Thermal-Electrical Study of an Ultra-fast Disconnect Switch with a Piezoelectric Actuator

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Abstract:

A research team at FSU CAPS is developing a novel fast disconnect switch based on a piezoelectric actuator for use in next-gen electric power distribution systems. COMSOL Multiphysics 4.4 was used to optimize geometry and material selection of the disconnect switch. Current conduction, mechanical stress, and electrostatic simulations were performed to confirm that design requirements of the switch had been satisfied. The thermal field was calculated in a transient model, allowing for the effect of temporary over-current to be studied. Structural analysis helped determine optimum thickness of insulator features holding moving contact elements, thus keeping von Mises stresses to a safe level. The electrostatic field calculations confirmed that the chosen hemispherical contact geometry resulted in minimum field enhancement in the gap. Motivation for the work is given, simulation results are presented and explained, and future work is discussed.

Keywords: Power electronics, distribution systems, fast disconnect switch, piezoelectric actuator, hybrid breaker, vacuum switch.

1. Introduction

With increased adoption of intermittent sources of power generation and the need for dynamic and reconfigurable power grids, a paradigm shift in power system design emerges towards power electronics based, fault current limited distribution systems (PEDS). These systems may utilize typical power frequency (i.e. 50 or 60 Hz) AC or even medium voltage DC (MVDC) to deliver power from renewable resources and storage devices to local loads. This has created an opportunity for a new kind of circuit breaker, since due to the fault-current-limiting (FCL) nature of these systems, design requirements for the breakers will focus on ultra-fast operation to handle dynamic grid changes, rather than breaking large magnitude fault currents, as is the focus of conventional breakers. The last several years have seen the emergence of hybrid breaker designs which combine the speed and current breaking capabilities of high power semiconductors with the low losses of a fast mechanical disconnect switch [1, 2, 3]. Also, with PEDS, since all electrical sources and loads will be connected to the system through power electronic based converters (PECs), fault current breaking could potentially be accomplished by the PECs, effectively removing the need for circuit breakers entirely and allowing for rapid fault isolation and system reconfiguration to be accomplished by fast disconnect switches, thus reducing system complexity and reducing losses during nominal operation.

The research team at FSU CAPS is developing a novel fast mechanical disconnect switch based on a piezoelectric actuator to support the NSF funded Future Renewable Electric Energy Delivery and Management (FREEDM) System Center's development of a medium voltage, megawatt scale, single phase hybrid breaker based on SiC semiconductors. This breaker is intended for use in a PEDS system demonstration at nominally 12.47 kV (phase to phase; RMS) with maximum line currents of around 200 A.

2. Design and Operation of the Disconnect Switch

The design of the fast disconnect switch is based upon the piezoelectric actuator's advantage of sub-millisecond operation while recognizing its limitation of relatively short travel. Since the contact force and contact travel of the actuator are limited to around 1 mm and a few hundred Newtons, respectively, contact design is critical to minimize resistance during the closed state of the switch and improve voltage withstand capability during its open state. To maximize voltage withstand capability when open, the piezoelectric actuated switch (5) in Figure 1 is integrated inside a high vacuum

(10^{-4} to 10^{-7} Pa) chamber (1). Based on the 10-30 kV/mm breakdown field value given in literature [4, 5] this switch is expected to provide a dielectric strength between separated contacts sufficient for a 7.2 kV single phase application. Two ceramic bushings (2) provide the power leads and a multi-pin feedthrough (3) allows for actuator drive and feedback signals to be accessed from outside the chamber. The vessel itself is at ground potential, also known as a "dead tank" design. The elliptical shell of the piezoelectric actuator is housed in a high strength polymer frame (4), which also holds the fixed and moving contacts.

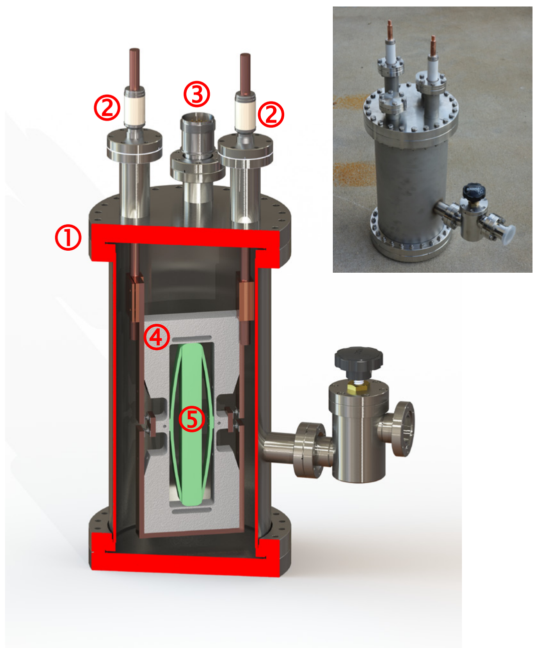

Figure 1. Design of the disconnect switch shown by a cutaway of the experimental vacuum chamber. Patents pending [6, 7].

Operation of the switch is as follows. During the closed state as shown in Figure 2 the two pairs of hemispherical moving contacts mounted on moving conductors (4) and (5) are pressed against their counterparts, the fixed hemispherical contacts, mounted on the main conductors (1) and (3) providing a continuous current path through the switch.

To transition the switch to its open state, voltage is applied to the piezoelectric stack (6) causing it to vertically extend. This in turn results in the tabs (7) and (8) to flex and the sides of piezoelectric stack's elliptic shell to be drawn inward towards the center of the stack, pulling the moving conductors (4) and (5) toward the stack as well. This separates all the hemispherical contacts and creates four contact gaps between them. During this open state, the voltage difference between the main conductors in (1) and (3) is divided across the four contact gaps. In AC applications the division of voltage is governed by the stray capacitances of those four contact gaps. In DC applications, additional resistive grading may be necessary.

It is important to note that as this is a disconnect switch and not a circuit breaker. The transition from the closed state to the open state does not occur while current is being conducted. Therefore the design of the switch did not need to make considerations for arcing.

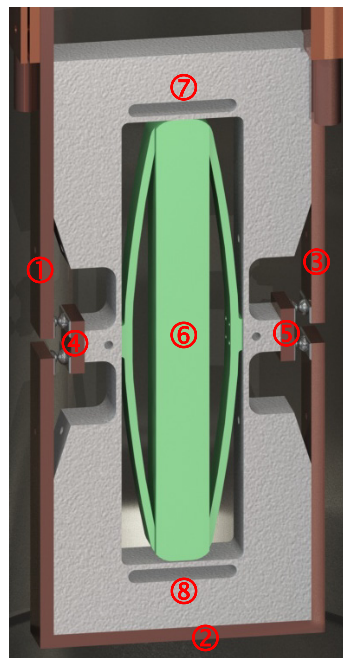

Figure 2. Design of the active parts of the disconnect mechanism including the actuator (green), the insulator (grey), the copper conductors (brown), and the contacts (white). Patents pending [6, 7].

3. Use of COMSOL Multiphysics

From the beginning of the project, it was clear that the design of the disconnect switch requires careful optimization. COMSOL

Multiphysics 4.4 was chosen as a tool to allow studying different physics using the same geometry or a subset of the same geometry. The mesh resolution was optimized for each of the studies. Four studies were of particular interest:

1. The static mechanical stress in the insulator while the contacts were open (*solid*, *stationary*)
2. The static deformation of the contact elements by contact force in closed state (*solid*, *stationary*)
3. The amount of losses and resulting thermal field (*ec* + *ht*, *time dependent*)
4. The capacitive electrostatic field when the contacts were open. (*es*, *stationary*)

These four studies are described in the following subsections.

3.1 Static Mechanical Stress in Open State

The insulator frame has several important functions: it electrically isolates the fixed and moving contacts, contributes to the voltage grading in the open state, keeps the actuator aligned, transfers actuator movement into contact force, and allows adjusting the contact separation in open state for experimental purposes. A simulation of the von Mises stresses in the insulator frame was used to design the optimum thickness of the bridge parts, permitting the required motion while not exceeding material stress limits.

The model was implemented using the static *Solid Mechanics (solid)* interface. The loads were applied as displacements on the four interfaces between the elliptical shell of the actuator and the insulator frame. The long axis of the elliptical shell was assumed to expand by 2 × 86.2 µm while the short axis was assumed to contract by 2 × 500 µm. The fixed constraints were the flat vertical surfaces on the outside of the high strength polymer frame. A maximum value of 15.8 MPa was determined (Figure 3), which is well below the yield strength of the material. Future studies are expected to focus on fatigue, since the disconnect switch is designed for thousands of switching operations.

The mesh consisted of 44k tetrahedral elements, resulting in 215k degrees of freedom and required approximately 20 s to calculate (2× Intel Xeon X5570 with 24 GB of RAM).

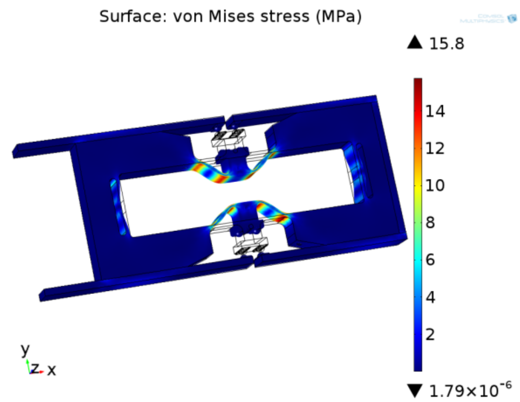

Figure 3. Von Mises stresses in the insulator frame while the piezoelectric stack expands and the contacts retract.

3.2 Static Contact Deformation

Choosing the right contact material and shape is crucial for reliable operation of the disconnect switch. The shape of the material must be maintained over thousands of switching operations while the electrical contact resistance must be kept low enough to minimize heating and keep the losses low. Contact tabs with hemispherical contact surfaces were chosen since they allow minimize the electrical field in open state while minimizing contact resistance in closed state. The contact resistance is a function of inherent resistance of the material, surface contamination resistance, and constriction resistance [8]. The contamination resistance is assumed to be negligible due to vacuum environment. The inherent resistance can be lowered by choosing materials with a high electrical conductivity while the constriction resistance can be lowered by a material with low modulus of elasticity and a high Poisson's ratio. The chosen silver alloy is a very promising material for the disconnect switch. However, it must be ensured that the stresses due to contact pressure do not exceed the elastic limit, thus avoiding permanent deformation.

A static model using *Solid Mechanics (solid)* was set up to determine the maximum von Mises stresses in the closed contacts. A maximum value of 130 MPa was observed at a contact force of 100 N (Figure 4). Most of the material experienced stress values below 10 MPa. The total vertical displacement of the top contact tab was 0.92 µm. This was considered to be acceptable for the silver alloy chosen.

In future work, a more detailed model is planned to be developed based on a dynamic approach.

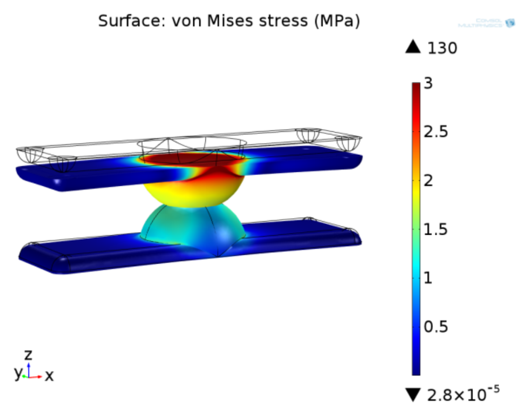

Figure 4. Von Mises stresses in the contact elements under vertical load.

The mesh for the two contact tabs consisted of 356k tetrahedral elements, resulting in 1.56M degrees of freedom and required approximately 5 min to calculate.

3.3 Losses and Peak Temperature

A time dependent thermal-electrical co-simulation was set up to determine the total losses by Joule heating and the peak temperature as a function of time. The *Heat Transfer in Solids (ht)* and the *Electric Currents (ec)* interfaces were chosen. On the thermal side, the ends of the conductor bars were held at a fixed temperature of 293 K. All other boundaries had a *Surface-to-Ambient Radiation* boundary condition with a given surface emissivity and an ambient temperature of 293 K.

On the electrical side, the current path is from the left end of the top left conductor bar clockwise to the left side of the bottom left conductor bar. The start of the current path was modeled by a terminal. A constant DC current of 200 A was injected. The end of the current path was grounded.

There is a total of ten solder joints: eight joints between the contact tabs and the conductor bars and two joints at the right end connecting the vertical bar to the horizontal bars. Solder joints have been modeled by COMSOL's *Contact Impedance* feature assuming the *Thin Layer* approach (0.2 mm; conductivity according to the solder alloy). The mechanical contacts were modeled by a slight geometrical overlap, simulating the elastic compression of the spherical surfaces. Similarly to the solder joints, the contact surfaces have been modeled by a *Contact Impedance* feature with a *Surface Impedance* adjusted to model the constriction resistance calculated in a separate spreadsheet. A more sophisticated model for the contact based on a static Hertz model is currently under consideration [9]. The total voltage drop at 200 A was determined to be approximately 26.9 mV (Figure 5), amounting to approximately 5 W of expected losses.

Figure 6 shows the stationary thermal field at a continuous load current of 200 A. The transient temperature development of the hotspot is shown in Figure 7. The maximum temperature increase was approximately 6 K, which is low enough to exclude effects of reduced voltage withstand capability in open state.

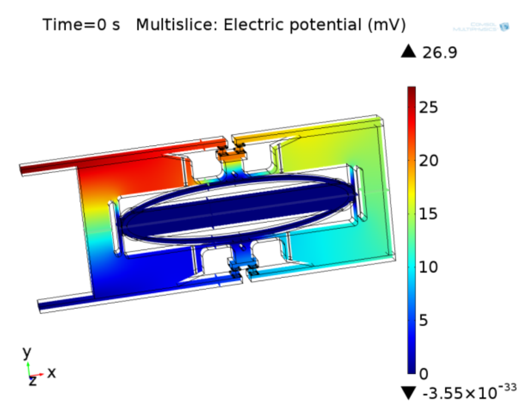

Figure 5. Voltage potential field at 200 A, resulting in a total voltage drop across the switch of 26.6 mV.

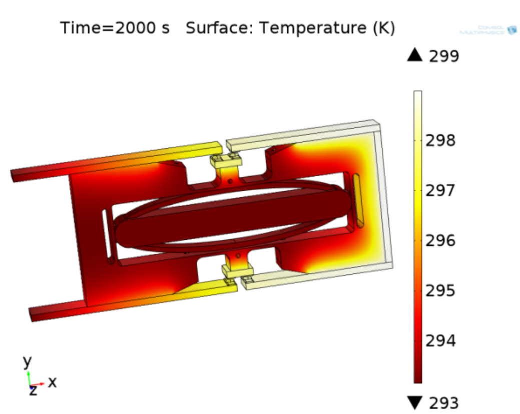

Figure 6. Stationary thermal field in vacuum at a load current of 200 A.

The complete mesh for the thermal field calculation consisted of 75k tetrahedral elements, resulting in 236k degrees of freedom and required approximately 2 min to calculate 20 time steps.

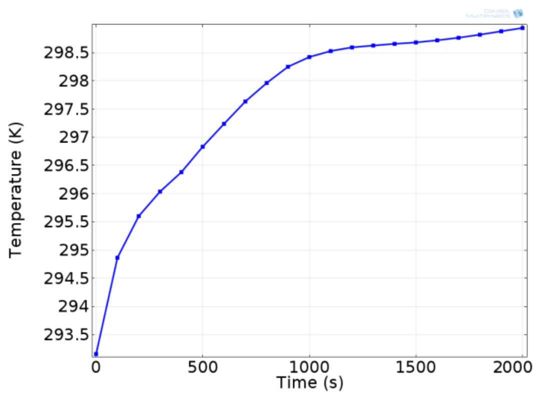

Figure 7. Peak temperature as a function of time at a load current of 200 A.

3.4 Electrostatic Field

The disconnect switch is designed to withstand 15 kV_{RMS} (60 Hz AC) in open state. The only locations with relevant electric fields are between the contact elements. Assuming equal contact separation distance and uniform capacitance between all four contacts, an even distribution of the total voltage drop can be expected, yielding 3.75 kV per contact gap. This assumption is based on a capacitive field distribution as expected during transients and steady-state AC conditions. The properties determining the field distribution are the relative permittivities, rather than the conductivity of the materials.

The maximum allowed electric field in vacuum is determined by the work function from a metallic surface into the vacuum. For most metals that are of interest, the work function is approximately 4.5 eV, corresponding to an electric field of 1000 kV/mm at room temperature [4]. However, this ideal value can never be met, since microscopic surface imperfections lower the barrier for electrons to be released substantially. The literature provides practical values of around 10 kV/mm to 30 kV/mm [4, 5]. Since the contact separation is approximately 0.5 mm, the maximum electric field was expected to be around 7.5 kV/mm plus a certain amount of field enhancement due to non-uniform distribution between the spherical surfaces. This electric field appears low enough to provide the expected voltage withstand capability.

The model used the *Electrostatics (es)* physics. A bounding box was put around the volume of interest to allow calculating the electric field in vacuum (blue box in Figure 8).

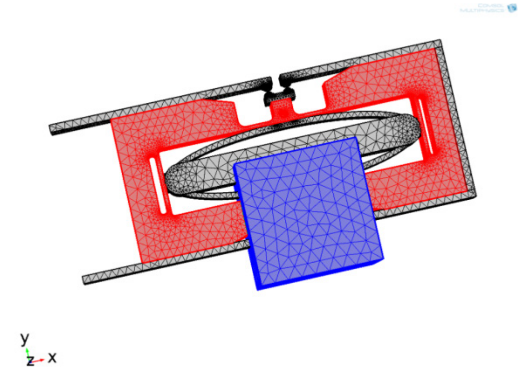

Figure 8. Bounding box (blue) around the contacts to allow calculating the electrostatic field distribution in vacuum.

Figure 9 shows the calculated electrostatic field with a maximum electric field of 7.84 kV/mm, which corresponds well with our expectations of 7.5 kV/mm.

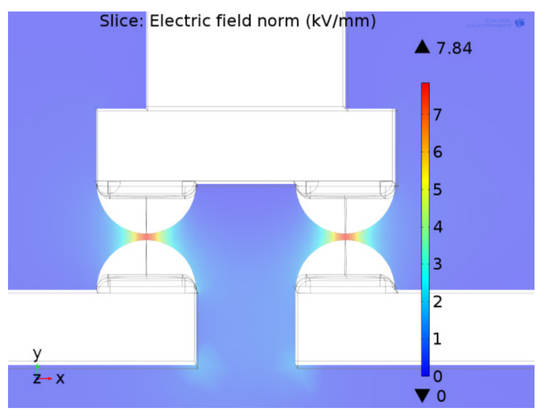

Figure 9. Electrostatic field between the open contacts assuming uniform voltage grading across all four contacts in series.

The mesh consisted of 285k tetrahedral elements in the bounding box, resulting in 790k degrees of freedom and required approximately 40 s to calculate.

4. Conclusions

The use of COMSOL Multiphysics proved to be essential in the design and optimization process of this novel fast disconnect switch. By adapting the geometry and cycling through materials with different properties, all design requirements were met. Parts for the first prototype are currently being machined and a subsequent phase of experiments is expected to start in a few weeks.

The disconnect switch will be fully tested and subsequently integrated into a hybrid circuit breaker [1, 2, 3]. Future work will focus on optimizing the full potential of the disconnect switch, and exploring additional applications in various industries.

5. References

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9. Acknowledgements

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