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Soft Sensor Approach to Detect Failures in Circuit Breaker Components

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Summary: A digital twin for circuit breaker monitoring has been developed, focusing on the trip coil and adjacent mechanisms. The twin is based on a fast-to-evaluate system of ordinary differential equations (ODEs). It works as a soft sensor which integrates measurements of observable quantities (e.g. current, force) and parameter identification algorithms. The approach allows to infer the drift of non-measurable quantities such as damping. This gives new options for predictive maintenance and increased reliability of circuit breakers. Calculational results demonstrate the digital twin's effectiveness in real-time monitoring and fault detection.

Keywords: predictive maintenance, soft sensor, circuit breaker, digital twin, optimization

Introduction

Reliability of switchgear systems is crucial for the energy transition, due to increased power demand and decentralized, generation. Frequent switching heightens the risk of failures, safety hazards and operational disruptions. Cost-efficient sensors in grid components are enablers for appropriate maintenance strategies.

Trip coils as circuit breaker components

The trip coils in a circuit breaker initiate the opening or closing operation [1]. If the circuit, e.g., is supposed to be interrupted, the opening coil is energized. The trip coil pin is driven upwards to initiate the kinematic chain ending with the release of the opening spring and the main contact separation. In Fig. 1 we see the interior or a circuit breaker drive with the trip coil highlighted.

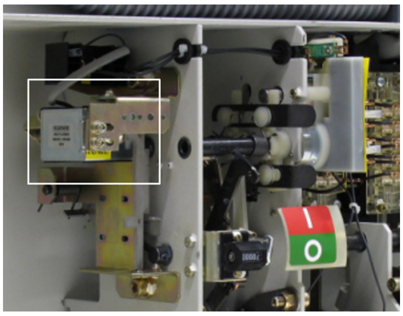

Fig. 1: Interior of a circuit breaker drive.

Physical model of the trip coil

We focus on the digital representation of the trip coil. Our aim is to have a system of ordinary differential equations (ODEs), which can be efficiently solved within the operating circuit breaker. We obtain the following system

$$\frac{d\lambda}{dt} = U - R \cdot i(\lambda, x) \tag{1}$$

$$\frac{dv}{dt} = \frac{1}{m} \cdot F_{\mathrm{coil}}\,, \quad \frac{dx}{dt} = v \tag{2}$$

where λ denotes the flux linkage, U the supply voltage, R the coil resistance, i the current, x, v the trip coil pin's vertical position and speed, and m the pin's mass. Equation (1) describes the electromagnetics of a linear reluctance motor [2]. Equation (2) is Newton's law for the pin dynamics. In F_{coil} all forces acting on the trip coil pin are summarized: The damping force F_{d}, the spring stiffness F_{s}, and the gravity force F_{g} have negative sign and tend to hold the pin at the bottom. The electromagnetic force F_{em} pushes the pin upwards (positive sign). The mechanical forces are defined by

$$F_{\mathrm{d}} = -c(x) \cdot v \tag{3}$$

$$F_{\mathrm{s}} = -k(x)(x - x_0) \tag{4}$$

$$F_{\mathrm{g}} = -m \cdot g \tag{5}$$

with possibly non-linear damping coefficient c and spring stiffness k, and the spring equilibrium point x_0.

Soft sensor use case

This fast-to-evaluate model can be used for soft sensing potential drift of important parameters. With physical sensors, quantities such as i or F_{coil} can be measured in operation, thereby turning the model into a continuously updated digital twin. If a change in these measured quantities is observed, for maintenance reasons it would be useful to determine which model parameters have changed. Relevant degrading parameters include the damping of the pin or the spring stiffness. Possibly degrading parameters are then set as optimization variables (e.g., the damping coefficient c). Then, we minimize the difference (according to a suitable norm $|.|$) between the force $F_{\mathrm{DT}}(c)$ calculated by the twin model as a function of the degrading parameter, and the force measured F_{m}, at a number of points in time, i.e. we solve the optimization problem

$$\min_{c} |F_{\mathrm{DT}}(c) - F_{\mathrm{m}}| \ , \ c \in A \subset \mathbb{R}^n. \qquad (6)$$

The optimal solution gives an estimate how much, in this case, the parameter set $c \in \mathbb{R}^n$ has drifted. In Fig. 2, an illustrative case with $n = 1$, the force F_{m} is plotted vs time in the reference state and after degradation. These curves can be measured in the field, however, in our test both are simulated using the digital twin model (1 - 2). In the reference curve, negligible damping is assumed, i.e., $c_{\mathrm{ref}} = 0$. To simulate a degradation, we set this coefficient to $c_{\mathrm{degr}} = 15$. Solving the optimization problem described above, we obtain the optimal solution $c^{\star}_{\mathrm{degr}} = 15.03$. The deviation between true degradation c_{degr} and the degradation measured with the soft sensor $c^{\star}_{\mathrm{degr}}$ is $0.2\,\%$. This result validates our approach.

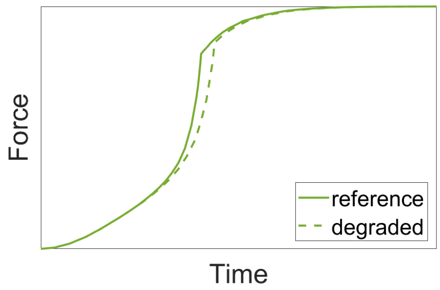

Fig. 2: Schematic representation: Trip coil pin's force vs. time during an opening operation. The degraded state shows a delayed force build-up as compared to the reference.

Digital twin of the mechanical part

Once the trip coil pin is pushed upwards by the electromagnetic force, a kinematic chain is initiated, as illustrated in Fig. 3. The pin hits a lever which is connected with the off (or on) button. This hits the antipumping part, which, after overcoming a clearance, hits the lever of the opening (or closing) shaft. The rotation of the shaft then starts the release of the opening (or closing) spring. Since relevant faults can occur in this mechanical subsystem, it needs to be included into the ODE system (2) in form of additional terms. The detailed formulation is beyond the scope of this paper, but the reasoning is given in (7). We replace F_{coil} in (2) by F_{total}, which is defined by

$$F_{\mathrm{total}} = \qquad (7)$$

$$\begin{cases} F_{\mathrm{coil}}, & \text{if } x < x^{\mathrm{c}} \\ F_{\mathrm{coil}} + F_{\mathrm{lever}}, & \text{if } \frac{L_{\mathrm{L}}}{L_{\mathrm{b}}} x^{\mathrm{c}}_{\mathrm{b}} + x^{\mathrm{c}} > x \geq x^{\mathrm{c}} \\ F_{\mathrm{coil}} + F_{\mathrm{lever}} + F_{\mathrm{shaft}}, & \text{if } x \geq \frac{L_{\mathrm{L}}}{L_{\mathrm{b}}} x^{\mathrm{c}}_{\mathrm{b}} + x^{\mathrm{c}}. \end{cases}$$

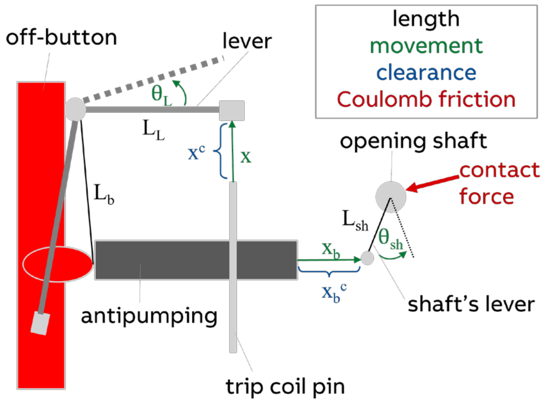

Fig. 3: Illustration of the circuit breaker drive's opening mechanism.

The meaning of the variables in (7) can be taken from Fig. 3. The force F_{total} acting on the coil pin now also includes contributions from lever and shaft. Both terms have negative signs, F_{lever} represents the inertia of the plastic lever, F_{shaft} contains the inertia of the shaft, the stiffness of the shaft's spring, and a damping force. The case distinction is required due to the clearances between pin and lever and between antipumping part and shaft. Hence, in the first case, if $x \leq x^{\mathrm{c}}$, the extended ODE system coincides with (1-2).

Conclusion

We presented an approach to use a digital twin of the trip coil and adjacent mechanisms of a circuit breaker as a soft sensor. It has been shown that degrading parameters can be identified, which are difficult to measure directly.
The twin, therefore, can continuously update its internal parameters according to the status of the real asset. This is an important element allowing predictive maintenance. We have already formulated the equations for the ODE system, including mechanical components behind the coil.
The next step is to integrate this system into the soft sensor to detect degradation in the mechanics of levers and shaft.

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