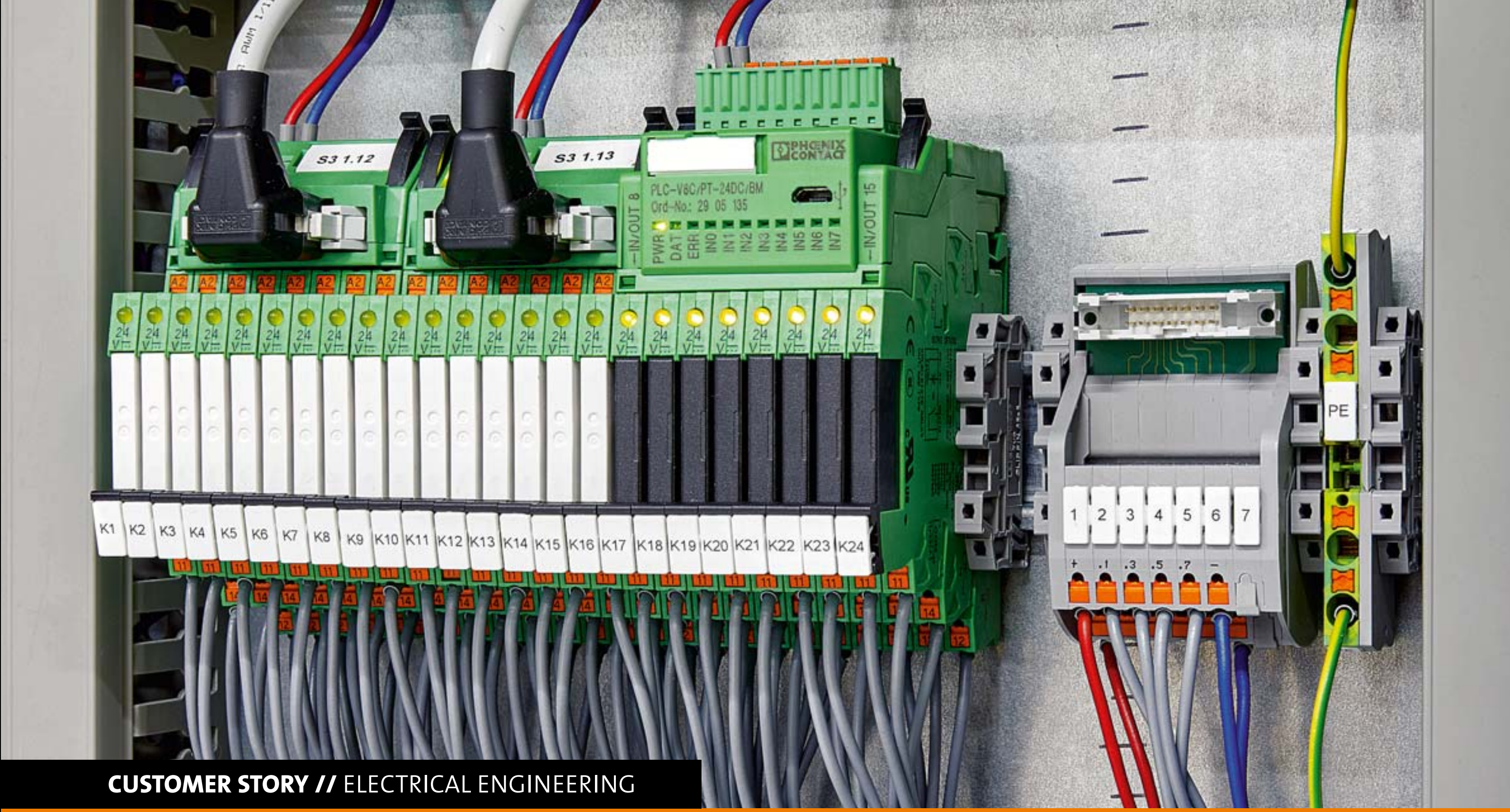


METAMODELS IN A CYBER-PHYSICAL SYSTEM

In order to determine the remaining lifetime of safety relays, simulation models of the whole system are combined with the real data of an operating elementary relay in a cyber-physical system. Phoenix Contact Electronics GmbH applies optiSLang for parameter identification by means of metamodels used as Functional Mockup Units (FMUs).

Introduction

Safety relays are applied in many fields and industrial environments, including:

- Two-hand control
- Emergency stop
- Control of safety doors

Essential components of many safety relays are forcibly guided contacts according to EN 61810. The operational characteristics of these components enable the analysis of failure evolution. For example, the relay failed due to abrasion of the load contacts caused by its operating function. Such a malfunction would not basically lead to immediate hazardous situations because of redundant arrangements and other internal safety functions. However, the system is switched off and no longer available. If the failure occurs unexpectedly, subsequent disconnections can lead to further malfunctions. The failure of a single component, e.g., in a chained automated process, could interrupt the entire production line. Furthermore, a failure might result in compensation costs for contractually guaranteed services, e.g., in the operation of wind turbines. It is therefore advisable to detect and track the possibility of an impending failure as accurately as possible for on time replacement of worn components within planned maintenance and operating cycles.

The characteristics of a relay in a switchgear can be described by means of system simulation. The involved physical domains of mechanics, electromagnetics and temperature are considered by using the Finite Element Method (FEM). The derived models of reduced order are transferred into the system simulation in order to be coupled on the system level.

The behavior of the firmware (software) of the switchgear is considered on the system level using a Functional Mockup Unit (FMU). The empirical models, e.g., contact resistance or arc voltage, are displayed in function blocks using the programming language VHDL-AMS. Until now, it has been problematic to integrate the wear behavior of the operating electrical contacts of the relay because an accurate knowledge about load and environmental conditions is often not available. Thus, the prognosis of the system's durability has to be based on statistical test data considering the most critical load and environmental scenarios. This results in a very conservative lifetime estimation. Another problem is the measurement of the mechanical characteristic values of the operating relay inside the device. These are usually measured on open and freely accessible relays, although, in operation, the relay is encapsulated. These two issues of existing system simulation models need to be considered for an accurate tracking of the lifetime during operation.

In a cyber-physical system, the relay is coupled with a simulation model for data exchange. Based on this data, the device is then analyzed using a simulation model. The results of this analysis are used in the cyber-physical system to predict and track product conditions.

Terms and Definitions of a cyber-physical system

A cyber-physical system is a network of informatic and mechatronic parts connected via data infrastructure (VDI 2013). In the reference architecture industry 4.0 (RAMI 4.0), cyber-physical systems are defined as follows (BMWI 2016, IEC 62890): implementation of a (standardized) communication and system infrastructure with required management and productive services as well as with defined QoS (Quality of Service) properties as the basis for an efficient setup and integration of I4.0 systems in an application domain. Therefore, cyber-physical systems are applicable in all areas of the value chain, e.g., marketing, product development, testing, production, sales, customer support, operation, predictive maintenance or return management. For example, a typical application is within a “smart grid”, i.e., systems of power generation are coupled via IT networks for functional optimization. Another example is the communication via “CartoX”, i.e., between a network of vehicles as well as central systems, such as manufacturers or transport infrastructure (VDI 2013). The cyber-physical system in this presentation deals with the coupling of measurements of product operation conditions and lifetime estimation for predictive maintenance and optimal operation.

Objectives, Methodology

The aim of the present study is to determine the contact lifetime of the relay NSR01 from Phoenix Contact Electronics GmbH. The analysis is conducted by using a simulation model of a safety relay. The resulting information is provided to the customer and allows the prognosis of malfunctions.

The implementation is achieved by linking a simulation model of the switchgear with the real operating relay by means of a data interface. For this purpose, a simulation model of the entire connector is created. A data interface serves as a connection for transmitting the measured characteristic values to the simulation model. The model is typically derived from simulation models generated during the development of the relay. The software Simplorer (Electronics) from ANSYS Inc. is used for generating the system simulation model. Since the transient coupling of FEM models is very complex causing a high amount of computation time, such real-time system models coupled to a device are not practical. Therefore, the simulation model considers various physical domains represented by individually derived reduced order models, which are coupled on the system level. In addition, characteristics, e.g., contact resistance or arc voltage, are included by experimentally determined empirical correlations.

The electrical lifetime of the relays is determined under laboratory conditions for different load ranges as a function of the relay parameters and other environmental conditions, e.g., temperature, operating voltage or installation. Based on the measurements, Metamodels of Optimal Prognosis (MOP) are generated using Dynardo’s optiSLang. They represent the contact life in the simulation model regarding the respective load areas. The mechanical parameters of the relay in the switchgear are determined by measuring the magnetic field and the coil current. Again, MOPs are generated to calculate the mechanical parameter based on magnetic field measurements. The results, together with other measured parameters, are used to predict the remaining lifetime of the relay (Fig. 1).

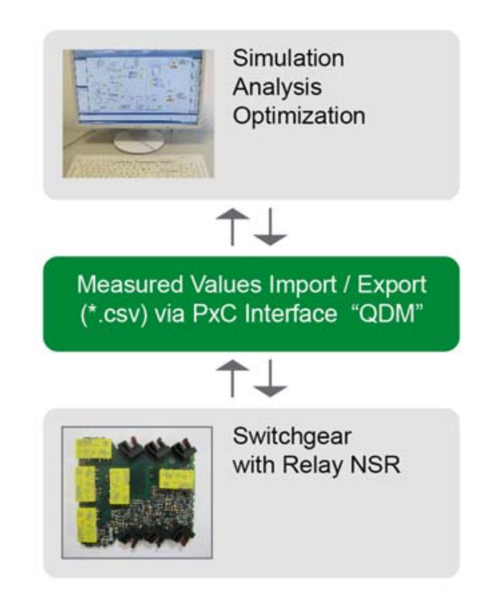


Fig. 1: Linking a simulation model to an operating relay NSR

Relay corresponding physical domains and simulation methods

Mechanics

The mechanical parameters (Fig. 2) are simulated using FEM (ANSYS). The motion ratios as well as force and stress conditions can thus be determined for the various mechanical components of a relay, e.g., contact springs, anchor bearing springs, holding springs, return springs, or transmission elements. This is achieved by using static and transient (time-dependent) simulation. The transfer of the motion ratios (displacement-time) into a reduced order model is implemented by transforming the eigenfrequency modes of the points (nodes) in a matrix (space state matrices) and the following export via spm file. Here, only linear correlations can be transformed and transferred. For modeling the complex mechanical system of a relay, it is divided into individual linear parts, which become connected with corresponding coupling elements on the system level.

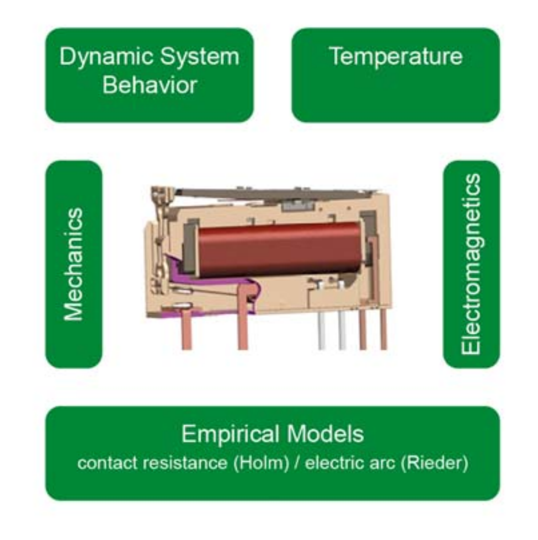


Fig. 2: Physical domains of a relay

Electromagnetics

The simulation of the electromagnetics (Fig. 2) is also conducted by using FEM. The coupling of the complex FEM models can be dispensed if parasitic effects, e.g., eddy currents or iron losses, play only a subordinate role. This is the case if small electromechanical relays are regarded. Instead of coupling the FEM models by co-simulation, the generalized forces from the coupling of the magnetic co-energy and the interlinked flows are simulated using the FEM simulation of the magnetic systems. In this case, the torques and loads of the system are considered in a characteristic diagram including various working points, e.g., rotation angle, stroke or electrical excitation using the dissipation of the magnetic co-energy via angle and stroke. In this characteristic diagram (ECE model), the transmission behavior of the magnetic system is interpolated between the operating points. By linking the magnetic co-energy with the mechanical part by using linked flux, the mechanical feedback effects in regard to the magnetic-electric system are also taken into account.

Temperature

The thermal correlations in the relay can be represented by analytical formulas in combination with measured values. At the system level, thermal correlations are modeled by using numerical blocks.

Dynamics / System Behavior

The dynamics of the relay are considered in the simulation model by transient coupling of the individual subsystems, e.g., mechanical, magnetic or thermal subsystems.

Contact Resistance, Electric Arc

For some characteristic values of relays, e.g., contact resistance of the operating contact or electric arc of the opening contact, empirically determined formulas (Holm, Rieder) are used (Fig. 2). This allows the derivation of electrical characteristics, e.g., current, voltage, of the load circuit as a function of current mechanical values.

Contact resistance according to Holm

$$Rk = 280r\sqrt{E/(Fk - r)} \tag{1}$$

Arc voltage according to Rieder

$$U = s^{1/1.57} * 0.00385^{-1/1.57} * I^{-0.49/1.57} + U_M \tag{2}$$

Contact Lifetime

Normally, for the determination of contact lifetime, characteristic values measured during continuous tests at proper facilities are considered. Here, the failure behavior is determined from a number of tested relays with scattering characteristics and corresponding to the expected basic population of the relays. Usually, a characteristic value of the service life is chosen which represents ten percent failure among the tested relays under these particular conditions (B10 –value), see Fig. 3.

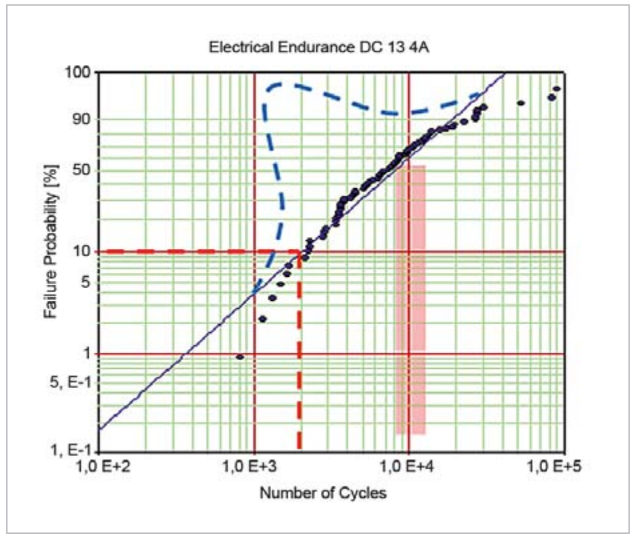


Fig. 3: Contact life of operating contacts – Weibull Diagram

However, the statistical uncertainty in estimating lifetime of a certain relay is a disadvantage of this method. In addition, replacing the relay at 10 percent failure probability is very conservative. Therefore, a more accurate estimation of contact lifetime can be achieved by using metamodels (MOPs) based on test results. This includes the measurements of the most important electrical and mechanical relay values under laboratory conditions depending on the relay parameters as well as on the load and environmental conditions (Fig.4).

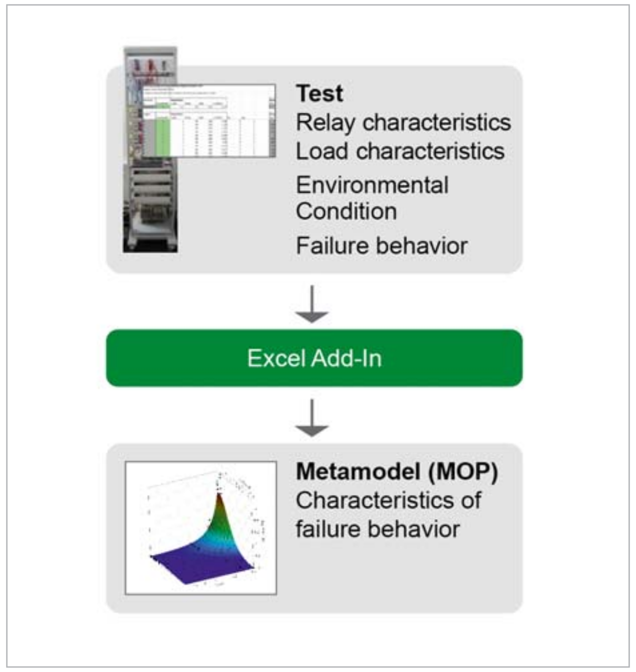


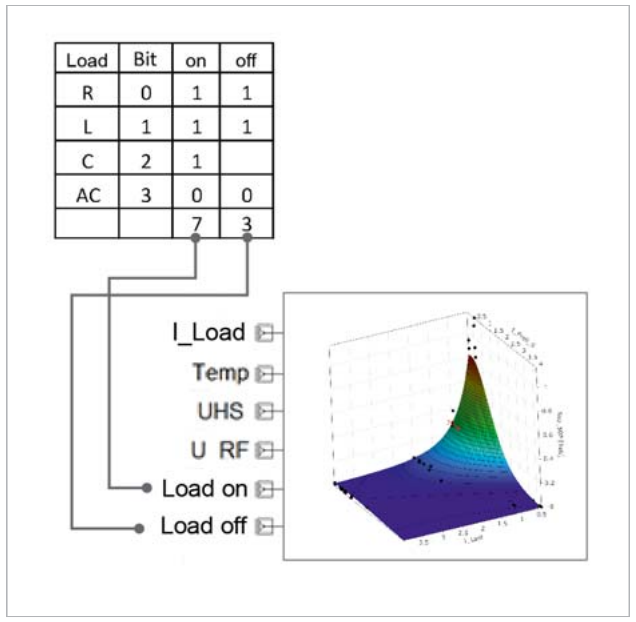
Fig 4: Consideration of experimentally measured contact lifetime parameter using metamodels (characteristics)

These metamodels are used as an FMU in the system simulation model. Since the contact lifetime varies in behavior and dependencies regarding different load types, e.g., ohmic, inductive, capacitive, direct current and alternating voltage, as well as for different load ranges, e.g., small/large current/voltage, the currently valid load range and load type has to be identified and scanned by experiments. This identification is required during the switching on and off operation. The relevant characteristics can thus be selected and activated based on the load profile.

The load identification (Fig. 5) is carried out by transforming the measured signals. Here, on the one hand, capacitive loads, e.g., current peak when activated, are modeled, e.g., by fourier transformations. On the other hand, inductive loads, e.g., slow current rise while activating, are identified, e.g., by Laplace transformations. As an advantage of this method, no signals but transformation coefficients have to be used for the classification of characteristics. This leads to a considerable reduction of calculation effort.

Mechanical Characteristics

The mechanical characteristic values of relays are typically measured under laboratory conditions on open devices (Fig. 6). Because of the harsh operational conditions, relays are usually encapsulated. This has to be considered when calculating the mechanical in regard to the magnetic field.



Load	Bit	on	off
R	0	1	1
L	1	1	1
C	2	1	
AC	3	0	0
		7	3

Fig 5: Load types and load area classification

Fig 6: Measurement of mechanical characteristics under laboratory conditions on an open relay

The solution approach has to consider whether the magnetic field, generated by the magnetic circuit, and the anchor position show a correlation. Also a reversed dependence on the measured magnetic field regarding the determination of the position and the rotation angle of the anchor should be observed. The evaluation of the simulation results regarding the magnetic system indicates positions near the relay with a strongly changed magnetic field depending on the anchor position (Fig. 7).

The simulation results of the magnetic flux density B (x, y, z-direction) as a function of different anchor positions (angle of rotation) and coil excitations are converted via Excel interface in optiSLang's binary database. Strong input correlations were found between the excitation current of the coil and the flux densities Bx1 and Bz1(Fig. 8).

The reduction of the strongly correlated input parameters finally results in an MOP with very high prognosis quality regarding the variation of flux densities (Coefficient of Prognosis - CoP of 99 percent). In order to solve the task, the inversion to mechanical parameters needs to produce unique results. Fig. 9 shows the input MOP and Fig. 10 (see next page) the inverted MOP.

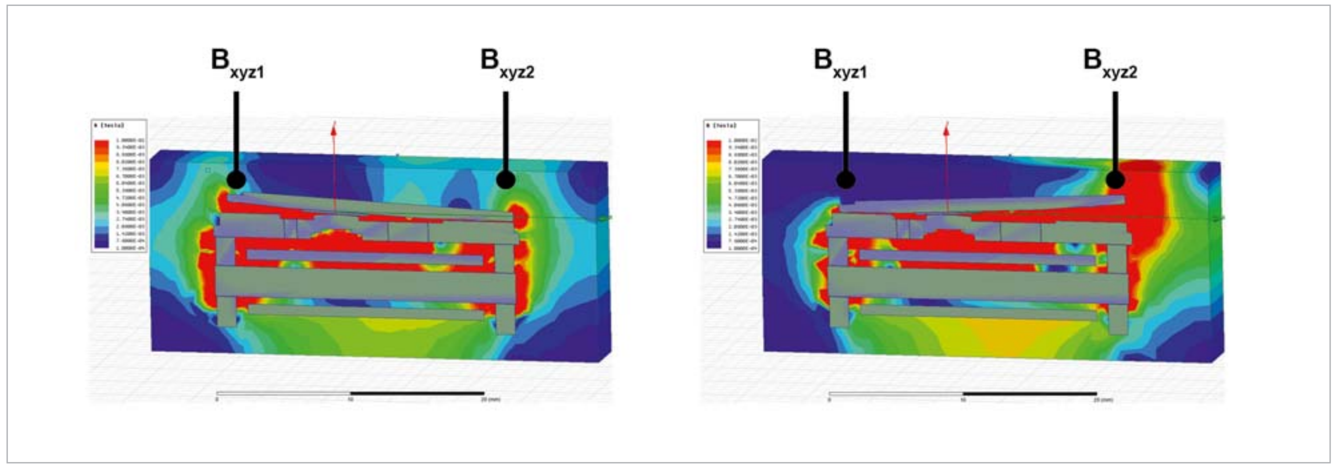


Fig. 7: Magnetic field at different armature positions

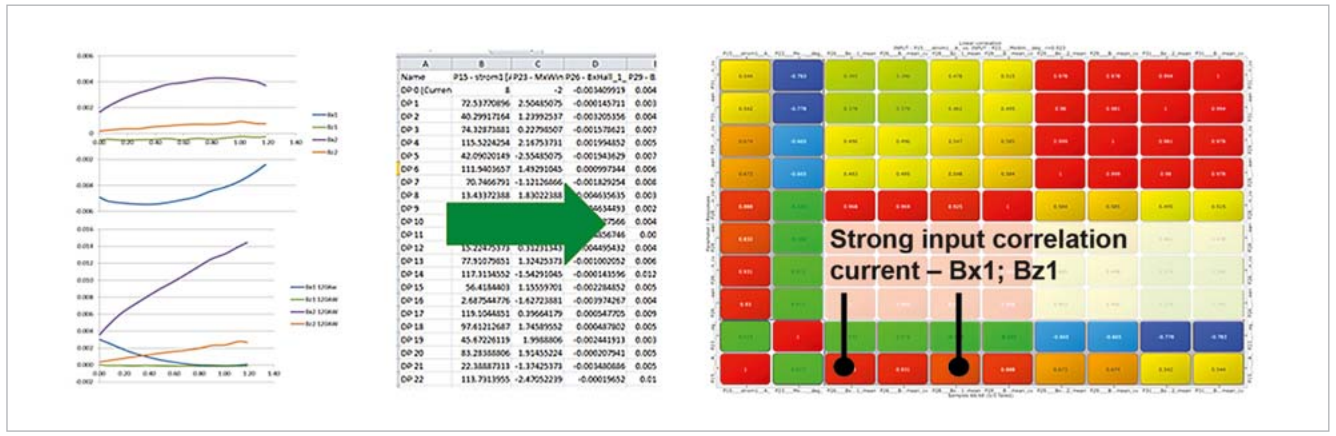


Fig. 8: Simulation and MOP$_{Bxyz(1,2)}$ = f(Mxwin; current)

The inversion shown in Fig. 10 (see next page) produces unique results. However, the extrapolation within the MOP beyond technically meaningful limits of the rotation angle is a problem. This was solved by conducting a sensitivity analysis with constraints. The resulting MOP is fitted and, thus, capable of representing the anchor position as a function of the magnetic flux density and the excitation current of the coil within meaningful physical limits (Fig. 11, see next page).

Fig.12 (see next page) shows the derivation of different MOPs with varied measurement values of the flux density, i.e., with different effort regarding the number of sensors. Accordingly, under the given conditions and with only one magnetic sensor, it is possible to measure a flux density value and a value of the excitation current of the coil showing a CoP of 93 percent.

Electronics

The electronics simulation is conducted in the environment of the system simulation within the electrical domain. Extensive libraries and algorithms are available for this anaylysis.

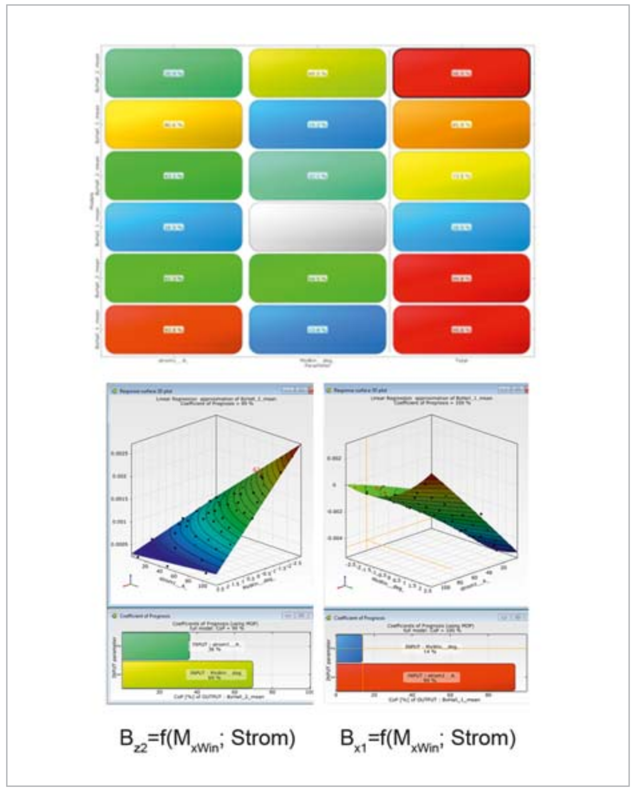


Fig 9: CoP Matrix and MOP without strongly correlated input parameters

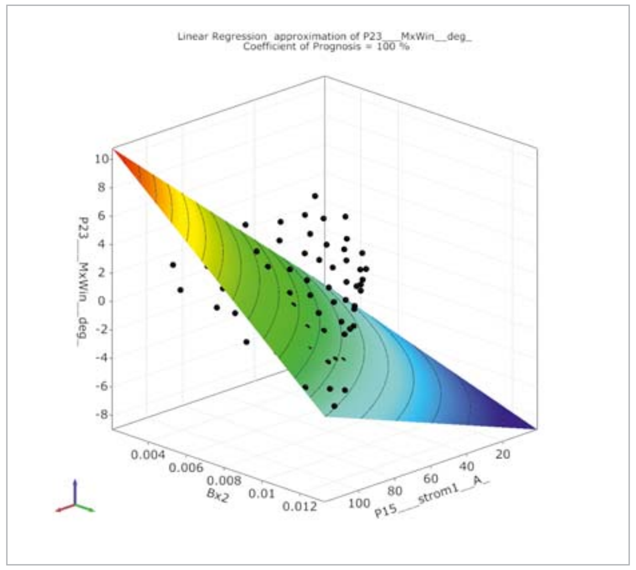


Fig 10: Inversion M_{xwin}=f(B_{x12z2}); current

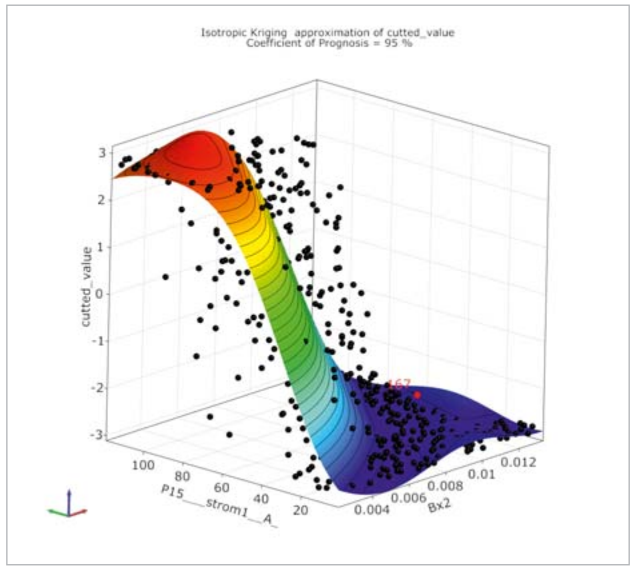


Fig 11: MOP with fitted range of values, MOP: M_{xwin}=f'(B_{x12z2}); current, CoP=96 percent

Firmware

The firmware used in the operational relay is generated with the help of an FMU and is represented in the simulation model using the program module Scade from Ansys Inc.

Simulation model of the relay including metamodels for contact lifetime and mechanical parameters (anchor position)

Fig. 13 schematically shows the block diagram of the simulation model with the objects of various physical domains. The parameters of the relay are transmitted via Simplorer blocks, which provide the measured values as internal parameters. The simulation model of the relay includes all necessary physical domains. Elements of ECE (electromagnetics), spm (mechanics) and Simplorer coupling elements were used for the modeling of the relay NSR01. The Simplorer model is connected to the relay via a QDM interface. The communication is carried out by means of a PC interface. On demand, it transmits measured values of the relay to the model for simulating the relay behavior.

Nr.	Signal Parameter	CoP	Extrapol.	Signals	Sensors
1	$B_{X1X2Z1Z2}$ Strom	100	2	5	2
2	B_{X1X2Z2} Strom	100	2	4	2
3	B_{X2-X1} Strom	69	1	3	2
4	B_{X2Z2} Strom	98	1	3	1
5	B_{Z2-X1} Strom	97	1	3	2
6	B_{X2} Strom	96	1	2	1
7	B_{X1X2} Strom	99	(2)	3	2

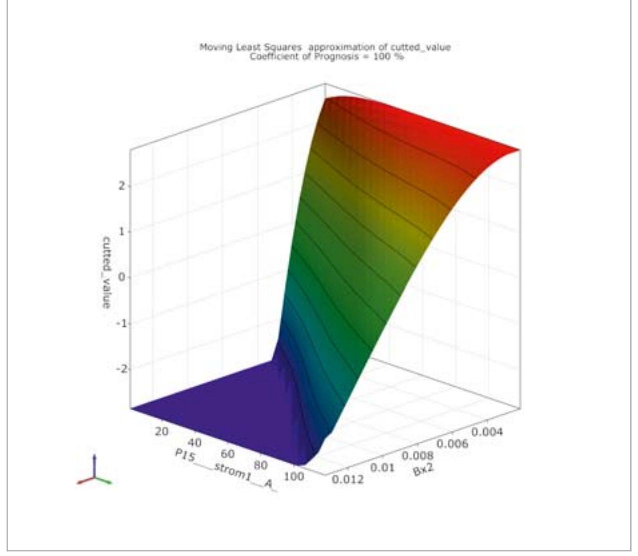


Fig 12: Overview of signal parameters and MOP with a flux density value

Special relay characteristic values and properties, e.g., arc behavior, contact resistance or coil heating, are simulated via VHDL function blocks. The corresponding lifetime characteristic and the anchor position is calculated with the help of MOPs depending on the determined load range. Based on the measured and simulated parameters, the remaining contact life is calculated and displayed via a PC interface. For the different references, please refer to the indicated formatting.

Demonstrator of the safety relay with firmware, electronic components, electromechanical components and load

Demonstrator

The demonstrator of the safety relay is integrated on a test board with an ARM Cortex M0 CPU. In terms of the hardware architecture, this represents real operational conditions. Thus, parts of the firmware could be adopted. The functionality corresponds to “emergency off”, where the load is immediately switched off when receiving a certain sensor signal. The reactivation is achieved by means of separate sequences in order to prevent an unintentional restart. The data is transferred via a serial interface to the PC, which also runs the simulation model of the relay. The analog values of the relay and the load are measured by using the AD converter of the board.

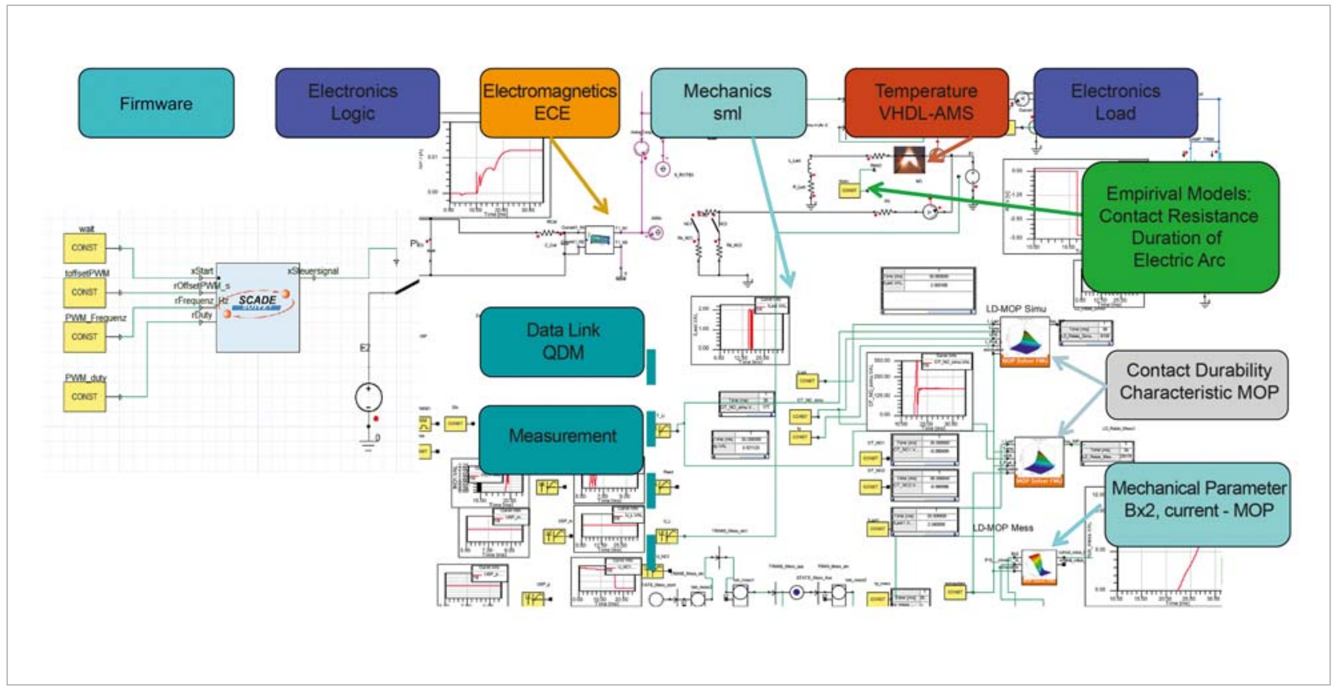


Fig. 13: Simulation model of the relay with metamodel of contact life and anchor position

Operational case of switch-on relay chatter: danger of contact welding

For the load case of switch-on contact chatter, which has a strong influence on the service life (welding of the contact), the switch-on load current is measured on the demonstrator and the signal is transferred to the simulation model. The analysis of the load current and the calculation of the switch-on contact chatter duration (Prelldauer tp) is conducted with the simulation model. Using the value of the chatter time, further characteristics of the load (current, voltage) and the characteristic values of the relay, the expected service life up to failure mode is calculated with the load corresponding lifetime characteristic using the MOPs.

For this case, the simulation shows the following values:

Chatter time tp (ms)	switches up to failure mode
1.592	297
0.826	29343

Conclusion and Prospects

The basic functional verification of a cyber-physical relay model by means of a demonstrator could be conducted. The simulation model was successfully coupled with a safety relay device for transmission of measured values from the device to the model. The analysis of status and behavior of the safety relay was also implemented by using the simulation model.

In further development steps, the coupling of the hardware with the simulation model should be improved in order to implement a real-time analysis. In addition, a more precise contact model and the consideration of the load circuit feedback can make a contribution to further enhancement of the relay model.

Author //

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