Magnetic Switch Mechanism for Circuit Breakers

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***Abstract*—Nowadays, motor starter combinations for tool-less plug connection or compact starters are used to ensure safe operation of electric motors in industrial applications. According to requirements these types of devices have separate actuators for driving the main contacts for motor protection and operational switching. In our study, we present a new magnetic actuator for frequent normal switching, fast circuit breaking and resetting after tripping as well. The actuator has been designed using simulation models for system design and design optimization in form of coupled multi-domain network models of the actuator system and finite element models of the magnetic circuit. Prototype actuators were designed, assembled and experimentally characterized.**

***Keywords*—switchgear, circuit breaker, polarized magnetic actuator, network models, system design,**

I. Introduction

Motor starter combinations or compact starters for low-voltage applications are of major importance in industrial automation and are continually developed further. Higher nominal current per volume, lower power consumption, additional functionality like wider setting ranges or fully electrical controllability and a same or better performance are the challenges for new innovative product generations to be achieved by a cost efficient design in short development time.

A. Motor Starter Arrangements

Conventional motor starter combinations consisting of a separate contactor and a separate circuit breaker have two main contact systems in series driven by a particular actuator each (Fig. 1.a). A magnetic actuator drives the contactor and a mechanical switch locks the circuit breaker. The magnetic actuator is controlled by the external control voltage whereas the switch lock is tripped by internal overload and short tripping units. Normally, manual resetting is necessary after an overload or short circuit break directly on the device.

Recent compact starters have also such two actuators inside but they act in parallel on only one contact system (Fig. 1.b). This leads to a more compact design, a reduced wiring effort as well as less thermal losses and less required material compared with motor starter combinations. Like standard motor starter combinations, compact starters need two different actuators to achieve fully electrical functionality up to now. Even a third actuator is required to transduce the detected short-circuit to the mechanical lock when a fully electronic tripping system is used.

The next logical step in advancing this switchgear is the use of only one actuator interacting with one contact system and the electronic control unit. In our study, we present a new magnetic switch mechanism for that purpose.

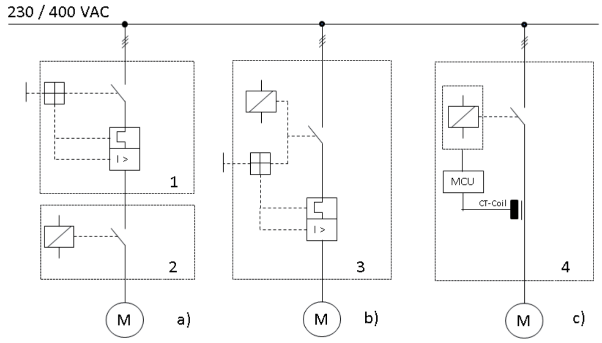

Fig. 1. Principles of motor control: (a) Standard setup with circuit breaker 1 for protection and contactor 2 for control; (b) Compact starter 3; (c) Fully electrically controlled compact starter 4 with new magnetic actuator and microcontroller (MCU)

This actuator offers the additional functionality of fully electrical controllability even after tripping. In combination with a current transformer (CT-Coil) and a microcontroller (MCU) it enables a new class of fully electrically controlled switchgear (Fig. 1.c). The pre-development process of these actuator was realized for a standard contact system with nominal currents up to 32 A (approx. 15 kW / 400 V). DIN EN 60947-4-1 defines the system requirements for these devices [1].

B. Design Requirements of the Operating Modes

The merged functionality of a circuit breaker and a contactor requires an actuator which enables the operating modes according to TABLE I. A rather different dynamic behaviour is necessary between the closing and opening of the contact system in case of normal operation mode (like a contactor) and the fast contact opening in case of short-circuit. In connection with the static forces and permissible power losses, these dynamics are the major challenge in the actuator design.

The rough actuator design parameters have been derived from the properties of the known standard contact systems, which are technically mature for its device class. Contact force and stroke, spring rates and moving mass

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determine the static working point and the inertia of the mechanical system. The optimum contact velocities are known from life time tests.

TABLE I. REQUIREMENTS OF FUNCTIONALITY

Values	*Specification*
Contactor mode	
Time to CLOSE / OPEN the contacts	< 30 ms
Velocity for CLOSE contacts	0,5 m/s …0,75 m/s
Overload protection mode	
Time to OPEN contacts	< 30 ms
Circuit Breaker mode	
Short circuit break time (incl. detection, contact opening and arcing)	< 5 ms
Velocity for OPEN contacts	2 m/s … 5 m/s
After short circuit break	Resetting and CLOSE contacts like contactor
Fail Safe	
After elimination of supply voltage	OPEN contacts by self-actuating
General	
Contact Forces	Accord. 3-phase system, 32 A
Holding Power	0,5 W … 1 W
Shock Resistance	20 g
Range of Temperature	-20°C … 70°C
Life Time	> 100.000 cycles

Compared to other actuation principles, e.g. electrodynamic [2] or solid state actuators, the electromagnetic principle has the best overall properties concerning force, stroke and velocity and the highest design flexibility to adapt the design on the specific requirements.

II. WORKING PRINCIPLE OF THE MAGNETIC ACTUATOR

The developed magnetic actuator is a polarized type having coils and permanent magnets as well. This kind of actuators is of high volumetric energy compared to unipolar solenoids. It is particularly suitable for applications with short switching times or high forces despite of limited installation space [3]. Polarized magnetic actuators can be designed for bistable and monostable behaviour by type of structure [4].

Appropriate to [5], we have applied a parallel acting magnetic structure, consisting of two coils, two working air gaps and fixed permanent magnets. Design variants with moving magnets or magnets arranged directly in the force flux are discarded due to the high mechanical impact loads. Fig. 2 illustrates the principle actuator design in interaction with the contact system of the compact starter.

In normal power-off or fail safe mode, the contacts have to be in open position. In this case, the forces by the compression spring (1) and the permanent magnets (3) push the armature (7) against the contact system (5).

Coil-A (2) provides for the contactor functionality (contact closing). If it is powered by the control voltage, the contacts will CLOSE. Switching off the control voltage opens the contacts again. Something similar happens in case of overload detection. The control voltage then will be internally switched off by the MCU.

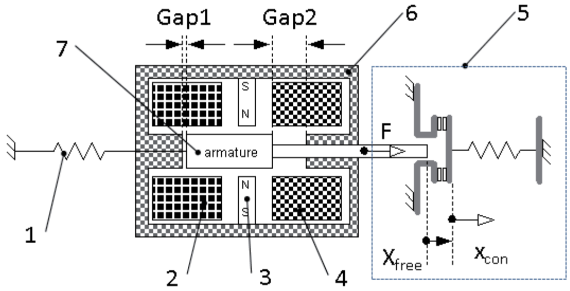

Fig. 2. Principle actuator design: 1 spring, 2 coil-A, 3 permanent magnet, 4 coil-B, 5 contact system with contact spring, 6 yoke, 7 armature

In case of a short-circuit requiring a fast opening of the contacts, the coil-B (4) is additionally fed and accelerates the armature. Furthermore the mechanical momentum of the armature and the plunger is exploited to open the contacts by impact. This impact should be designed to have low dissipation. In practice certain losses will occur by the endless stiffness of the parts, the hardness of their surfaces and friction effects as well.

III. MODEL DESCRIPTION

A. *Modeling of the Actuator*

The design of magnetic actuators is an iterative process which requires descriptions and methods of calculation at different levels of detail [6]. In order to simulate the whole actuator dynamics, models are required which are able to calculate the transient behaviour of the different subsystems and physical domains as well, namely the electrical circuitry, the magnetic circuit and all mechanical loads and elements. Therefore two different models have been developed and used:

- a multi-domain lumped element network model in order to simulate the whole system dynamics and
- a static finite element models of the magnetic circuit in order to compute flux linkage and magnetic force.

The dynamic network model applies the results of the static magnetic model in form of look-up tables [7, 8]. This coupling has a lot of the advantages, especially the low computational effort compared to a transient finite element model which involves the actuation by a comparatively high precision of the calculated fluxes and magnetic forces. In turn, the low computational effort allows a further coupling of the network model to optimization tools for numerical design optimization purposes. In our work, we applied the software tools SIMULATIONX [9] for the network model, FEMM [10] for 2D- and ANSYS [11] for 3D magnetic force calculations and OPTIY [12] as optimization tool.

B. *Static Magnetic Finite Element Models*

2D and 3D static magnetic models have been used to calculate the look-up tables necessary for the simulation of the system dynamics with network models. Depending on design and material parameters, including the geometry of the magnetic flux path, air gaps, coil winding section and permanent magnets, nonlinear material characteristics, the characteristic maps of the actuator force F, and the flux linkages of both coils $\Psi_{coil\text{-}A/coil\text{-}B}$ have been computed for numerous combinations of the coil currents i_1 and i_2, and armature positions x:

$$F = f(i_{coil-A}, i_{coil-B}, x), \quad (1)$$

$$\Psi_{coil-A} = f(i_{coil-A}, i_{coil-B}, x), \quad (2)$$

$$\Psi_{coil-B} = f(i_{coil-A}, i_{coil-B}, x). \quad (3)$$

Fig. 3 shows the calculated actuator force $F(x)$ for 2D- and 3D-FEM for an exemplary design compared to measurements.

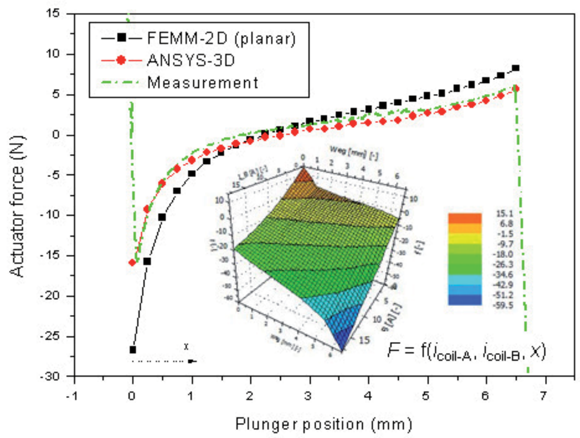

Fig. 3. Static actuator force F(x) for 2D- (square) and 3D-FEM (circle) compared to measurement (dashed) for Rev.1 (i_1 = 0 A, i_2 = 0 A)

Of further interest are the magnetic cross section loads of the iron parts. Ideally, the material should remain below saturation in all operation modes. Fig. 4 shows critical sectors of flux density (B_{max}) for the contactor (a) and circuit breaker (b) functionality.

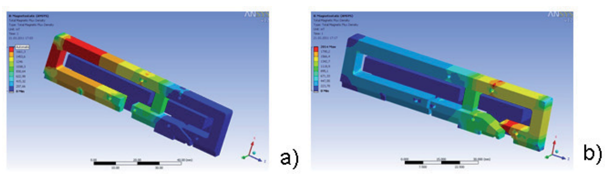

Fig. 4. Flux density for Rev.1: (a) – contactor with 2500 ampere turns and B_{max} = 1,7 Tesla, (b) – circuit breaker with 2200 ampere turns and B_{max} = 2,0 Tesla

Although the results of the 3D-FEM are more accurate than those from 2D models, they cannot be used for optimization purposes because of the huge computation time for the calculation of the look-up tables (about 6500 minutes for one design). In contrast, the 2D model needs just 20 minutes using a standard desktop PC. Therefore only the 2D models have been applied for design optimization.

C. *Multidomain Network System Model*

The network model couples multiple physics domains and simulates the system dynamics. It is implemented in SIMULATIONX. The model includes lumped elements for moving masses, springs, dampers and further components. Fluxes and magnetic forces are modelled by the above mentioned look-up tables. The components of the electrical circuitry are described by common electric network elements. Furthermore the model contains a logical control of all time and system states. In contrast to reluctance forces, electrodynamics Lorentz and Holm-forces are neglected, because of their little influence on the system behaviour up to medium short circuits.

Mainly, the network model solves for the equation of motion for each mechanical component balancing the inertia, magnetic and elastic forces. Exemplarily it is given for a contact using the look-up table of the magnetic force:

$$m_c \cdot \ddot{x} = F(i_{coil-A}, i_{coil-B}, x) - F_{load}(x) \quad (4)$$

with m_c – mass of movable contact and F_{load} – force of contact system.

The induced coil voltages $U_{coil\text{-}A/coil\text{-}B}$ are derived from the look-up tables of the flux linkages. They couple back to the electrical network:

$$U_{coil-A/coil-B} = \frac{d\Psi_{coil-A/coil-B}(i_{coil-A}, i_{coil-B}, x)}{dt} \quad (5)$$

Fig. 5 depicts the structure of the network system model with its electrical, magnetic and mechanical domain.

The network model allows for the dynamic simulation of all operating modes and functionalities:

- Short circuit tripping - contacts OPEN,
- Contactor ON - contacts CLOSE,
- Contactor OFF - contacts OPEN,
- Fails safe - contacts OPEN.

D. *Numerical Design Optimization*

We applied the OPTIY software to perform the design optimization process.

In a first step, a sensitivity analysis was performed to analyse the influence of several design parameters. The four design parameters which have most influence on the system dynamics have been used as variables in the design optimization for the objective of maximum contact opening velocity in the fast switch off operating mode. The optimum design is characterized by specific values of the idle stroke X_{free}, the number of turns of the coil-A (contactor) and coil-B (circuit breaker) and the tension of the spring 1.

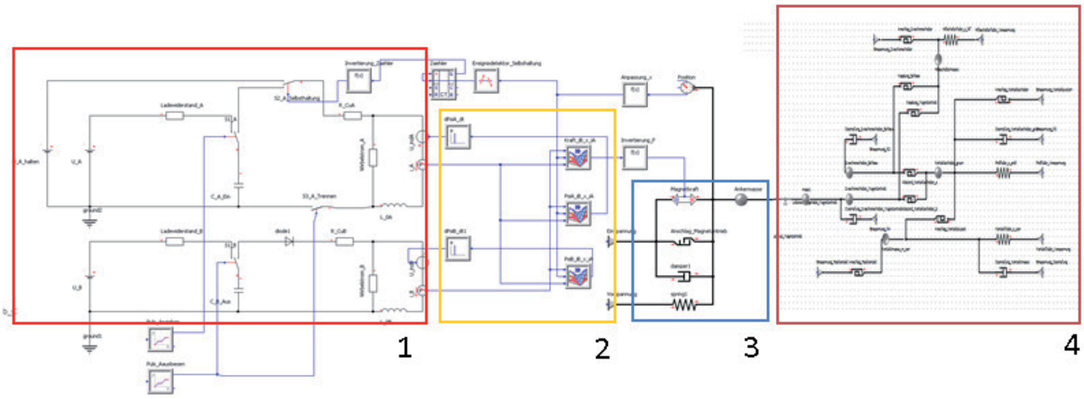

Fig. 5. System Network Model: 1 Ideal circuit, 2 look-up tables from finite element model, 3 armature and plunger of actuator with spring and damper, 4 contact system

IV. Functional System Demonstrator

A. Design Engineering of Functional Samples

Three revisions of functional samples (Rev.1 - 3) were model-based developed with different research goals:

- Rev.1 evidence of principal functionality, analysis of static force level, eddy currents and system stiffness,
- Rev.2 optimization of friction and overall size, analysis of different magnetic influences,
- Rev.3 improving of short circuit break time, reducing of power consumption and analysis of the temperature influence.

The simulation models have been adapted and simplified in each case to the specific research goals. However, the general workflow with coupling the dynamic network and the static magnetic model in form of look-up tables was maintained for all three revisions. For example, the network model of Rev.1 contains only spring and stop elements in the mechanical and signal blocks in the electrical domain. In contrast, the Rev. 2 Model was substantially extended by shock absorbers in the mechanical and idealized electrical switches in the electrical domain. Moreover, it was coupled to the optimization tool. The model of Rev.3 additionally contains the major circuit components in form of ideal electronic and thermal elements.

The different functional samples of these revisions are shown in Fig. 6. The fundamental design structure of these three samples is similar. Fig. 7 show details of Rev.2.

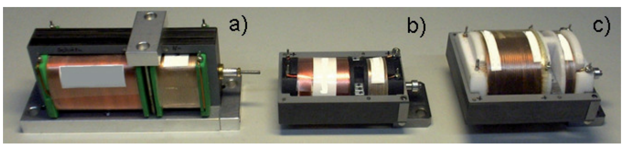

Fig. 6. Functional samples: (a) Rev.1, (b) Rev.2, (c) Rev.3

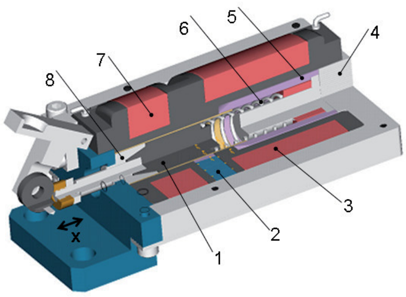

Fig. 7. Functional sample Rev.2: 1 armature in a bearing of brass, 2 permanent-magnets, 3 contactor coil-A, 4 yoke (laminated magnetic steel), 5 pole piece of coil-A, 6 actuator spring1, 7 circuit breaker coil-B, 8 pole piece of coil-B

The contacts are normally open by static force balancing. For closing them, coil-A is fed by the full control voltage. After a specific time, when the contacts are definitely CLOSED, coil-A is further driven by pulse width modulation (PWM) for reduced power loss. For contact operation OPEN the PWM is switched off. This is also the case for the fast contact opening operation. For the circuit breaker functionality coil-B is fed by power supply and provides additional reluctance forces to accelerate the armature. In order to achieve a fast opening of the contacts, the coil-B works together with the switching off coil-A controlled by MCU.

Some issues have to be considered to achieve outstanding dynamics. Brass bearings have been used to reduce friction on the armature. The magnetic energy stored in coil-A counteracts a fast acceleration of the armature due to reluctance forces. Therefore, its fast degradation after switching of coil-A is necessary. In addition, switch-off voltage peaks must be limited. For that purpose, several circuitries are known [6]. Fig. 8 schematically shows the circuit for coil-A and coil-B.

A switchable Zener diode controlled by an MCU and in series to a normal diode gives the best damping and discharging performance of the contactor coil. This circuitry has the advantage of low power consumption and fast tripping time compared to other circuitry concepts. A small duty cycle (DC) of PWM is sufficient for retaining the contacts closed.

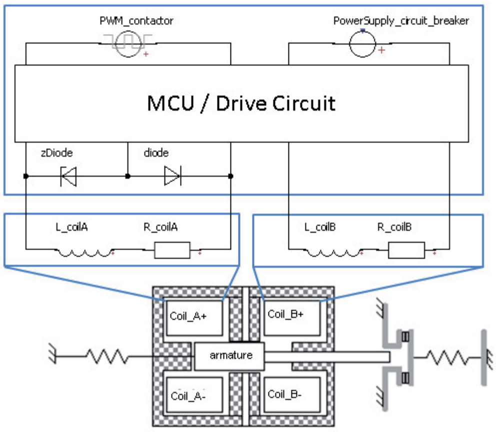

Fig. 8. Simplified electrical circuit controlled by MCU for the contactor coil-A and the circuit breaker coil-B (coil-A driven by pulse width modulation, coil-B driven by power supply)

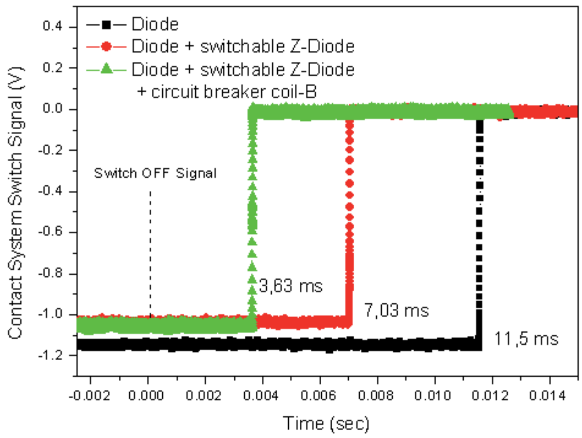

Fig. 9. Contact OPEN time for different electrical discharge concepts at Rev.2: *Diode* (square), Diode + switchable Z-diode (circle) and circuit breaker tripping (triangle)

TABLE II. KEY PERFORMANCE PARAMETER OF FUNCTIONAL SAMPLES

	Rev.1	***Rev.2***	***Rev.3***
Armature Characteristics			
Cross section design	Square	Cylindrical	Cylindrical
Electrical Actuation Drive Concept			
Contactor coil-A	Power Supply	PWM, 10kHz	PWM, 20kHz
Circuit Breaker coil-B	Power Supply	Power Supply	Power Supply
Fast discharge concept of coil-A	None, voltage peak accept	Zener diode	Switchable Zener diode
Switching Results (Time and Velocity)			
Contactor CLOSE	13,8 ms 1 m/s	21,5 ms 1,2 m/s	26,2 ms 0,8 m/s
Contactor OPEN	15 ms 1,5 m/s	7,1 ms 1,0 m/s	27,1 ms 0,6 m/s
Circuit breaker OPEN	2,8 ms 2,5 m/s	3,6 ms 1,7 m/s	2,45 ms 1,7 m/s
Overall Size			
Length x Width x Height	99,2 cm³	72 cm³	148 cm³

Fig. 9 illustrates the time differences from switch OFF signal until to OPEN contacts for the two discharge concepts in case of circuit breaker tripping for Rev.2. TABLE II. compares key performance parameters of the different functional samples.

B. *Experimental Verification*

The contact system of a Siemens 32 Amps compact starter from the shelf was used to test the functional samples. The functionality was tested successfully for all of them. Fig. 10 illustrates the experimental setup.

The displacement of the contact bridge was measured by a laser triangulator (*KEYENCE LK-G32*). The displacement signal allows to calculating the velocity of the contacts with sufficient accuracy. The displacement signal was recorded together with the electrical switching signals by an oscilloscope (*Lecroy Wave Surfer 400 MHz, 2,5 GS/s*).

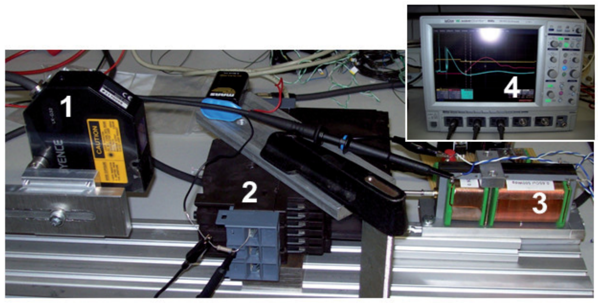

Fig. 10. Experimental Setup with Rev.1: (1) Laser triangulator, (2) contact system, (3) magnetic switch mechanism Rev.1, (4) oscilloscope

The dynamic system behaviour was analysed in all operation modes. Fig. 11 shows the result for short-circuit tripping of Rev.3 which is the best compared to the other revisions. The contacts open when the motion of contacts starts. The circuit breaker coil-B was activated by power supply and the induction voltage peak of coil-A was limited by a switchable Zener-Diode.

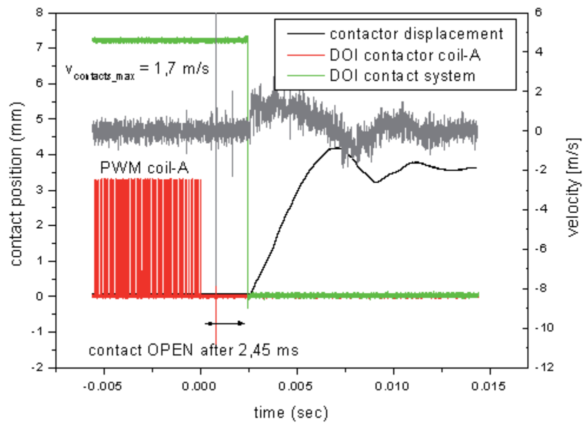

Fig. 11. Final experimental result of dynamic behaviour of Rev.3 at short circuit tripping – contact OPEN after 2,45 ms with a velocity of 1,7 m/s

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The static actuator and the dynamic system models were verified by measurements. As an example, Fig. 12 compares the simulation and measurement results for different operation modes performed on Rev. 3.

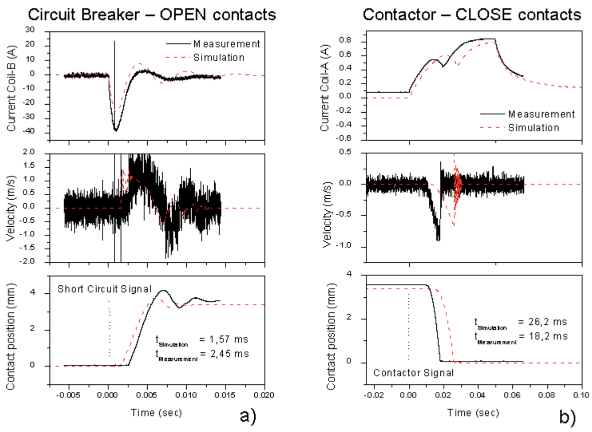

Fig. 12. Measurement results (contact position, velocity, current) compared to simulation using the example Rev.3: a) Contacts OPEN after short circuit signal, b) Contacts CLOSE as generally contactor functionality

In principle, the network system model in SIMULATIONX covers the dynamic behaviour very well. Differences between simulation results and measurements are mainly caused by inevitable idealizations in the model, especially for the mechanical components which are mostly assumed to be stiff. The deviations can be minimized by setting selected element parameters.

V. SUMMERY

In our study we have designed a new magnetic switch mechanism for a new class of fully electrically controlled compact starters. The bi-stable magnetic actuator fulfils all requirements concerning short-circuit tripping and contactor closing. The dynamics at short-circuit trip is comparable to that of a mechanical switch-lock. The electronic trip unit can work together with the main actuator directly. The actuator achieves mono-stable fail safe behaviour in interaction with the contact system and other mechanical components.

It must be pointed out that the actuator design was optimized for only one specific contact system of such a compact starter. Other variants, especially other contact forces or mechanical systems can influence the magnetic design considerably.

In general, this feasibility study has shown, that polarized magnetic circuits are suitable for fast-switching actuators and offer a high potential for further dynamic applications with asymmetric motion behaviour. The high complexity of the actuator, but also the all-inclusive design consideration requires a model based development and the use of quite complex system simulation tools too. The practical usability of such a simulation based approach was also demonstrated.

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