investigated TC geometry. In the figure armature deformation is exaggerated for illustration purposes.

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.

$$\sigma_e \frac{\partial \vec{A}}{\partial t} - \sigma_e \vec{v} \times \vec{B} + \vec{J} = \vec{J}_e \qquad (1)$$

$$\vec{\nabla} \times \vec{A} = \vec{B} \qquad (2)$$

$$\vec{\nabla} \times \vec{H} = \vec{J} \qquad (3)$$

$$\vec{J} \times \vec{B} = \vec{F}_l \qquad (4)$$

$$\rho \frac{\partial^2 u}{\partial t^2} - \vec{\nabla} \cdot \vec{S} = F \qquad (5)$$

$$\sigma_{e0} \left[1 + \alpha (T - T_0)\right]^{-1} = \sigma_e \qquad (6)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{v} \cdot \vec{\nabla} T \right) = \vec{\nabla} \cdot \left(k \vec{\nabla} T \right) + Q \qquad (7)$$

Variable	Description
$\vec{B}$	Magnetic flux density
$\vec{H}$	Magnetic field intensity
$\vec{J}$	Current density
$\vec{J}_e$	External current density
$\vec{A}$	Magnetic vector potential
$\vec{F}_l$	Lorentz force
$\vec{v}$	Velocity
$\vec{S}$	Stress tensor
σ_e	Electric conductivity
σ_{e0}	Reference electric conductivity
T	Temperature
T_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 1: FEA software equations variables.

Parameter	Value	Parameter	Value
Capacitor bank	2mF	Armature thickness	15mm
Bank voltage	2400V	Armature material	Cu (100% IACS)
Turn number	32	Conductor cross section	1.12x3.36mm
Armature radius	50mm	Turn gap	0.1mm

Table 2: TC parameters.

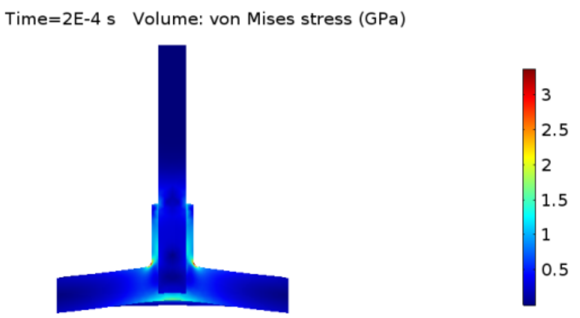

Fig. 3: TC FE simulation stress

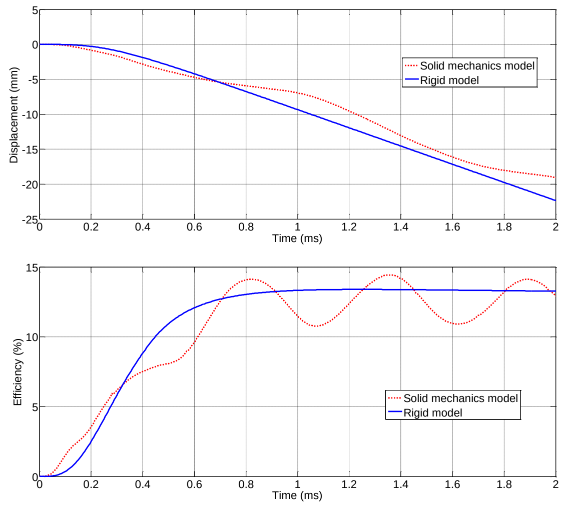

Fig. 4: Electrical to mechanical energy conversion efficiency (top) and armature displacement (bottom) comparison for the TC with and without considering material bending.

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 6.8mF capacitor charged at 280V is used to initiate armature displacement, and a 10mF capacitor charged at 180V is used to produce a long lasting varying current. The larger capacitor is discharged 1ms later than the smaller one; at 1ms a relatively short air-gap of around 1mm exists between armature and coil. It should be noted that for HVDC breaker applications 1ms 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] (10mF at 210V) takes 3.25ms to complete the full stroke travel of 6mm, while the double pulse set up takes only 2.75ms. 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 in this paper. 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).

$$n = \frac{W_k}{W_e} \times 100 \qquad (8)$$

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 0.5mF 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.

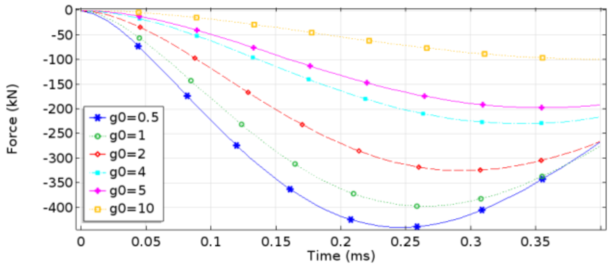

Fig. 5: TC armature electromagnetic force for different coil-armature gaps.

No.	Capacitance [µF]	Voltage [V]
1	10000	1073.3
2	5000	1517.9
3	2000	2400
4	1000	3394
5	500	4800

Table 3: Capacitor size-charging voltage combinations used to evaluate the TC performance for an input electrical energy of 5760J.

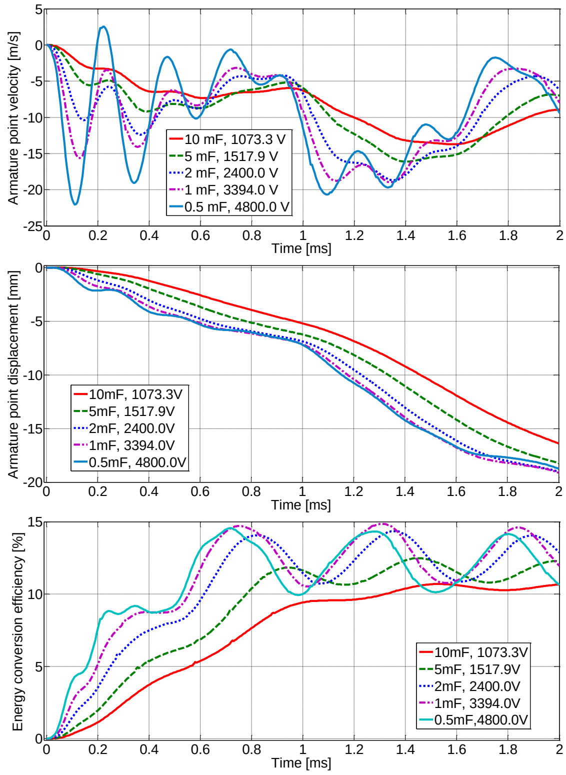

Fig. 6: TC actuator velocity (top), displacement (middle) and energy conversion efficiency (bottom).

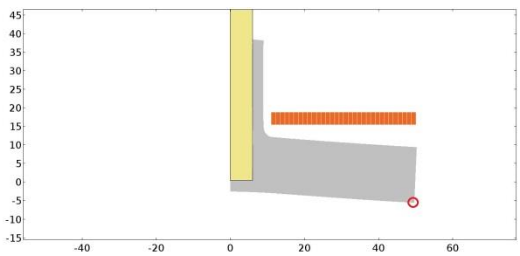
Fig. 7: Armature corner used for point velocity and displacement calculation.

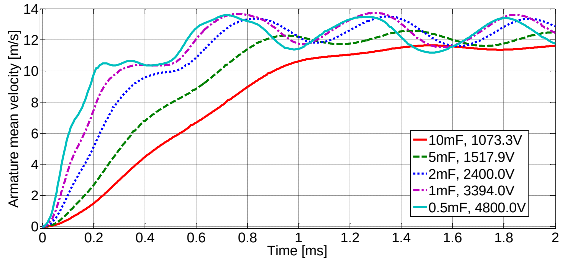

Fig. 8: TC armature's mean velocity.

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 1ms an armature displacement in excess of 5mm has occurred. Thus, if a double discharge strategy is adopted, the discharge of the second capacitor must start sooner than the 1ms 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 minimize armature vibration. Thus to assess the convenience of the double discharge configuration, the capacitor that enabled the higher efficiency and longer displacement for the 2ms simulation considered in section 4, is paired with the capacitor that produced the smallest armature vibration. For the 2ms simulation in section 4 a maximum armature displacement of 19mm is achieved with both the 1mF and 2mF capacitor. However with the 1mF capacitor the actuator exhibits a slightly shorter response time and higher efficiency. Therefore, the 1mF capacitor is selected as the small size, fast discharging capacitor, while the 10mF 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_{stray} and L_{stray} represent the stray resistance and inductance of the circuit connection leads. Values of 3mΩ and 9mH for R_{stay} and L_{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 5760J of stored electrical energy should be shared between the two capacitors. However how to establish the energy share 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 1mm 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 5760J. For brevity, only a reduced set of combinations is considered in this paper. 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 1mF capacitor is compared 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. In Fig. 12 the magnitude of the oscillations for the two discharge case are smaller compared with the single discharge approach. 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

In this paper 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.

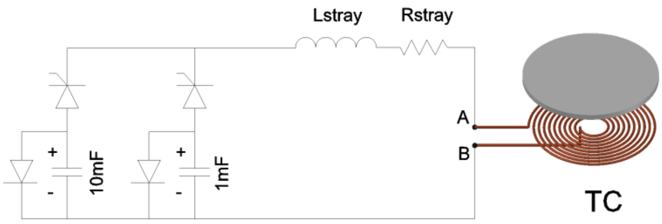

Fig. 9: Two discharge stages circuit, schematic representation.

1mF Capacitor		10mF Capacitor	
Energy share [%]	Voltage [V]	Energy share [%]	Voltage [V]
10	1073.30	90	1018.20
20	1517.90	80	960.00
50	2400.00	50	758.95
80	3035.80	20	480.00

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

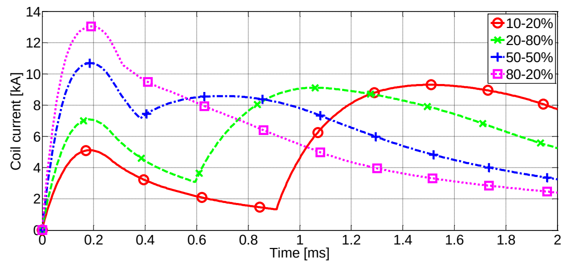

Fig. 10: Coil current traces from the double pulse setup cases.

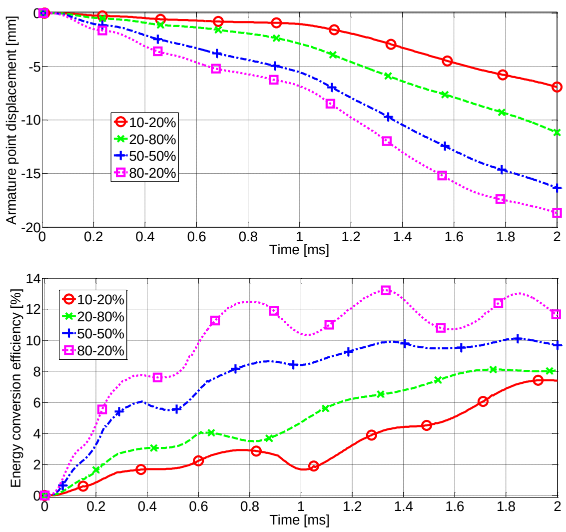

Fig. 11: Displacement (top) and energy conversion efficiency (bottom) from the double pulse setup.

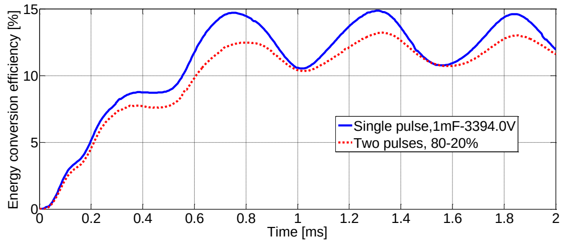

Fig. 12: Single pulse, double pulse energy conversion efficiency comparison.

Acknowledgements

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References

[1] W. Li, Y. W. Jeong and C. S. Koh, "An Adaptive Equivalent Circuit Modeling Method for the Eddy Current-Driven Electromechanical System," in IEEE Transactions on Magnetics, vol. 46, no. 6, pp. 1859-1862, June 2010.

[2] W. Holaus and K. Frohlich, "Ultra-fast switches- a new element for medium voltage fault current limiting switchgear," 2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.02CH37309), 2002, pp. 299-304 vol.1.

[3] J. M. Meyer and A. Rufer, "A DC hybrid circuit breaker with ultra-fast contact opening and integrated gate-commutated thyristors (IGCTs)," in IEEE Transactions on Power Delivery, vol. 21, no. 2, pp. 646-651, April 2006.

[4] A. Bissal, J. Magnusson and G. Engdahl, "Electric to Mechanical Energy Conversion of Linear Ultrafast Electromechanical Actuators Based on Stroke Requirements," in IEEE Transactions on Industry Applications, vol. 51, no. 4, pp. 3059-3067, July-Aug. 2015.

[5] D. S. Vilchis-Rodriguez, R. Shuttleworth and M. Barnes, "Finite element analysis and efficiency improvement of the Thomson coil actuator," 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), Glasgow, 2016, pp. 1-6.

[6] B. L. Damsky, I. Imam and W. Premerlani, "A New HVDC Circuit Breaker System Design For -+ 400 kV," 1979 7th IEEE/PES Transmission and Distribution Conference and Exposition, 1979, pp. 230-236.

[7] E. Dong, P. Tian, Y. Wang and W. Liu, "The design and experimental analysis of high-speed switch in 1.14kV level based on novel repulsion actuator," 2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), Weihai, Shandong, 2011, pp. 767-770.

[8] M. Callavik and A. Blomberg, “The Hybrid HVDC Breaker - An innovation breakthrough enabling reliable HVDC grids” ABB Gris systems, Nov. 2012.

[9] C.C. Davidson, R.S. Whitehouse, C.D. Barker, J.P. Dupraz and W. Grieshaber, "A new ultra-fast HVDC Circuit breaker for meshed DC networks," 11th IET International Conference on AC and DC Power Transmission, Birmingham, 2015, pp. 1-7.

[10] D. S. Vilchis-Rodriguez, R. Shuttleworth and M. Barnes, "Modelling Thomson Coils With Axis-Symmetric Problems: Practical Accuracy Considerations," in IEEE Transactions on Energy Conversion, vol. 32, no. 2, pp. 629-639, June 2017.