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A comparison of damping techniques for the soft-stop of ultra-fast linear actuators for HVDC breaker applications

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Keywords: Ultra-fast linear actuators, Thomson coil, moving coil, Lorentz force, hybrid HVDC breakers.

Abstract

This paper assesses the advantages, drawbacks and overall suitability of different soft-stop techniques to provide smooth deceleration of ultra-fast linear actuators used in hybrid HVDC breaker designs, with the help of FEA simulations. The paper compares active and passive damping techniques in terms of efficacy, energy consumption and interference with the ultra-fast operation needed from the actuator. The possibility of combining active and passive damping techniques is discussed.

1 Introduction

Owing to the inherent low impedance and poor over-current capability of VSC based HVDC networks, fast acting breakers are required for their protection. From existing DC breaking technology only hybrid designs are able to comply with the short isolation time and low on-state conduction losses demanded for such applications [1-3]. A hybrid breaker combines mechanical and semiconductor components to achieve low conduction losses under normal operation while enabling short interruption times under fault conditions [1-8]. Although many hybrid DC breaker topologies with different operating principles and semiconductor types have been proposed, all these rely on a mechanically operated switch to provide a low impedance path under normal, on-state operation [2-8]. Under fault conditions the switch electrodes are rapidly separated to transfer current to a semiconductor current breaking branch. The gap required between switch electrodes depends on both the breaker voltage rating and switch technology.

For redundancy and to increase voltage rating, HVDC breakers are often designed to follow a modular philosophy [2, 3], so that an HVDC breaker is formed by series connecting several Medium Voltage (MV) DC breaker cells. Therefore MV mechanical switches may be used in each breaker cell. To provide rated voltage isolation, while minimizing the gap required between switch contacts, the contact gap insulation medium must have strong dielectric properties (such as SF₆ or vacuum). For MV applications

Vacuum Interrupters (VIs) are the preferred switching technology. Commercial VIs up to 72.5kV are readily available [9], with VIs up to 145kV planned for commercialisation [10]. Thus assuming an 80kV, 2kA (9kA SC) breaker cell with VI switching technology, switch mass can be estimated from publicly available data. The moving mass of commercially available 40 kV, 2kA VIs is around 3kg, with a stroke length of about 15-20 mm [11]. Suppose that the 80kV switch is formed by two series connected 40kV VIs, the switch moving mass is 6kg, and the total ultra-fast actuator and switch moving mass is 8kg. Switch opening times for HVDC prototypes rated at 80 and 120 kV have been reported to be around 2ms [2, 3]. Thus the actuator must be able to displace the combined mass of the actuator and switch over the required gap length in around 2ms. Using VIs as an example, a combined moving mass of 8kg is to be displaced 20mm in 2ms, a total of 400J of kinetic energy has to be dissipated at the end of the actuator travel, if average speed is assumed.

For ultra-fast switch operation, Thomson Coil (TC) based actuators are mostly employed [12-15]. However, recent research has shown that the Moving Coil (MC) actuator is also suitable for ultra-fast operation when a long stroke is required [16, 17]. In both cases, the kinetic energy stored in the actuator-switch moving components must be rapidly dissipated, ideally with no bouncing or high speed contact between hard surfaces; this in order to avoid excessive mechanical stress, accelerated aging, dielectric breakdown or destruction of the actuator-switch pair. Kinetic energy dissipation is complicated by the brevity of the travel and the high operating speed. A high deceleration rate of the moving mass with minimal physical contact is wanted so that a soft stop of the moving mass is implemented.

In this paper, active and passive soft-stopping techniques for use on TC and MC actuators are evaluated with the help of FE simulations. Energy requirements of each soft-stop technique are quantified and their convenience of implementation on both actuator types is discussed. Active and passive soft-stop techniques are initially considered separately in the simulations and then combined use of both techniques is discussed.

2 FE Implementation

The TC, Fig. 1, relies on magnetic repulsion to achieve fast reaction time. Thus to enable bidirectional displacement a secondary coil is placed at the end of the armature travel. On the other hand to achieve displacement the MC relies on the Lorentz force induced by a circulating current in a coil immersed in a magnetic field, Fig. 2. The force exerted over the actuator coil is proportional to the circulating current, coil conductor length and magnetic field density. Bidirectional displacement of the MC can be achieved by a simple change of the coil current direction. In order to assess the suitability of different soft-stop techniques, numerical models of the two actuators types were implemented using FEA software. COMSOL 5.3 multi-physics software was used to conduct the numerical simulations. A deformable moving mesh was used to accurately account for displacement of the actuator moving components. For simplicity the actuator moving components are assumed to be infinitely rigid during the simulations, therefore the mechanical behaviour of the system can be simply 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/moving coil, m is the moving mass, a is the acceleration, v is the velocity and x is the displacement of the moving element. In addition, equations (4)-(10) are used by the FEA software for the model solution, with the corresponding variables listed in Table I. Vector variables are identified with the symbol $\vec{\cdot}$.

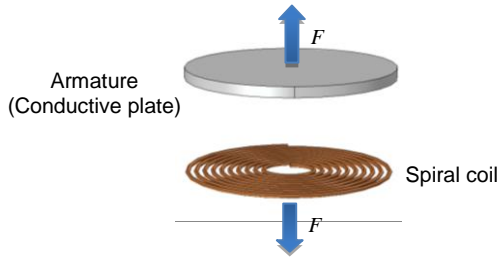


Fig. 1. Thomson coil

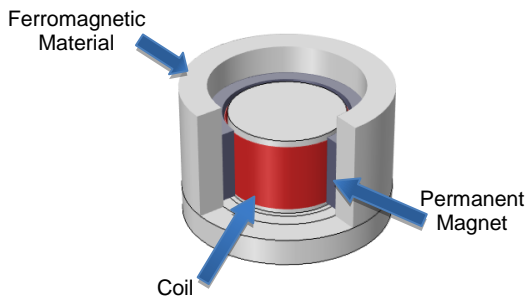


Fig. 2. Moving coil

$$\sigma_e \frac{\partial \vec{A}}{\partial t} - \sigma_e \vec{v} \times \vec{B} + \vec{J} = \vec{J}_e \quad (4)$$

$$\vec{\nabla} \times \vec{A} = \vec{B} \quad (5)$$

$$\vec{\nabla} \times \vec{H} = \vec{J} \quad (6)$$

$$\vec{J} \times \vec{B} = \vec{F}_l \quad (7)$$

$$\sigma_{e0} [1 + \alpha(T - T_0)]^{-1} = \sigma_e \quad (8)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{v} \cdot \vec{\nabla} T \right) = \vec{\nabla} \cdot (k \vec{\nabla} T) + Q \quad (9)$$

TABLE I
FEA SOFTWARE EQUATIONS VARIABLES

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
σ_e	Electric conductivity
σ_{e0}	Reference electric conductivity
T	Temperature
T_0	Reference temperature
α	Temperature coefficient
ρ	Density of the material
C_p	Heat capacity
k	Thermal conductivity
Q	Resistive losses

There are several passive and active techniques that may be used to achieve smooth deceleration of ultra-fast actuators, such as gas damping [18], regenerative braking [19] and electromagnetic repulsion [20, 21]. For regenerative braking and electromagnetic repulsion based soft-stop techniques (with little to no air flow restrictions) equations (1)-(9) are enough to describe the dynamic behaviour of the system. However to account for drag, flow compressibility and other fluid effects that become significant when gas damping techniques are employed, additional equations are required. In this assessment the effect of air compressibility is modelled using the high Mach number flow interface from the COMSOL CFD module, with laminar flow regime assumed. In this scenario the Navier-Stokes and continuity equations are considered by the FE model and solved jointly with equations (1)-(9). For the exemplary VI arrangement discussed in Section 1 a moving mass of 8 kg is to be displaced 20mm in around 2ms. Thus the TC and MC designs as well as their respective energy sources are sized accordingly during simulations. Since high speed isolation is a requirement for HVDC protection, active damping is assumed to start once the required dielectric gap has been achieved, thus over-travel will be incurred in the simulations.

For a VI the over-stroke may require a special interrupter design with an extended stroke, or the use of a Bell Crank lever to reduce the stroke length. The Bell Crank lever approach is not considered in this paper for simplicity.

3 Active damping

Active damping involves the execution of a specific action to initiate deceleration of the moving mass. For the TC, this action may consist of providing excitation to the actuator secondary coil (or closing coil, see Fig. 3) at a specific instant during the armature travel. By exciting the closing coil, a force opposing the armature displacement is produced, reducing the armature speed. Fig. 4 shows the TC actuator profiles for several quantities obtained from FE simulations when the closing coil is used to decelerate the moving mass. The actuator design parameters are listed in Table 2. In the figure the negative sign on the velocity and displacement signals is related to the perceived direction of travel.

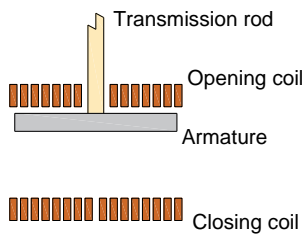


Fig. 3. TC cross section diagram

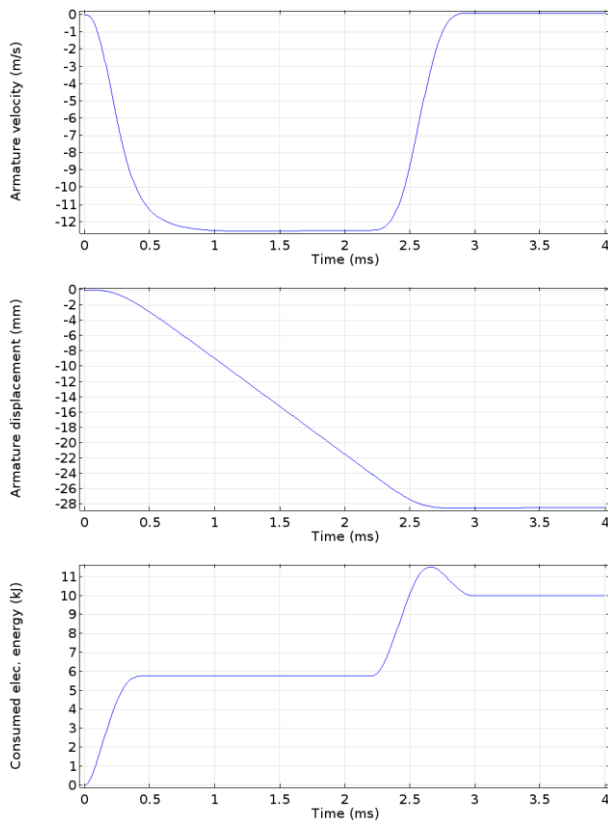


Fig. 4. TC actuator speed profile (top), armature displacement (middle) and consumed electrical energy (bottom)

Parameter	Value	Parameter	Value
Capacitor bank	2mF	Armature thickness	25mm
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.

As can be seen in Fig. 4, the velocity at the end of travel is low. Air cushioning, or direct impact with a soft surface, may be used to dissipate the remaining kinetic energy. The main inconvenience of the active damping technique is that a sizeable amount of electric energy is required to reduce the armature speed to a manageable level. This energy is additional to that required for switch re-closure. Thus the capacitor bank required to provide the energy necessary for armature deceleration and switch re-closure may be larger than that required for switch opening, thus impacting negatively on actuator cost. This is an important consideration given the typically low electrical to mechanical energy conversion efficiency of a TC. For instance, a peak efficiency of only 13% was observed in FE simulations. In contrast, the double differential MC actuator (DD-MC), Fig. 5, has been shown to be competitive in terms of performance with the TC, while exhibiting much higher energy conversion efficiency [16]. Therefore the DD-MC design is considered in this paper for comparison. The DD-MC actuator design parameters are listed in Table 3. In this assessment, the coil terminals are connected to a fully controlled H bridge in order to enable control of the coil current direction. During actuator operation regenerative braking is used for deceleration: once the required stroke length has been reached, the polarity of the coil terminals is reversed by the H bridge. Fig. 6 shows FE simulation results for the DD-MC.

As can be seen in Fig. 6, there are several advantages associated with the use of the DD-MC compared to the TC. For instance, owing to the MC high energy conversion efficiency, a single capacitor bank, storing a similar amount of electric energy to that used by the TC, can be used to initiate and stop actuator displacement. In addition MC stop can be easily achieved by removing coil excitation when zero speed is reached. However as shown in Fig. 6, a longer distance is required to reduce coil speed at manageable levels; the deceleration rate is considerably lower than that of the TC in Fig. 4. For comparison, the TC requires only 6mm to decelerate from 12m/s to 1m/s, while the MC takes 20mm to decelerate from 18m/s to a similar low speed. It should be remembered that for the MC to produce any mechanical force, the coil turns must be immersed in a suitable magnetic field. This implies that ferromagnetic and PM material, necessary to complete the required magnetic circuit, must be present for the full coil travel distance, thus affecting the actuator cost.

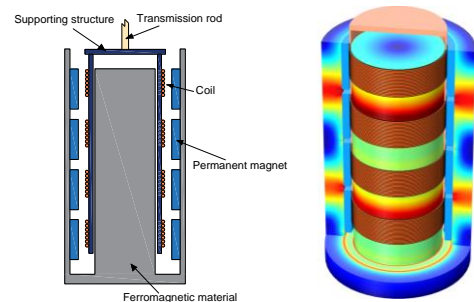


Fig. 5. DD-MC actuator (left) and flux density distribution with no coil excitation (right).

Parameter	Value	Parameter	Value
Capacitor bank	10mF	Conductor cross section	2x3mm
Bank voltage	1100V	Coil mean radius	96mm
Turns per coil	20	PM thickness	15.2mm
PM remanence	1.2 T	Wall thickness	40mm

Table 3: DD-MC parameters.

An alternative to reducing the coil over-travel is to force a higher deceleration rate. This may be achieved by using for deceleration a secondary capacitor bank capable of providing a higher current over a shorter period. This is illustrated in Fig. 7, where a capacitor of the same size as the primary capacitor but charged to twice the voltage is used for coil deceleration. As can be seen in Fig. 7 the energy consumption is even higher than that of the TC in Fig. 4, while the traveling distance until coil velocity flattens is reduced by 10mm. Thus the convenience of this approach is debatable. This design trade is at the expense of an increase in capacitor size, energy consumption and design complexity.

From the simulation results it is clear that in terms of energy consumption the MC is a far superior alternative than the TC. The electrical energy consumed by the MC is almost half that used by the TC, reaching in the process a peak efficiency of about 38%. However the TC offers a simpler, more robust and compact design. Thus the preferred actuator technology will depend on the operating environment restrictions. It is important to mention that ultra-fast actuator operation is mostly sought for switch opening. Therefore switch re-closure may be performed at low velocity. Consequently a much simpler, low speed damping system may be employed for switch re-closure. If otherwise required, active damping may be also used for switch re-closure without altering any physical connection. To this end the function of the actuators coils is just reversed, thus providing a similar damping effect.

4 Passive damping

Passive damping takes place when no external action is required for deceleration of the moving mass to occur, thus deceleration happens naturally, as part of the actuator design. The main advantage of this approach is that electric energy is usually not consumed during the process. On the other hand its main drawback is the lack of flexibility: no control over the deceleration rate is possible during operation, the deceleration rate being intrinsic to the actuator design.

In this paper passive gas damping, using air at atmospheric pressure is considered. It should be noted that, for instance, by using a denser fluid than air (e.g. SF₆), increasing gas initial pressure or a combination of both approaches, a faster deceleration rate may be achieved. However, a more robust, complex seal system would be required. The damping effect is achieved by limiting the flow at which the air can escape a containing chamber. This is achieved by carefully choosing the size of the chamber discharge vents. Thus the velocity at which the air within the vessel escapes is limited (choked flow regime) and the air pressure inside the gas container builds up, reducing armature speed. The principle of operation is illustrated in Fig. 8 for the TC and MC actuators. As shown in Fig. 8, a gas chamber can be easily realized for the MC actuator by making use of the coil supporting

structure. On the other hand, the TC actuator requires the addition of a purpose built gas chamber.

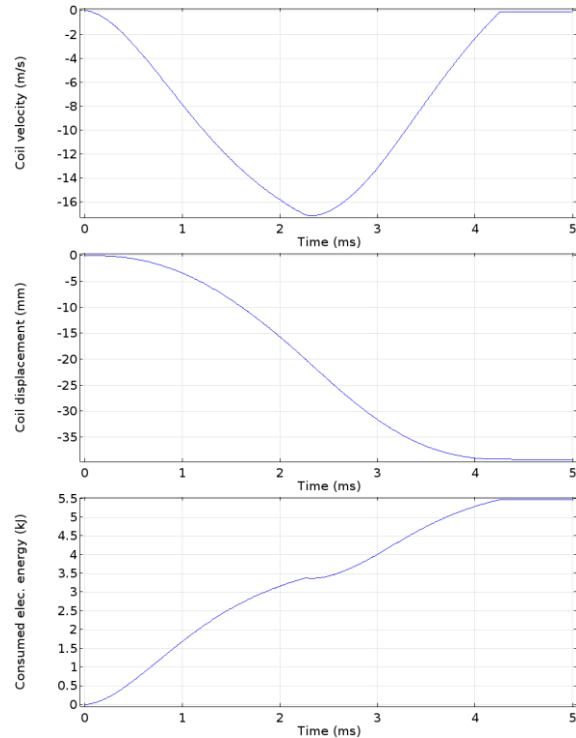


Fig. 6. DD-MC actuator performance quantities, from top to bottom: coil velocity, displacement and electrical energy consumed.

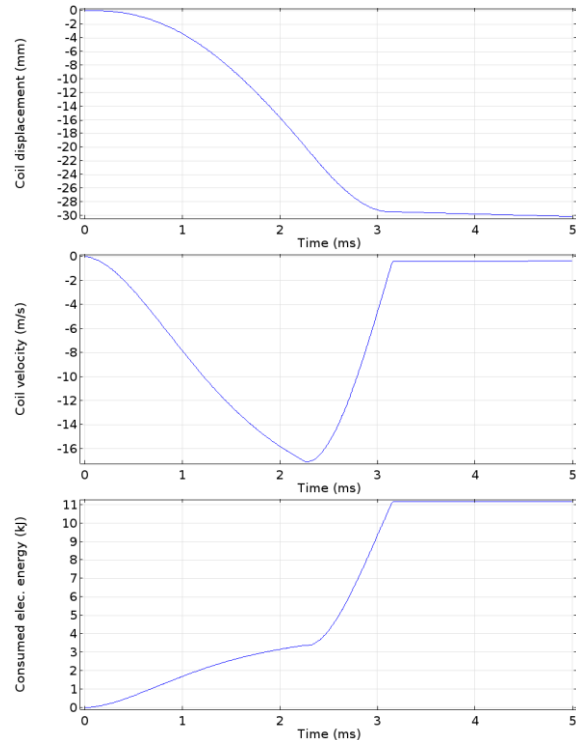


Fig. 7. DD-MC actuator with two capacitor banks simulation results. From top to bottom: coil displacement, coil velocity and electrical energy consumed.

In Fig. 8 the MC discharge vents are conveniently defined by the gap between the coil supporting structure and the actuator ferromagnetic core. If required, additional vents may be made in the top plate of the supporting structure. For the TC the discharge vents may be placed at the top, bottom or at both ends of the structure [18]. In this paper the discharge vents of the TC are assumed to be placed at the top of the gas chamber only. A large escape vent was deliberately chosen for the TC so as to not limit the incoming air flow. In this design, the air trapped in the cavity below the TC armature can only escape by the narrow gap between the armature and lateral walls, thus the air pressure below the armature increases rapidly, while the air pressure at the top of the armature is essentially atmospheric pressure. In this analysis a vent size of 10mm is considered for the TC with a 0.5mm gap between walls and armature, meanwhile a 0.5mm gap is assumed for the MC.

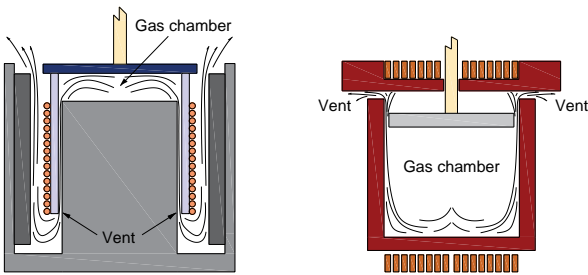


Fig. 8. Moving coil (left) and TC (right) discharge vents for passive gas damping.

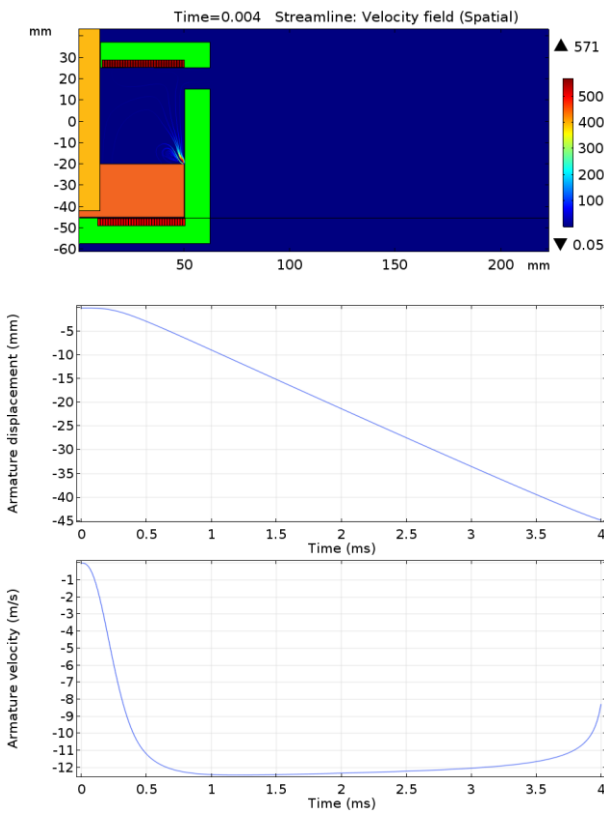


Fig. 9. TC with passive damping air speed stream (top), armature displacement (middle) and velocity profile (bottom).

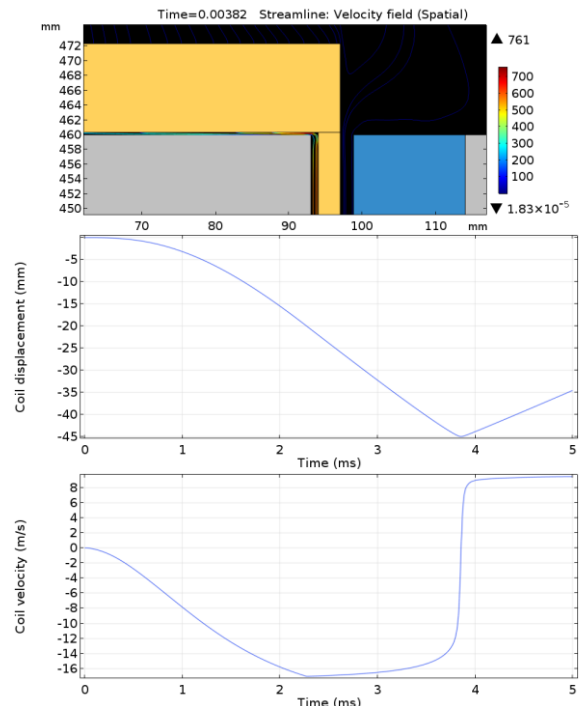


Fig. 10. MC actuator with passive damping: air speed stream detail (top), coil displacement (middle) and velocity profile (bottom).

Figures 9-10 show simulation results for the TC and MC actuators fitted with the passive damping schemes discussed above. For the MC results in Fig. 10 coil excitation is completely removed once the coil displacement exceeds the required 20mm gap, while for the TC the secondary coil is never excited. In the simulations, the stroke of the TC was extended to 45mm to better illustrate the gas damping effect, otherwise both actuators designs are identical to those used in section 3. As can be seen in Fig. 9, the armature velocity of the TC experiences a sudden drop in speed near the armature's end of travel. Thus although the damping effect persists during the whole actuator operation, the damping effect at the beginning of the armature travel is almost negligible. In contrast, since no electric energy is required for damping, the total electrical energy required for the actuator operation almost halves. Thus the benefits of a passive damping scheme easily outweigh its drawbacks. One of the inconveniences of this damping scheme is that if the pressure force at the end of travel is very high, a marked bouncing of the moveable mass may occur. This is clearly seen in Fig. 10, where the MC structure bounces dramatically once it reaches the end of travel, thus the deceleration rate is not enough to achieve a soft-stop of the moving components. To reduce this problem, a counteracting force can be applied until bouncing recedes, for example, by maintaining coil excitation in the MC until bouncing recedes. However this alternative approach inevitably results in the consumption of additional electrical energy, thus defeating one of the technique's main purposes. One important advantage of the implementation of a passive damping scheme is that in the case of failure (i.e. due to a wall break or seal failure) active damping can still be used, thus enabling actuator operation. In contrast, if only active

damping is implemented no safeguard exists in case of failure, and the actuator cannot be safely operated at normal speed. The existence of a redundancy mechanism is of utmost importance in mission critical applications, such as HVDC protection.

4 Conclusions

In this paper active and passive damping mechanisms for the soft-stop of ultra-fast linear actuators used in hybrid HVDC breakers are investigated. It is found that the active damping concept is an effective damping technique for the investigated TC and DD-MC actuator designs. It was found that when using active damping the DD-MC has the potential to operate at a fraction of the energy required for a TC of similar performance. However lower deceleration rates are achieved for the DD-MC and a longer overall travel is required if the energy consumption is to be kept at minimum. For passive damping, the DD-MC can be easily adapted while the TC requires a purpose built chamber to incorporate this damping mode. The use of passive damping techniques has been found to have a small detrimental effect on actuator speed, but a reduction in electrical energy consumption is achievable. The damping provided by the use of air at atmospheric pressure is insufficient and bouncing due of insufficient damping is a concern. The use of a denser fluid than air at a higher pressure may be necessary. The joint implementation of active and passive damping techniques ought to be considered to add a layer of redundancy to ultra-fast actuators when used in mission critical applications.

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