

The trip coil as a soft sensor for medium voltage circuit breakers

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Summary: This paper presents electromechanical modeling and experimental validation of the interaction between the tripping coil and the mechanical drive of a vacuum interrupter circuit breaker during the closing operation. A model of the coil connected to the mechanical drive is developed, capturing the plunger motion induced by a constant input voltage and its subsequent transfer through a lever system to rotate the closing shaft and enable de-latching. To validate the model, an experimental setup replicating the actual breaker mechanism was constructed. The setup incorporates the coil mounted on a reduced mechanical drive, with a latching mechanism that utilizes a spring-loaded push stick to simulate the latching force applied to the closing shaft. The push stick's initial spring compression is adjustable, allowing tests under varying latching force conditions. A regulated 60 V supply energizes the coil. Coil current is measured using an oscilloscope, while force and displacement sensors provide synchronized measurements on a common time scale. Three experimental configurations are investigated: (1) locked position with the closing shaft fixed at the de-latching position, (2) free movement without latching force, and (3) full engagement with complete latching force applied. The results demonstrate close agreement between simulation and experiment, providing insights into the dynamic behavior of the coil-mechanical drive system and establishing a reliable foundation for both design optimization and condition monitoring of vacuum interrupter circuit breakers.

Keywords: trip coil, testing, actuator, soft sensing, circuit breaker, condition monitoring, energy transition

Introduction

Digitalization of electrical power systems is crucial for realization of the energy transition. Trip coil actuators (Fig.1) as important components of switchgears offer well-known opportunities for monitoring their own performance and partly that of the complete safety system [1].

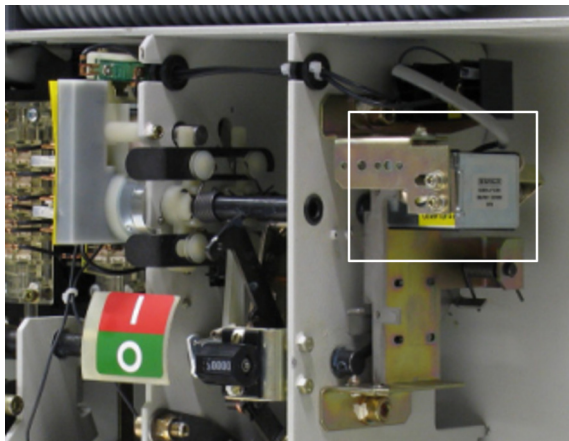


Fig. 1: Interior of a circuit breaker drive.

A circuit breaker is a key component in sustainable, safe, and continuous power distribution for households and industries. In addition, breakers play an important role in protecting utilities from system failure. Overvoltages and reignition behavior of vacuum circuit breakers can cause significant damage. This makes the proper function of circuit breaker essential to the network. As a result, the circuit breaker requires regular maintenance to ensure they can safely disconnect the network. Besides regular maintenance, diagnosing and predicting system behavior and possible failure in advance is crucial to

avoid catastrophic failure. The main method is the system's regular service, which is quite costly, dangerous, and time-consuming over the life span of circuit breaker. Therefore, more sensors are developed to be implemented inside the circuit breaker to check circuit breaker status remotely and in shorter time intervals while reducing the number of on-site maintenance and faster diagnostic of the possible problems in the system.

Sensors are inherently expensive, as additional parts in manufacturing, with special quality requirements and possibly need for maintenance or calibration. Significant money and effort can be saved by reusing existing data recorded by the circuit breaker as a virtual sensor to predict circuit breaker performance in future cycles.

As an important step towards soft sensing and monitoring of parts of the breaker mechanism, experimental investigation of tripping dynamics is presented, with a focus on parameter-dependent interaction between the tripping coil and the main mechanical drive of the breaker during closing operation.

The paper is organized as follows: First, a lean simulation model is created, as a system of ordinary differential equations, which has the potential of being run in field components, in the future. Second, an experiment, or test rig, has been set up where the tripping mechanism behavior can be investigated under varying parameters such as the latching force load. The trip coil current and other quantities can be measured as functions of time and the dependence on parameters can be interpreted. Finally, the test rig results are used to validate the simulation model, so that in the future the latter can be used as a reference in cases of parameter drifts or even for soft sensing of such parameters via automatic model adjustments [2].

Coil-breaker simulation model

To better understand the dynamics and to provide an online condition monitoring system for the circuit breaker's tripping coil, we develop a simulation model.

The model captures all electromagnetic and mechanical dynamics during the initiation of the switching operation. Specifically, it covers the sequence starting from energizing the tripping coil, inducing an electromagnetic field that drives the plunger upward, initiating a kinematic chain as the plunger strikes a plastic lever, and ultimately releasing the closing or opening shaft through a series of mechanical mechanisms. The subsequent mechanical response – including the rotation of the main shaft and the opening or closing of the push rods – is not directly related to the condition of the tripping coil and is therefore not covered in our simulation model.

Figure 2 presents a simplified illustration of the switching mechanism. The components represented in our simulation model are highlighted in green, yellow, and blue boxes. Note that this illustration is highly simplified, and the tripping coil is intentionally oversized for emphasis, as it is central to our analysis.

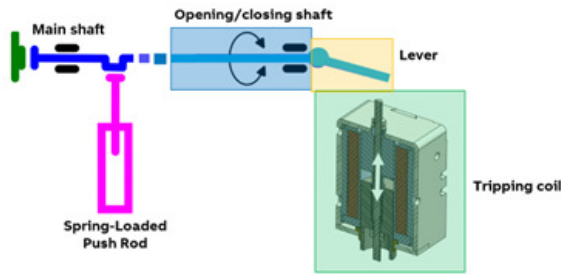


Fig. 2: Simplified illustration of the switching mechanism. Parts represented in the simulation model marked with green, yellow, and blue boxes.

The goal is to minimize hardware requirements for executing the simulation model. For example, it should run on a microcontroller without any proprietary software. For this reason, a complex finite element simulation or multibody simulation is unsuitable. Instead, we formulate a minimal model based on ordinary differential equations (ODEs) that describe the system dynamics [3, 4].

The ODE system contains three equations. The first describes the electromechanical energy transfer based on Kirchhoff's voltage law. The second is simply the definition of velocity. Let U denote the supply voltage, R the coil resistance, i the coil current, λ the flux linkage, x the plunger displacement, v the plunger speed, and t the time. Then, we obtain the first two equations by

$$\frac{d\lambda(t)}{dt} = U - Ri(\lambda, x), \quad (1)$$

$$\frac{dx(t)}{dt} = v(t). \quad (2)$$

Our focus lies on the third equation, which represents the electromagnetic and mechanical forces acting on the plunger based on Newton's second law, thus determining its motion. Since air gaps exist between the plunger and the plastic lever, and between the lever and the opening or closing shaft, we distinguish three cases in equation (3) based on which components of the kinematic chain are in contact with the plunger. Only components in contact affect the plunger's motion; we exclude disconnected parts. In the first case (green box in Fig. 2, eq. (4)), we consider only the electromagnetic and mechanical dynamics of the tripping coil itself. In the second case (yellow box in Fig. 2, eq. (5)), we include the mechanics of the plastic lever, accounting only for its moment of inertia, as other mechanical properties are negligibly small. In the third case (blue box in Fig. 2, eq. (6)), we also include the mechanical components up to the opening or closing shaft.

Let m denote the plunger mass, c the damping coefficient for the plunger motion, k the spring stiffness of the coil, x_0 the coil spring's equilibrium point, g the gravitational acceleration, $F_{\text{el.-mag.}}$ the electromagnetic force in the coil, I_L the moment of inertia of the plastic lever, L_L the length of the plastic lever, I_{sh} the moment of inertia of the closing/opening shaft, L_{sh} the length of the closing/opening shaft, L_b the length of the on-button, κ_{sh} the spring stiffness of the closing/opening shaft, $\theta_{\text{sh}} = \theta_{\text{sh}}(0)$ the rotation of the closing/opening shaft, $\theta_{\text{sh},0}$ the closing/opening shaft spring's equilibrium point, γ_{sh} the damping coefficient of the closing/opening shaft, and F_{latch} the latch force acting on the closing/opening shaft. Then, the third equation is given by

$$\frac{dv(t)}{dt} = \begin{cases} F_p(x), & \text{if only plunger} \\ F_{p,l}(x), & \text{if contact to lever} \\ F_{p,l,sh}(x), & \text{if contact to shaft} \end{cases} \quad (3)$$

where the forces in each case are defined by

$$F_p(x) = \frac{1}{m} (-c(v(t)) - k(x - x_0) - mg + F_{\text{el.-mag.}}) \quad (4)$$

$$F_{p,l}(x) = \frac{1}{m + \frac{I_L}{L_L^2}} (-c(v(t)) - k(x - x_0) - mg + F_{\text{el.-mag.}}) \quad (5)$$

$$F_{p,l,sh}(x) = \frac{1}{m + \frac{I_L}{L_L^2} + \frac{I_{\text{sh}}L_b}{L_L L_{\text{sh}}^2}} (-c(v(t)) - k(x - x_0) - mg + F_{\text{el.-mag.}} - \kappa_{\text{sh}}(\theta_{\text{sh}} - \theta_{\text{sh},0}) - \gamma_{\text{sh}}\dot{\theta}_{\text{sh}} - F_{\text{latch}}(\theta_{\text{sh}})) \quad (6)$$

Most quantities are derived from literature, datasheets, and measurements. For the remaining parameters, we generate lookup tables using finite element simulation. This computational step is required only once per coil specification; subsequently, the lookup tables can be accessed directly by the ODE solver, which operates independently. We generate lookup tables for both the coil current and the

electromagnetic force. In contrast, the latch force is obtained through linear interpolation from experimental measurements. The voltage is taken as an input quantity from the live measurement.

Experimental setup

The experimental test setup as given in Figure 3 consists of an electromagnetic coil mounted on a reduced mechanical spring drive mechanism derived from an ABB VD4 MV circuit breaker. A spring-loaded push stick simulates the latching force on the closing shaft. The spring-load is designed to be adjustable to enable tests at different force levels. The coil is powered through a contactor from a variable DC power supply set at 60. The switching operation is initiated via a push button, acting on the contactor.

Both, coil current (via a shunt) and voltage are measured with high resolution voltage probes. The coil position is measured indirectly through the crank lever by a laser displacement sensor.

Additionally, the closing shaft's rotation is measured using a hall effect rotary position sensor. The coil force and adjustable latching force are measured using 500 N strain-gauge force sensors. These sensors, interfaced through signal conditioners, deliver synchronized measurements on a unified time base. All measurement signals are acquired with a high-resolution digital oscilloscope running at 20 MHz. The coil voltage acts as a trigger for initiating a measurement.

Experimental results

Three experiments or test configurations are investigated: (1) The closing shaft is fixed at the de-latching position, (2) closing shaft coupled to trip mechanism, but not loaded by a latching force, and (3) closing shaft coupled to trip mechanism, and loaded by a latching force.

Figure 4 a) presents the test results of the experiment (1). It shows the input voltage, plunger displacement, coil current, and coil force over time. The coil force measured by the sensor represents the reaction force between the coil body and its housing. Upon application of the voltage signal, the coil force increases and then decreases as the plunger reaches its upper position, reflecting the dynamic response during plunger movement. Throughout the experiment, the applied coil voltage remains constant. Once the plunger reaches and is held at the upper position, its displacement stabilizes, and the coil current saturates at a steady value.

Figure 4 b) shows results of Experiment (2). In this experimental configuration, the coil force increases immediately after the voltage signal is applied. Unlike the first configuration, the force does not return to zero when the plunger reaches its upper position. This residual force is due to the engagement of the closing shaft and its torsional spring, which introduces an additional mechanical load on the system.

Figures 4 c) + d) show the results of experiment (3) where the complete mechanical system is engaged. The coil force increases immediately after the voltage signal is applied and then decreases to nearly zero once the plunger reaches its upper position. At this point, the closing shaft is secured by the latch, maintaining its position. In this configuration, the latching forces provided by the spring-loaded push stick are 90 N or 162 N, respectively. We see that for larger latching force there is a more pronounced second maximum in the current wave.

The results demonstrate good agreement with qualitatively expected behavior, now providing quantitative insights into the parameter-dependent dynamics of the coupled system "trip unit + mechanical drive". Foundations can be laid for both design optimization and condition monitoring of the circuit breaker.

Simulation model validation

This section validates our simulation model against experimental results, with primary focus on reproducing the coil current. The coil current waveform is important because literature shows it contains valuable diagnostic information about the tripping coil's health condition, see e.g., [1]. Reproducing this waveform from the ODE solution would enable further analysis, such as anomaly detection and identification of correlations with physical components experiencing degradation or faults. Although detailed health diagnostics are beyond the scope of this paper, we demonstrate that the simulation and experimental results align well.

Three setups were investigated experimentally. In the simulation model, we focus on setups (2) and (3), omitting (1), i.e., we look at

- Setup (2): Free movement, without latching force,
- Setup (3): Full engagement, with complete latching force applied.

For setup (2), we set the latching force F_{latch} to 0 N. This allows the plunger to move freely and rotate the closing shaft without significant impact. Consequently, the resulting current waveform is smooth with a single well-defined peak. Figure 5 shows the measured voltage (in V, divided by 100), the measured current, and the simulated current (in A).

As stated earlier, this simulation model targets condition monitoring of the tripping coil and adjacent mechanics, not the main mechanism. The relevant dynamics appear in the waveform before the characteristic dip. Therefore, we focus on the region marked by the gray box. Within this range, the measured and simulated current waveforms align very well.

For setup (3), a latching force of 90 N was applied. This force acting on the closing shaft becomes visible in the current waveform once contact is established (i.e., third case of the third ODE) as a small minimum preceding the characteristic dip. Figure 6 shows the measured voltage (in V, divided by 100), the measured current, and the simu-

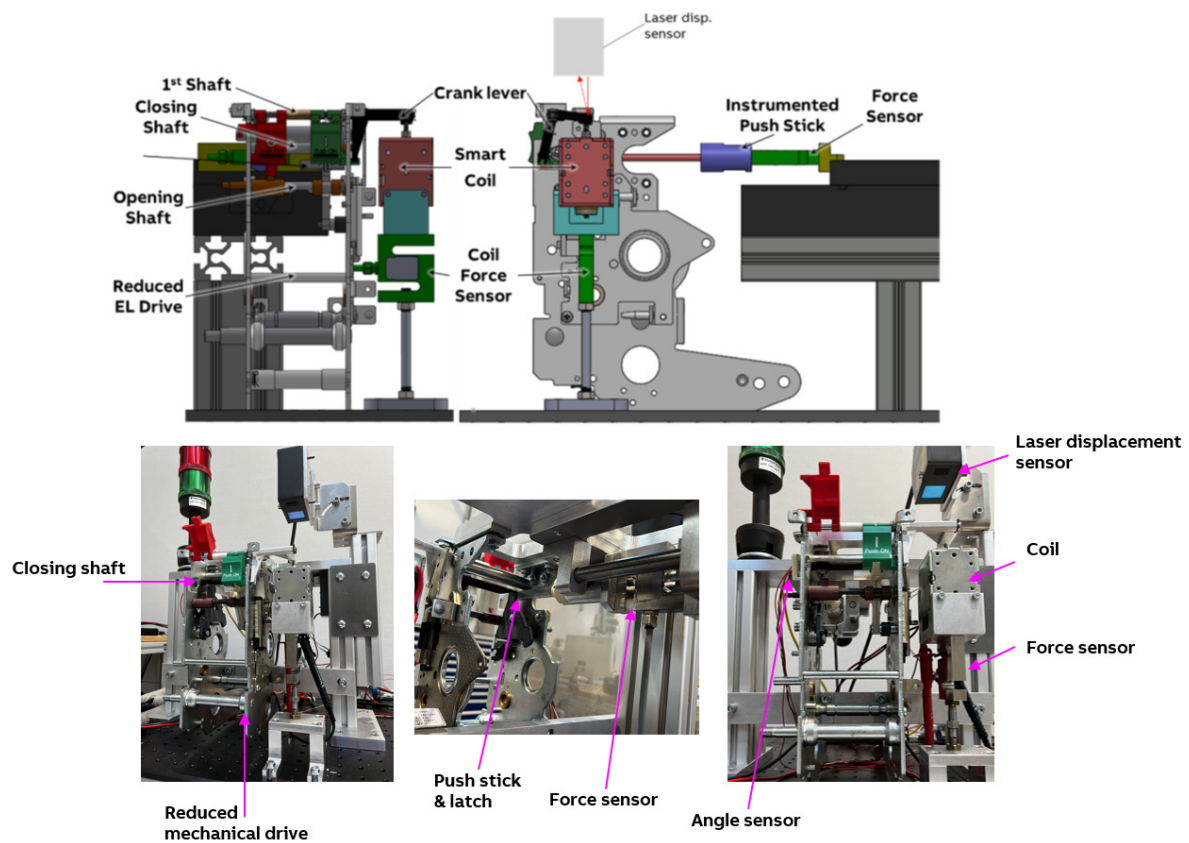


Fig. 3: Drawing and pictures of experimental setup of reduced mechanical drive.

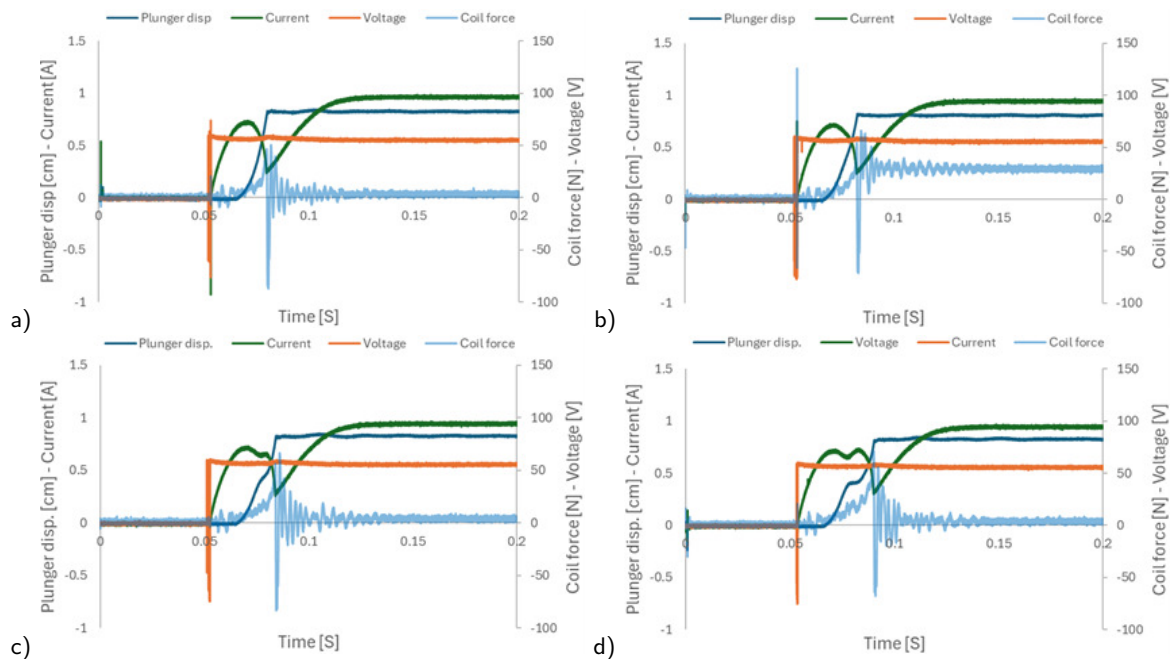


Fig. 4: Measured signals, including coil current and voltage, synchronized with plunger displacement and the coil mounting reaction force.
a) Configuration (1). b) Configuration (2). c) Configuration (3): latching force 90 N. d) Configuration (3): latching force 162 N.

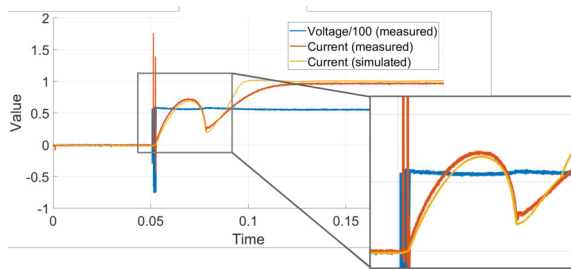


Fig. 5: Simulation model validation for experimental setup (2), i.e., free movement without latching force.

lated current (in A). We again focus on the region marked by the gray box. While the first peak is reproduced very well, deviations appear in the amplitude of the second peak, which correlates with the closing shaft dynamics.

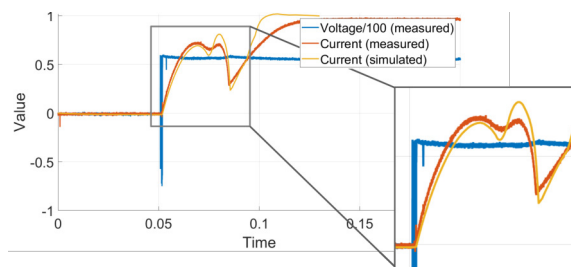


Fig. 6: Simulation model validation for experimental setup (3), i.e., full engagement with complete latching force (90 N) applied.

This discrepancy warrants further investigation; incorporating, e.g., Coulomb friction on the closing shaft may improve the model accuracy. However, for condition monitoring of the tripping coil and adjacent mechanics, the reaction time is critical. We define reaction time as the duration from coil activation until the closing/opening shaft releases the main mechanism, which occurs shortly before the characteristic dip. For condition monitoring purposes, the timing of this dip is the most important parameter. We observe excellent agreement between simulation and experiment in setup (3) regarding this timing. Moreover, the timestamps of both peaks and the intervening minimum also match very well.

This agreement can facilitate more sophisticated condition monitoring approaches that distinguish between coil degradation and closing/opening shaft degradation.

Conclusions

An electromechanical model has been presented, of the tripping coil–mechanical drive interaction in a vacuum interrupter circuit breaker during the closing operation. Modeling has been supported by systematic experimental validation. By coupling the electrical behavior of the coil with the nonlinear dynamics of the mechanical drive and latching mech-

anism, the proposed model captures the full chain of energy conversion from coil energization to shaft rotation and de-latching.

Complementary to that, an experimental setup representative of the actual breaker mechanism was designed to validate the model under well-defined and repeatable conditions. Measurements of coil current, force, and displacement were conducted under three distinct configurations - locked, free movement, and fully latched - allowing the influence of mechanical constraints and latching force to be investigated quantitatively. Across all configurations, the simulated results showed encouraging agreement with experimental observations, confirming the validity of the modeling approach and its capability to accurately describe the system's dynamic behavior.

The results highlight the useful correspondence between electrical excitation and mechanical response, demonstrating that readily available electrical signals, such as coil current, contain valuable information about mechanical state and loading conditions. This finding reinforces the concept of using existing measurements as virtual sensors for condition assessment, thereby reducing the need for additional hardware and costly on-site maintenance. Highly important performance indicators such as the tripping time are predicted very accurately by the model, even if some details of the mechanism dynamics are not yet fully reproduced.

All in all, the developed model and validated experimental methodology provide a robust foundation for design optimization, performance assessment, and condition monitoring of vacuum interrupter circuit breakers.

Next steps include making use of this understanding for parameter estimation and, finally, condition monitoring for trip coil and switchgear as a whole.

Acknowledgment

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