Active Damping of Ultra-fast Mechanical Switches for Hybrid AC and DC Circuit Breakers

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***Abstract*—An active damping method for Thomson coil actuated ultra-fast mechanical switches is proposed, including its control. Ultra fast mechanical switches are crucial for both DC and AC circuit breakers that require fast-acting, current-limiting capabilities. However, fast motion means high velocity at the end of travel, resulting in over-travel, bounce, fatigue, and other undesirable effects. The active damping proposed in this paper not only avoids such issues, but actually enables faster travel by removing limitations that would otherwise be necessary. This active damping mechanism is applicable in particular to medium and high voltage circuit breakers, but can be extended to actuators in general.**

A 15kV/630A/1ms mechanical switch, designed to enable the fast protection of medium voltage DC circuits, is used as a testbed for the concept. It is based on the principle of repulsion forces (Thomson coil actuator). By energizing a second coil, higher opening speeds can be damped with limited over-travel range of the movable contact. The overall structure is simple, and the size of the overall switch is minimized.

To validate the concept and to study the timing control for best active damping performance, both finite element modeling and experimental studies have been carried out.

***Index Terms*—Active damping, fast mechanical switch, hybrid circuit breaker, DC circuit breaker, Thomson coil actuator, repulsion coil actuator, finite element method**

I. INTRODUCTION OF THOMSON COIL ACTUATED FAST MECHANICAL SWITCHES

Medium and high voltage hybrid DC circuit breakers combine fast electronic switches with mechanical switches in parallel [1–6]. Their effectiveness is predicated on the mechanical switch opening as fast as possible to obtain a sufficient gap between the open contacts, so that they can withstand the transient recovery voltage (TRV) following current interruption. This is because the total interruption time of the hybrid circuit breaker is dominated by the operation speed of the fast mechanical switch (FMS) in such hybrid circuit breakers [1, 2, 7–9].

The mechanical switches used in this type of circuit breakers are typically based on repulsion forces with current induced in a conductive copper disc (so-called Thomson coil actuator). The switch actually comprises two coils, one for the opening operation and one for the closing operation, located on either side of the copper disc (above and underneath, Figs. 1 and 2). To open the FMS, the opening coil is energized so that a strong magnetic field is generated which penetrates into the conductive plate. This time varying magnetic field induces azimuthal eddy currents in the plate which in turn create an opposing magnetic field. These two fields oppose each other and a repulsive force is generated between the coil and the plate.

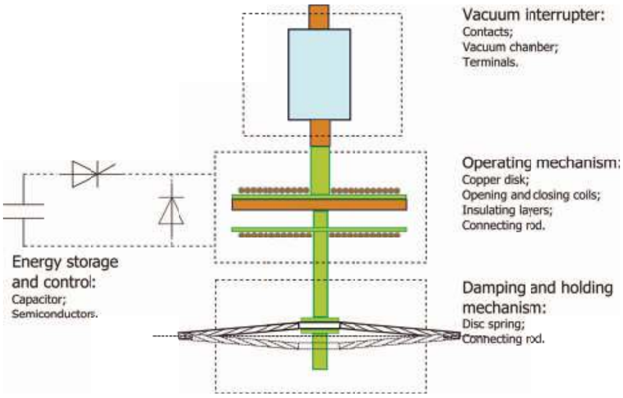

Fig. 1: Diagram of the Thomson coil actuator based fast mechanical switch.

In this paper, an active damping mechanism and its control are proposed for this type of actuator. Its goal is to absorb the kinetic energy at the end of motion, avoiding over-travel, bounce, and the like. In doing so, it becomes possible to actually excite the opening coil to higher levels, resulting in overall faster operation than would be possible without the active damping. This result will contribute to achieving ultra fast operation for the switches and therefore the hybrid DC circuit breakers. With this control, better performance is achieved. Further, the structure remains simple without adding extra damping mechanism. Smaller vacuum interrupters can be used and the size of the overall switch remains compact.

The paper includes finite element modeling of the transients of the active damping, and test results obtained on a 15kV/630A/1ms mechanical switch. The actuator design used in this study is described in details in [8], and the drive circuits have been discussed in [9].

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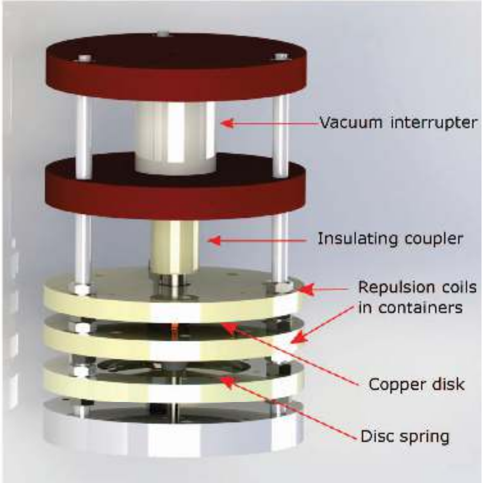

Fig. 2: Fast mechanical switch.

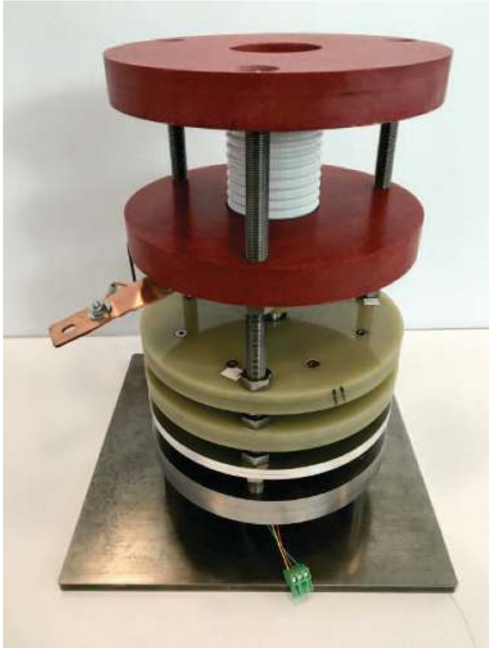

Fig. 3: Picture of the FMS prototype.

II. RECLOSING ISSUE WITH PASSIVE DAMPING MECHANISM

The general issue addressed in this paper is the design of effective, reliable damping mechanisms to absorb the kinetic energy due to fast opening. Mechanical means are effective, but need to be tuned to the energy imparted to the system during opening. Not enough damping can lead to damage, and too much generates bounce and long effective travel time. If the bounce is large enough, the system recloses (opening failure). Therefore, a fixed damping can actually limit the opening energy and lengthen the travel time, by forcing the designer to use a level of energy below that which will lead to bounce. This was observed during initial tests of a prototype switch (shown in Fig. 3). In order to illustrate this, Fig. 4 shows a successful opening with a capacitor bank that is precharged to 400 V: the displacement curve is linear, overshoots, and finally settles at a steady state open position. When driven by 420 V, however, see Fig. 5, the travel is initially faster, but at the end of the travel and following the overshoot the switch does not stay at a steady state open position; instead, it bounces back towards the closed position and the opening operation fails. The specific mechanism used in the experiments used non-linear disc springs (see [4] for a more detailed description of the design). Other mechanisms are possible [10–13], but all are expected to suffer from the same limitation due to their being set at the design stage, with no feedback control possible. With damping disc springs, a few factors can affect the damping process, such as:

1) The kinetic energy of the moving mass. Most of the energy is to be absorbed by the disc springs.
2) The non-linear load-versus-deflection characteristic of the disc spring (see [8]) and how much energy the disc spring can absorb. The disc spring provides holding forces both at the open and closed positions which correspond to different operation points on the load-versus-deflection curve.
3) The allowable over-travel during opening. Two components limit this over-travel range: the vacuum interrupter, and the disc spring. A longer over-travel results in larger sizes for both components, and therefore the overall size of the switch assembly.

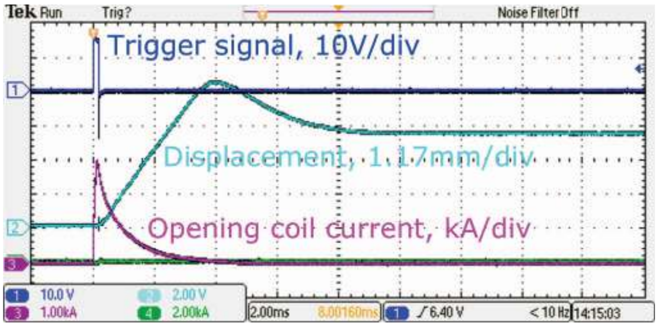

Fig. 4: Successful opening driven by 400 V.

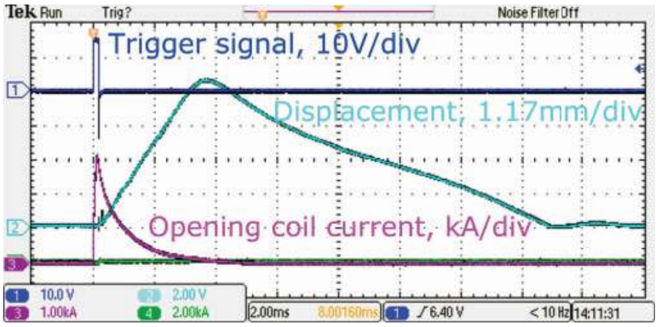

Fig. 5: Opening driven by 420 V followed by a reclosing.

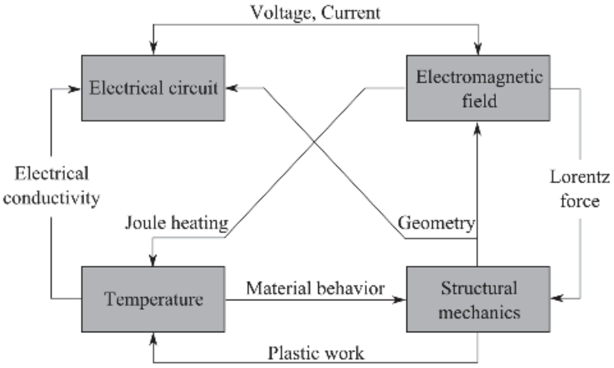

Fig. 6: Multiphyics interaction in the actuator.

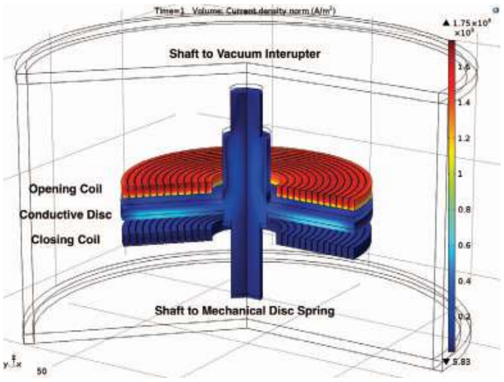

Fig. 7: 3D view of the FEM model.

III. Proposed active damping for Thomson coil actuated switches

This paper proposes an active damping method that utilizes the Thomson coils of such an actuator and does not require extra mechanical complexities in structure and design.

When the mechanical switch is to open, a large amount of energy is dumped into the opening coil, part of which is transferred to the movable mass as kinetic energy for acceleration. In the proposed method, as the fast opening is completed and the required gap is obtained, the closing coil is energized and used as a damping coil to generate a reverse, braking force which slows down the movement. Then the disk spring can easily handle the remaining kinetic energy and secure the moving parts in the open position.

Work on a similar concept was recently published [14] indicating that others working on the issue of DC current breaking are facing the same difficulties. The present paper adds to the literature a comprehensive parametric study as well as additional experimental investigations confirming the validity of the concept, including its potential for further shortening travel times.

The approach is developed here in the context of repulsion coils. It can be extended, at least in principle, to any actuator with two (or more) coils acting in opposite direction. Some work in that area was done, for instance, on actuators with permanent magnets [15–17].

The research was carried out first by comprehensive transient finite element method (FEM) simulation, complemented by experimental evaluation.

The FEM modeling includes different physics (electromagnetic, mechanical, and thermal), see Fig. 6. The mechanical actuator is designed for a 630 A prototype at medium voltage range (15-50 kV). The model geometry is shown in Fig. 7. Two typical snapshots of the simulated transients are presented in Figs. 8 and 9 to illustrate the eddy currents induced in the conductive copper plate upon the energization of the opening coil and the damping coil, respectively.

IV. Design of the active damping control

The general principle of active damping was presented in Section III. This section addresses how to design the damping control, or in other words when and by how much the damping coil should be energized. For a given pulse of the opening coil, there are a few variables in the damping pulse that can be changed to achieve the best performance for a given design of a FMS. They correspond to the timing, magnitude, and shape of the damping pulse, the magnitude and shape being controlled by the capacitance and voltage of the capacitor bank exciting the damping coil. If the same capacitor bank is used for both opening and closing operation, as is preferable for simplicity and to minimize cost, it is also the same for the damping operation. Therefore timing is the most convenient parameter to affect the damping performance. Voltage and capacitance may be used as additional degrees of freedom, if their impact on performance justifies the extra complexity.

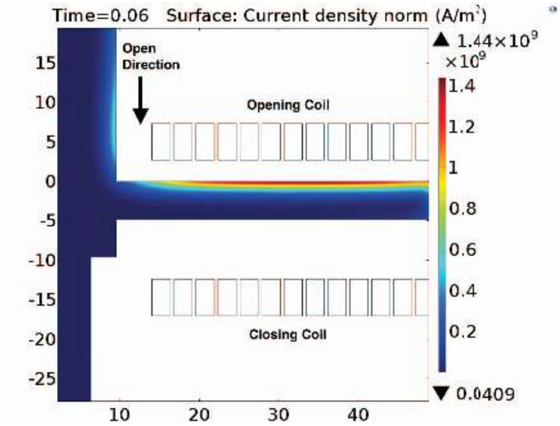

Fig. 8: Induced current in the plate, 60 us after energization of the opening coil, simulation result in axisymmetric 2D view.

Figs. 10 and 11 illustrate the active damping effects, as calculated by transient FEM modeling when the braking coil is energized at different times, with the same voltage and capacitance. Referring to Fig. 10, a negative force accelerates the moving mass, starting at time 0. Then, a positive force later dampens the movement, starting at time 2 ms or later (several model runs are superimposed on the same graph, all starting with the same opening pulse). Fig. 11 shows the corresponding displacements (solid traces) and velocities (dashed curves).

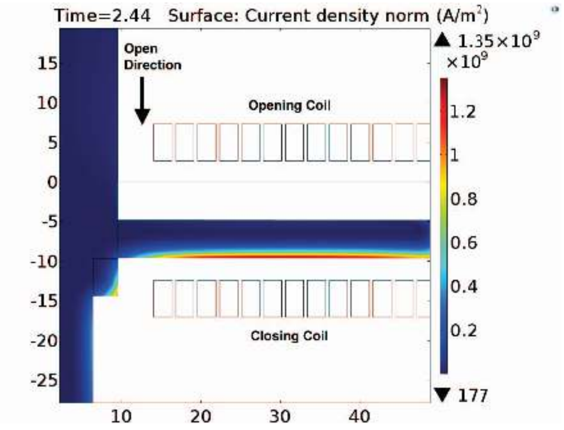

Fig. 9: Induced current in the plate, 440 us after energization of the damping coil, simulated result in axisymmetric 2D view.

With a capacitor bank of 2 mF pre-charged to 400 V, the actuator is accelerated to 2.6 m/s (Fig. 11). At 2 ms, the gap in the switch reaches 4.5 mm which can withstand 60 kV. A sweep of delay times from 2.0 ms to 3.0 ms is presented in Figs. 10 and 11, and the following observations can be made:

1) Energizing the braking coil has an immediate effect to dampen the opening movement. Braking therefore should not be initiated before the specified gap and opening time are reached, 4.5mm/2 ms in this case.
2) The later the damping coil is energized, the closer the disk becomes to the damping coil and therefore the damping force increases. Conversely, with shorter delays, the disk may be too far for the damping coil to have any substantial effect, the disk being out of range, so to speak. The largest peak damping force was obtained with a 3 ms delay. It is 160 percent that with a 2 ms delay.
   There is therefore an opportunity for optimization, with later pulses being more powerful, but intervening farther in the travel. Fig. 11 shows when the damping force starts to operate, and also shows the position at which the disk comes to a stop.
3) An earlier damping pulse results in a weaker force and takes a longer time to reduce the kinetic energy of the moving mass. But the travel is limited to a smaller range (the disk stops at position 6 mm at time 4 ms).
4) A later damping results in a stronger force, takes a shorter time to reduce the kinetic energy of the moving mass. However, the movable contact tends to travel further (7.7 mm at 4 ms).

V. EXPERIMENTAL TEST OF ACTIVE DAMPING

Experimental tests were performed on a Thomson coil actuated fast mechanical switch to verify the approach and the FEM model. These results provide additional validation of both the calculated parameters of active damping, and the interactions that occur between the repulsion coils and the conductive disc.

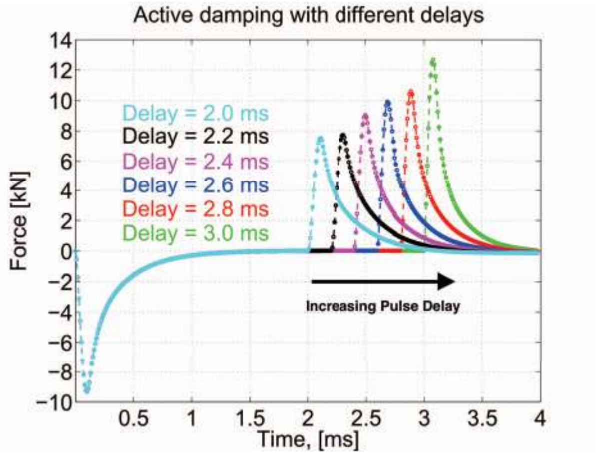

Fig. 10: Driving force (from 0 to 2 ms) and damping forces (from 2 to 4 ms), simulation results.

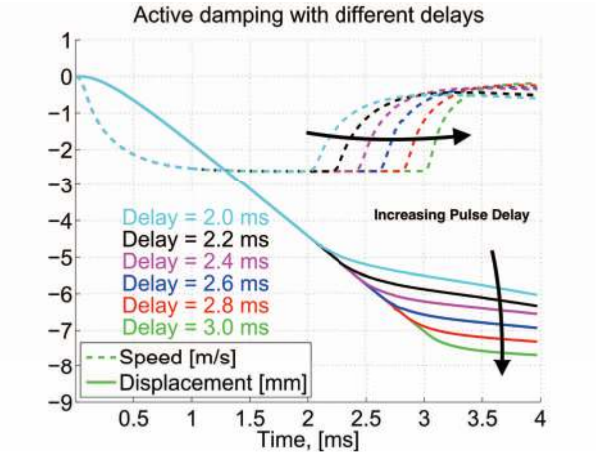

Fig. 11: Speed and displacement curves corresponding to Fig. 10 forces, simulated results.

A. Test Setup

A prototype of a Thomson coil actuated fast mechanical switch and associated driving mechanism was modified to test active damping in a laboratory setting. More details regarding the mechanical switch can be found in [8]. The closing coil was used as the damping coil; two capacitor banks of the same capacitance were independently controlled by two thyristor switches to energize the opening coil and the damping coil. The physical setup is shown in Fig. 12.

The test setup allows incremental variations of the opening coil voltage, damping coil voltage, and trigger delay between the opening and damping current pulses. Testing has been conducted using the parameters listed in Tab. I. Fig. 13 is a graph presentation of which combination of parameters led to a successful opening, and which led to either reclosure or insufficient opening (both are opening failures).

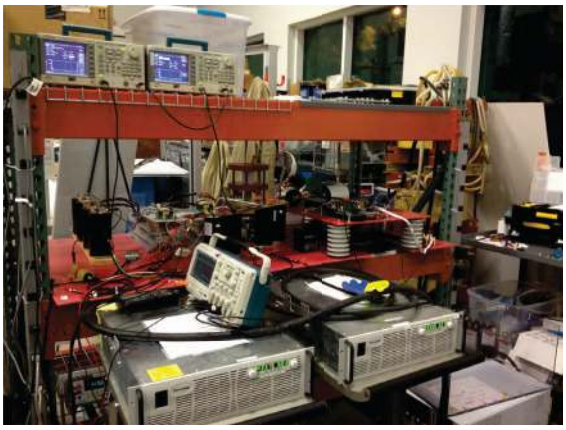

Fig. 12: Test setup of the active damping for a Thomson coil actuated fast mechanical switch (safety enclosure removed for picture).

TABLE I: Opening voltage, damping voltage, and damping delay tested.

Opening voltage (V)	Damping voltage (V)	Damping delay (ms)
• 355 • 370 • 385 • 400 • 415 • 430	• 322 • 345	• 3.0 • 2.8 • 2.6 • 2.4 • 2.2 • 2.0

B. Contribution of opening voltage

The impact of opening voltage for a fixed damping delay (either 2 ms or 3 ms) is shown as displacement curves in Figs. 14 to 17. Also shown in the figures, for reference, is a trace corresponding to the current pulses in the opening and damping coils. The force exerted on the movable mass for opening and therefore the acceleration of the opening contacts are controlled through the opening voltage applied to the opening coil. Increasing this opening voltage and therefore the magnitude of the current to flow through the opening coil, results in higher speeds being achieved during opening operation. However this also results in greater kinetic energy that must be damped out of the system. The figures show traces for opening voltages ranging from 355V to 430V. Lower opening coil voltages, such as 340V, are insufficient to open at all. They are not shown on these figures, but reflected on Fig. 13, first column 340V.

The variable voltage operations show that 3.0 ms damping is adequate to prevent reclosing of all test voltages as shown in Figs. 16 and 17. Given that the opening voltage was varied from 355 V to 430 V, this indicates a very favorable robustness for the system. That is, the system is able to guarantee a successful opening over a wide range of parameters, an important consideration for a device that is expected to preform reliably over a long period of time in varying environmental and other conditions.

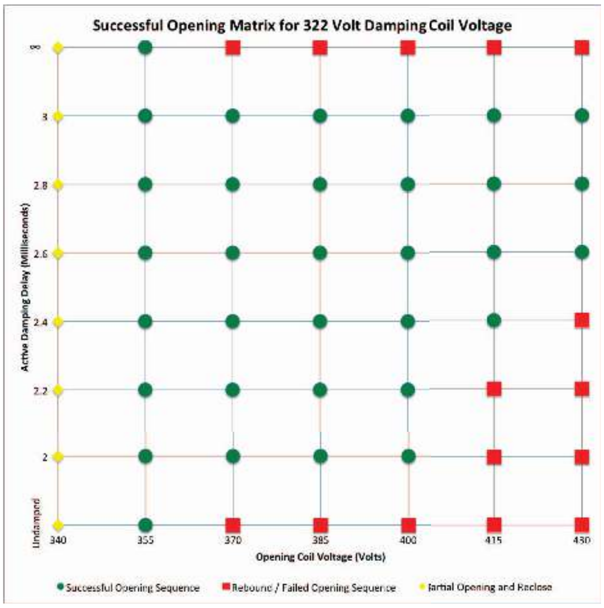

Fig. 13: Test results performed with an active damping voltage of 322 V.

With a shorter delay (damping pulse starting at 2 ms, Figs. 14 and 15), opening fails (large bounce leading to reclosure) if the damping pulse is too strong, see for instance traces 415 V and 430V in Fig. 14. This is primarily due to the distance from the damping coil at time of current flow. At 2.0 ms, the conductive disc is not within an effective range of the damping coil and cannot transfer enough kinetic energy to the damping coil. The excess kinetic energy remaining in the moving mass is too large for the disc spring to absorb, resulting in under-damping and eventual rebound, or reclosing of the switch.

C. Contribution of damping voltage

The effect of the damping voltage is shown in Fig. 18. Within the range of 322 V to 370 V damping voltages, the system opened the contact successfully. Further, it can be observed that the damping voltage has a significant impact on the amount of overshoot.

In terms of design, the damping coil is the same used for closing the actuator after the fault has been cleared. It appears that it may be desirable to have two different voltage levels in the design: For normal closing operation, the voltage should be smaller, simply large enough to close the switch reliably and avoid slamming and damage. However, higher closing coil voltages may be preferable for damping operations.

Having two operating voltages for this coil, one for normal closing and one for damping the opening pulse can be implemented with no additional complexity to the physical switch or driving mechanisms.

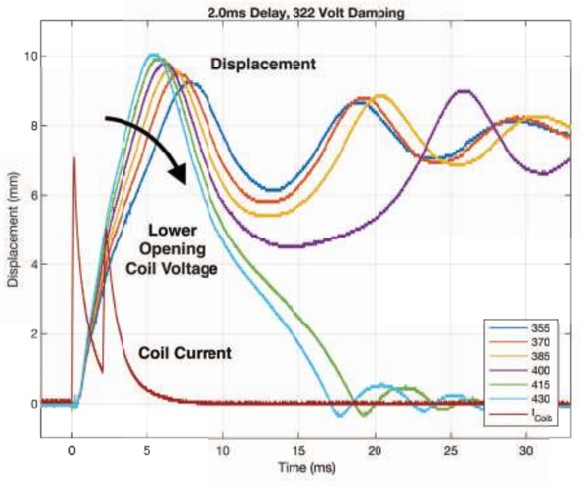

Fig. 14: FMS motion for various opening voltages, with 2.0ms damping delay and 322 V damping voltage.

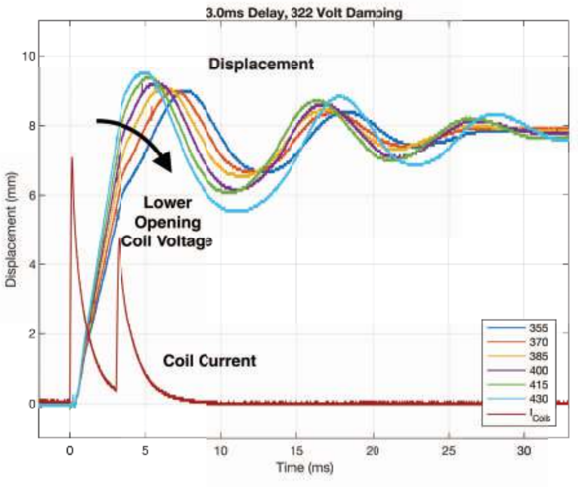

Fig. 16: FMS motion for various opening voltages, with 3.0ms damping delay and 322 V damping voltage

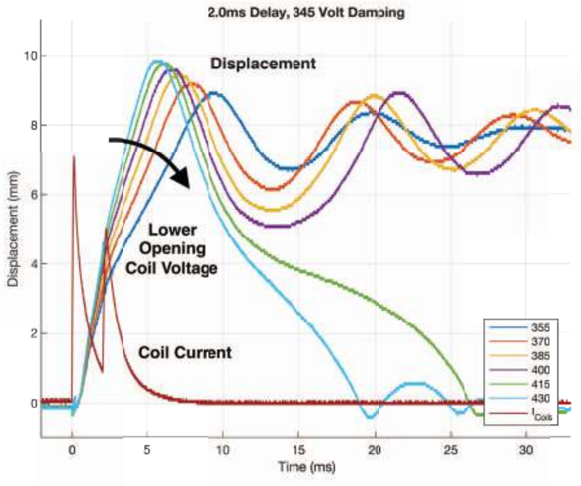

Fig. 15: FMS motion for various opening voltages, with 2.0ms damping delay and 345 V damping voltage.

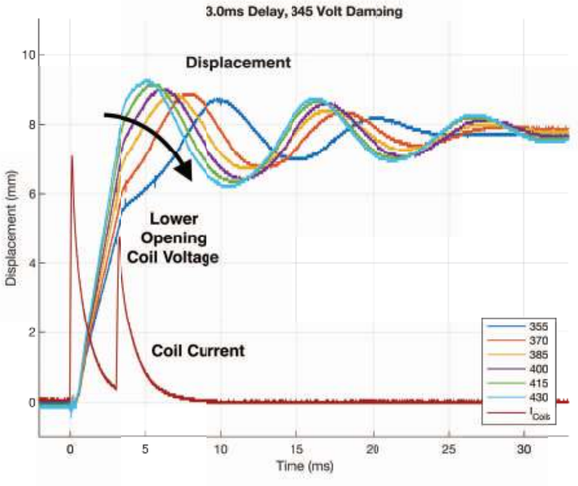

Fig. 17: FMS motion for various opening voltages, with 3.0ms damping delay and 345 V damping voltage

D. *Contribution of damping pulse timing*

How the time delay affects the damping transients is shown in Figs. 19 and 20.

In both cases of 322 V and 355 V damping voltages, a shorter pulse delay (comparing 2 ms with 3 ms) would generate a slightly higher overshoot in the traveled distance and relatively larger oscillation magnitudes later on. This is because at 2 ms the moving disk had not yet arrived in the most effective region for the damping coil to absorb the kinetic energy. However, the length of damping period for an early damping pulse is longer than that of a late one.

Figs. 21 and 22 are velocity plots. Two observations can be made: With increased opening voltages, faster peak speeds are obtained, resulting in faster operation. Yet at the same time, with increased opening voltage, the effectiveness of the damping pulse with the same damping voltage and delay is increased. This is because a higher opening voltage drives the moving mass closer to the damping coil within the same period of time.

VI. CONCLUSIONS

A novel active damping mechanism has been proposed to address the reclosing issues observed during high speed operations of Thomson coil actuated fast mechanical switches. The concept has been verified by a comprehensive transient FEM model based on coupled multiphysics involved in the operation, and with validation from experiments carried out on a DC breaker prototype.

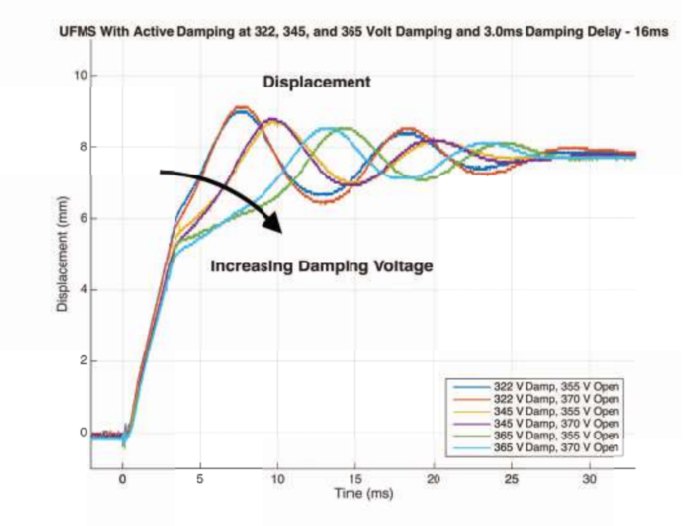

Fig. 18: FMS motion for various opening and damping voltages, with 3.0 ms delay.

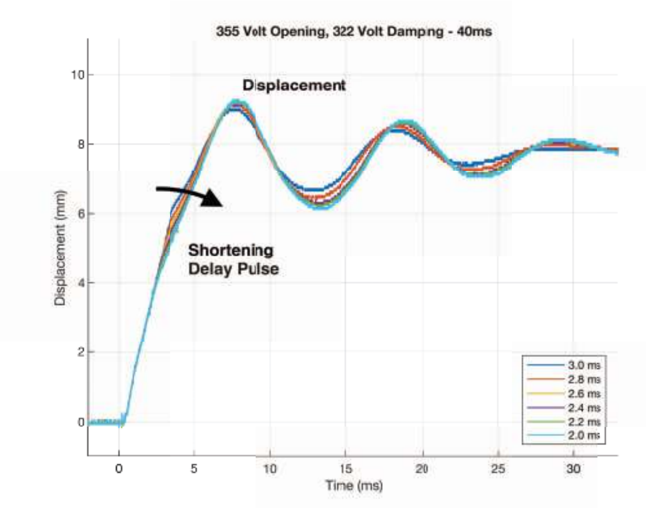

Fig. 19: FMS motion for various damping pulse timings with 430 V opening voltage and 322 V damping voltage.

An important contribution of this paper is that active damping not only helps absorb kinetic energy and minimizes the side effects of high actuator speed. It also makes it possible to select operating parameters that lead to faster, yet reliable, operation.

The evaluation of different damping delays for a particular design has been presented. It is found that earlier damping pulses result in weaker damping forces while later damping pulses generate stronger forces because the disc and the coils are closer to one another at the onset of the braking pulse. The optimization of the damping pulse should be a function of the design specifics, including the layout of the coils and the moving disk, as well as the disc spring characteristics.

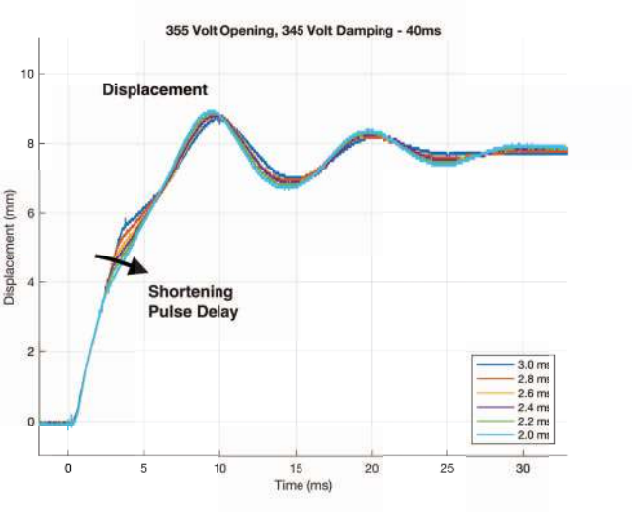

Fig. 20: FMS motion for various damping pulse timings with 430 V opening voltage and 345 V damping voltage.

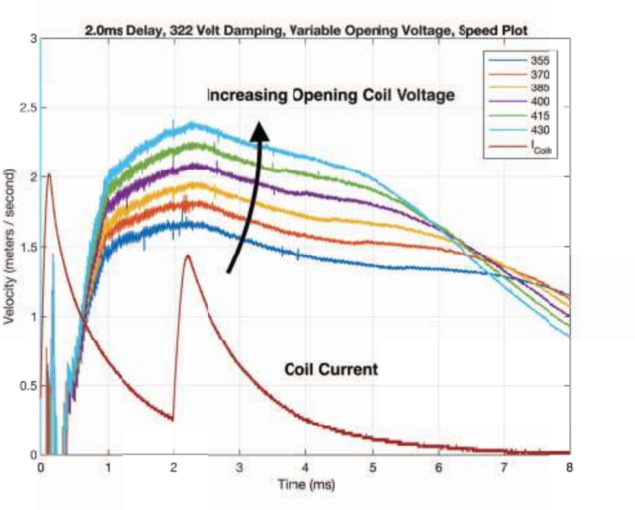

Fig. 21: FMS velocity pattern for various opening voltages, with 2.0 ms damping delay and 322V damping voltage

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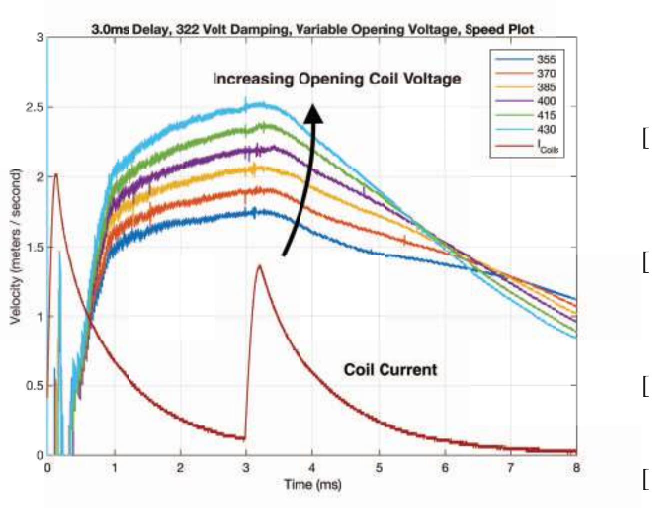

Fig. 22: FMS velocity pattern for various opening voltages, with 3.0 ms damping delay and 322V damping voltage

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