INVESTIGATIONS TO CONSIDER THERMAL INTERACTIONS BETWEEN SPATIALLY SEPARATED SUBSYSTEMS: CONCEPT OF A THERMAL COUPLING SYSTEM FOR X-IN-THE-LOOP TEST BENCHES

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ABSTRACT

The system behavior of new products can be validated with X-in-the-Loop (XiL) test benches. The potential spatial separation of the subsystems on those test benches interrupts the heat flows between the subsystems. This can lead to a different temperature distribution compared to the original assembly situation. It may change the system behavior because many functional relevant properties are temperature-dependent and the thermal interactions are not considered. The reliability of the test results concerning the system behaviour of the overall system is therefore reduced. This paper describes the investigations to consider thermal interactions between spatially separated subsystems on XiL test benches. A concept of a thermal coupling system for the transfer of thermal interactions by heat conduction is modeled. The model setup with sensors, actuators and control systems is described in detail. A simulation is used to check its feasibility for a future physical setup. The results of the simulation show small temperature deviations compared to the situation with spatially separated subsystems. With such a thermal coupling system, thermal interactions by heat conduction between spatially separated subsystems can be transferred. It is able to improve the product validation by using it on XiL test benches.

Keywords: X-in-the-Loop test bench, validation, heat transfer, thermal interactions, thermal coupling system, modeling, simulation, product development

NOMENCLATURE

α	Seebeck coefficient (V/K)
c_p	Specific heat capacity (J/(kg*K))
I	Current (A)
λ	Heat conductivity (W/(m*K))
$\dot{Q}$	Heat flow (W)
R	Electrical resistance (Ω)
R_θ	Absolute thermal resistance (K/W)
T	Temperature (K)
TCS	Thermal coupling system
XiL	X-in-the-Loop

1. INTRODUCTION

1.1 Motivation

Early validation of product properties enables the product development process to be accelerated while reducing development risks and costs [1]. In terms of product generation engineering, this can be realized with X-in-the-Loop test benches. In such test benches, the entire product is divided into subsystems. It enables the functional testing of individual components (System-in-Development) in the overall system [2]. The remaining subsystems (Connected Systems) occur physically or virtually. Coupling systems are used as an interface between virtual and physical subsystems [3]. These provide a specific coupling function to transfer the interactions between the subsystems. Coupling systems use a combination of sensors and actors to maintain the main functionality of the overall system. The coupling system itself should have no influence on the system behavior of the overall system [3]. The testing of components on the XiL test benches can result in a spatial separation compared to the original assembly situation [4].

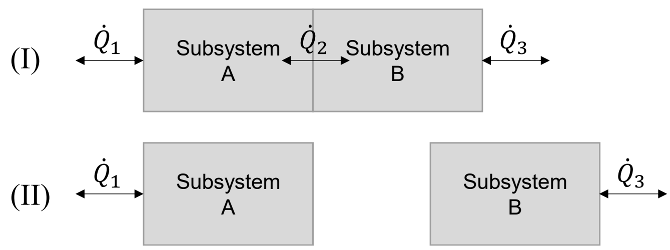

FIGURE 1: (I) HEAT FLOWS IN THE CONNECTED SUBSYSTEMS (ORIGINAL ASSEMBLY SITUATION) (II) HEAT FLOWS IN THE SPATIALLY SEPARATED SUBSYSTEMS

The spatial separation of the subsystems interrupts the heat transfer in its original configuration. The resulting heat flow of each subsystem therefore changes. Any form of variation in the resulting heat flow of the subsystem results in a change in the temperature distribution. Therefore, the spatial separation changes the temperature distribution in the overall system. Figure 1 visualizes the two states. Without system knowledge, the direction of the heat flow between the two subsystems is not apparent. Therefore, they are shown here with double arrows, because both directions would be possible.

So far, only coupling systems are used which are necessary to fulfill the intended main functions [5]. Thermal interactions are usually not considered because very often they are not directly under investigation on XiL test benches. However, there are some coupling systems where the thermal domain is an integral part of the investigation. Thermal coupling systems have been developed for the forced convection in a cooling system of a battery cell system [6]. Additionally, there are investigations to consider the thermal influence on test benches. For this purpose, usually, all systems are placed in climate chambers or are actively climatized [7]. Nevertheless, the focus is always on the influence of the environment on the subsystems under investigation. The heat flows are set according to a temperature boundary condition since the environment is regarded as an infinite energy source [8]. However, the thermal interactions between two individual subsystems cannot be implemented with this setup. The consideration of thermal interactions between the individual subsystems is becoming more and more relevant due to increasing power densities and the merging of components into integral assemblies.

1.2 Problem Description

The change of the temperature distribution due to the spatial separation of the subsystems leads to two crucial problems in product validation. First of all, a statement about compliance with the thermal load limit is not possible. Some subsystems might get colder or hotter than they would be in the original assembly situation. Neither qualitatively nor quantitatively statements about the temperature distributions can be made. Second, many functionally relevant parameters are temperature-dependent. Without considering the thermal interactions, the temperature distributions change and therefore the system behavior. Since mostly the system behavior on XiL test benches is tested, this reduces the reliability of the results in product validation.

1.3 Research Aim

The research aim is to develop a concept of a thermal coupling system that can transfer thermal interactions by heat conduction between spatially separated subsystems as they would be connected in the original assembly situation. This paper aims to describe the concept of such a thermal coupling system and to check its feasibility within a simulation.

2. CONCEPT OF THE THERMAL COUPLING SYSTEM

Initially, the thermal interactions are investigated to be able to describe a concept of a thermal coupling system. The known approaches for coupling systems are used. This is followed by the selection of suitable sensors and actuators. For a required control, the system is analyzed and the control is selected accordingly. Thus, a functional concept of the thermal coupling system is to be described.

2.1 Thermal Interactions

The aim of coupling systems is to transfer the physical interactions and thus to take them into account during product validation. In the following, the term interactions will therefore be described in more detail for this context.

If the individual subsystems are considered independently of the overall system, their individual behavior often has no clear causality. Only when sufficient information about the behavior in the preceding and succeeding subsystem is available, then the behavior of the individual subsystem can be understood and thus described in a definite way. The behavior of the individual subsystem can thus only be described causally by placing it in the overall context.

Physical interactions describe the transfer of power between subsystems where there is no clear causality. This also applies in the context of thermal interactions. Only if sufficient understanding of the system is available, causality can be established. If this is not available, the interactions must at least be transferred between the subsystems. A separation of the subsystems interrupts the transfer of power from the systems. A purely simulative validation would require a high level of system understanding to identify all heat sources and thus obtain a qualitatively and quantitatively accurate temperature profile.

2.2 Thermal Coupling Condition

In the following the concept to consider thermal interactions between spatially separated subsystems is described. The idea is to use a thermal coupling system that can transfer the unknown heat flows in such a way that a temperature profile as in the original assembly situation is obtained. This thermal coupling system consists of suitable sensors, actuators and control systems. The coupling function is to transfer a heat flow between two subsystems. The initial description of the thermal coupling system is depicted in figure 2.

For these investigations the subsystems will be considered only in the thermal domain. Power losses in the individual subsystems are descripted as heat sources. These are represented together with other occurring heat flows as a resulting heat flow. Those are described as $\dot{Q}_1$ for subsystem A and $\dot{Q}_3$ for subsystem B. Only the unknown heat flow $\dot{Q}_2$ between the subsystems A and B is not included in those resulting heat flows and is considered separately to be investigated in the thermal coupling systems. The contact resistance between subsystems A and B is to be neglected. Thermal radiation and convection are not considered. The focus is on the heat conduction and the heat transfer between the two subsystems.

Due to contact boundary conditions, the temperatures at the original contact points must be identical. The thermal coupling condition therefore states that the temperature difference between the two original contact points must be zero:

$$\Delta T = 0 \tag{1}$$

To fulfil this thermal coupling condition, two actuators have to be placed on each side of the original contact surface to transfer the heat flow $\dot{Q}_2$.

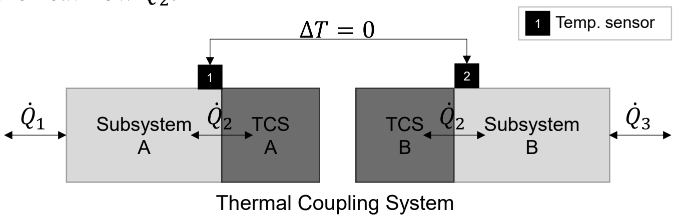

FIGURE 2: CONCEPT OF THE THERMAL COUPLING SYSTEM WITH THERMAL COUPLING CONDITION

2.3 Sensors and Actuators

A temperature sensor is placed on each side of the original contact surface. They are positioned on the same spot so they would be right next to each other if they would be assembled as in the original situation. They are assumed to be ideal in this model.

To comply with the thermal coupling condition, actuators are needed which can generate a heat flux. Peltier devices are particularly well suited due to the thermoelectric effect, which allows controlling a heat flow in both directions. They work with the thermoelectric effect, which describes the relationship between electrical and thermal energy. This means that electrical energy can be converted directly into thermal energy (thermoelectric cooler). The effect can also be reversed (thermoelectric generator). If the thermoelectric cooler is implemented, a heat flow between the two sides of the Peltier device is created by applying electrical energy. Depending on the side that is in contact with the subsystem, the Peltier device can be used as a cooling or heating source. Therefore, a Peltier device is applied to each original contact surface.

The heat flow generated by the thermoelectric effect can be described by

$$\dot{Q} = \alpha \cdot T \cdot I \tag{2}$$

The Seebeck coefficient α is primarily dependent on the semiconductor pairs used. The thermal mass of the Peltier element is comparatively small and is therefore very well suited for the application in such systems, as it is very reactive. For modeling purposes, the mass of the Peltier device is neglected in the following.

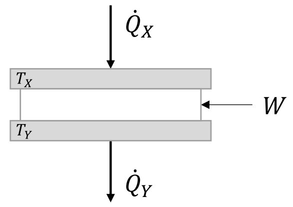

FIGURE 3: SCHEMATIC STRUCTURE OF A PELTIER DEVICE

The energy conservation equation is shown in figure 3 and results in

$$W + \dot{Q}_X - \dot{Q}_Y = 0 \tag{3}$$

An important effect, which must not be neglected in the equation, is heat conduction. As soon as a temperature difference has formed between the two sides of the Peltier device, an opposing heat flow is created by heat conduction. This can become such large values that the net heat flow becomes zero or even reverse, despite higher currents. The net heat flow of side X and Y of the Peltier device can be described by equations (4) and (5) [9]. The parameter R is the electrical resistance and R_θ the absolute thermal resistance due to conductivity.

$$\dot{Q}_X = \alpha T_X I - \frac{1}{2} I^2 R + \frac{(T_X - T_Y)}{R_\theta} \tag{4}$$

$$\dot{Q}_Y = \alpha T_Y I + \frac{1}{2} I^2 R + \frac{(T_X - T_Y)}{R_\theta} \tag{5}$$

The Peltier device is implemented in MATLAB according to its physical description with the formulas (4) and (5). The heat flows $\dot{Q}_1$ and $\dot{Q}_3$, however, are realized as ideal heat flow sources.

2.4 Control Systems

A control system is required to comply with the thermal coupling condition. For this purpose, a control system must be implemented which generates a corresponding heat flow in the Peltier devices based on the temperature difference between subsystems A and B. The control variable is the temperature difference between the two original contact surfaces. The reference variable represents the temperature difference between the two original contact points. This quantity should be zero for compliance with the thermal coupling condition. The manipulated variable is the change in the applied current. As an actuator, the Peltier device generates a manipulated variable in the dimension of a heat flow. Because the heat flows $\dot{Q}_X$ and $\dot{Q}_Y$ are unequal (equation (4) and (5)), the current that applies on the Peltier devices A and B should be unequal as well.

The heat flow $\dot{Q}_X$ of Peltier device A and $\dot{Q}_Y$ of Peltier device B must be identical so that the heat flow removed from subsystem A also corresponds to the heat flow added to subsystem B. This adjustment can be determined mathematically with the help of equations (4) and (5) and results in the following equation if heat conduction is neglected:

$$I_B = \frac{(\alpha \cdot T - \sqrt{(\alpha \cdot T)^2 - 2 \cdot \alpha \cdot T \cdot R \cdot I_A - (R \cdot I_A)^2})}{R} \tag{6}$$

The two temperatures at the original contact points are taken as the controlled variable. Their difference is fed back and compared with the requirement $\Delta T = 0$. The subsystems A and B can be described as first-order lag elements because no additional influence is considered that could lead to overshoot. The heat flows $\dot{Q}_1$ and $\dot{Q}_3$ acting on the subsystems A and B represent disturbance variables in the context of this control loop. For this application, an integral controller is used. A permanent control error should thus be prevented. Abrupt changes in the temperature are not to be expected. The block diagram of the control system is visualized in the following figure 4.

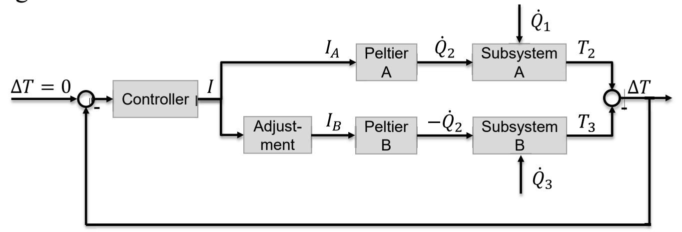

FIGURE 4: BLOCK DIAGRAM OF THE CONTROL SYSTEM TO FULFILL THE THERMAL COUPLING CONDITION

A second type of control system is required. This is used to acclimatize the Peltier device itself. It prevents that the temperature difference between the two sides of a Peltier device becomes too large. If this is the case, the heat flow cannot be transferred as intended by the main control because it is reduced due to a reverse heat flow by conductivity. The control system for acclimatization is implemented by a two-point control. Depending on the application, a heating or cooling device is attached to the other side of the Peltier device and is used as an actuator. Those are significantly more inert in terms of thermal behavior. The aim is that the temperatures between the two sides of the Peltier devices are as identical as possible.

The detailed concept of the thermal coupling system is visualized in figure 5. The next step is to simulate the concept. The control system to fulfil the thermal coupling condition is abbreviated with [A] and the two two-point control system with [B].

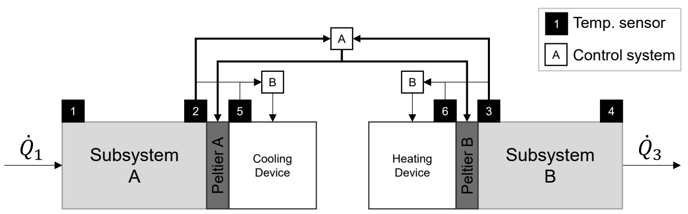

FIGURE 5: DETAILED CONCEPT OF THE THERMAL COUPLING SYSTEM

3. MATERIALS AND METHODS

To evaluate the concept of the thermal coupling system for its feasibility, it is implemented and tested in a simulation. The simulation was created with MATLAB R2020a Simulink 10.1. Simscape is used as an extension of the model database and simplification. Since MATLAB Simulink is modeling with lumped parameters, the temperature curve within the component is not resolved spatially, but only temporally. The solver ode14x with the fixed step size of 0.1 s is used.

3.1 Test Setup

Three different scenarios are considered. Scenario (I) is the basic thermal model with a heat transfer between the two masses. It represents the original assembly situation. Scenario (II) describes the use-case when the two subsystems are spatially separated compared to the original assembly situation. Scenario (III) additionally has the thermal coupling system between the spatially separated subsystems. The temperature profiles between the three scenarios are compared. The evaluation variable is thus the deviation between the temperature of scenario (II) or (III) to scenario (I). Figure 6 visualizes the three different scenarios.

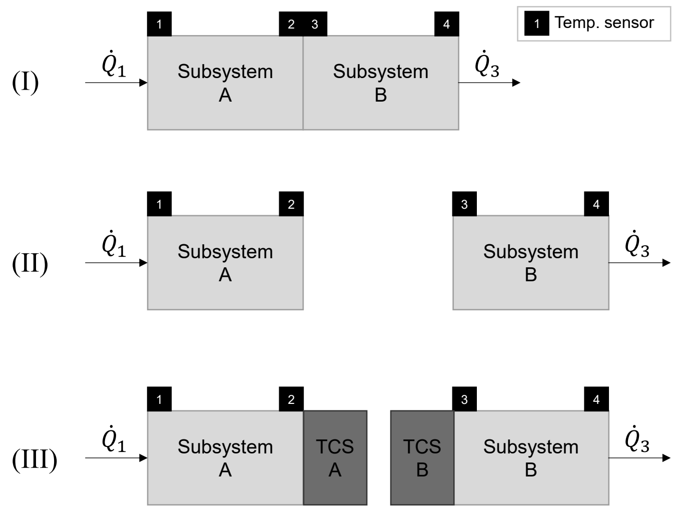

FIGURE 6: TEST SETUP OF SCENARIOS (I), (II) AND (III)

3.2 Load Cases

Two different load cases are investigated. In both cases, the starting temperature is 300 K.

The following assumption applies to the first load case. It represents a thermal load case that reaches a steady state. A heat flow of 100 W is applied to subsystem A ($\dot{Q}_1$), while a heat flow of 100 W is continuously extracted from subsystem B ($\dot{Q}_3$). Thus, a heat flow of 100 W must be mathematically transferred via the thermal coupling system. In the overall system, a net heat flow of 0 W stays inside the system and therefore a steady state should occur.

The second load case describes a permanent unsteady state. A heat flow of 100 W is applied to subsystem A ($\dot{Q}_1$). The only heat flow to subsystem B is the thermal conduction to subsystem A. The heat flow $\dot{Q}_3$ is zero.

3.3 Parameters

The subsystems A and B are each made of aluminum alloy EN AW-6061. It has a density of 2.7 g/cm³, a specific heat capacity c_p of 1106 J/(kg*K), and a thermal conductivity λ of 172 W/(m*K) [10].

Subsystem A has the geometric dimensions of 40mm x 40mm x 50mm, while subsystem B has the geometric dimensions of 40mm x 40mm x 100mm.

Peltier devices are used for the thermal coupling system. The Seebeck coefficient α has a value of 0.05 V/K, the electrical resistance R 1.1 Ω, and the absolute thermal resistance R_θ 0.625 K/W. The parameters used are taken from Peltier device ETC-200-14-06-E, which has already been selected for a physical test bench setup planned later [11].

The integral controller for maintaining the thermal coupling condition has a value of -0.167. The two-point controller for acclimatization of the Peltier elements has the switching limits of ±0.5 K each.

4. SIMULATION RESULTS

The concept of the thermal coupling system for the transfer of thermal interactions by heat conduction is now being tested in simulation scenarios. The previously described scenarios are compared with each other with regard to the temperature curve.

4.1 Behavior Until Steady State is Reached

First, the results of the load case to reach a steady state are analyzed. For this purpose, the temperature curve of temperature sensor 2 of all three scenarios is shown as an example in Figure 7.

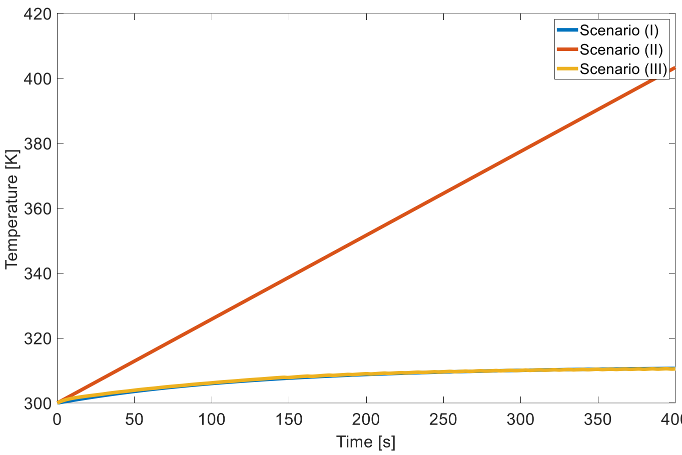

FIGURE 7: TEMPERATURE CURVE OF TEMPERATURE SENSOR 2 WITH FIRST LOAD CASE TO REACH STEADY STATE

Considering temperature sensor 2 in scenario (I), the result is a steady state of 310 K. The heat flow thus leads to a temperature increase of 10 K compared to the initial situation at room temperature. In scenario (II), as expected, the interruption of the heat flow for subsystem A results in a permanent unsteady state. The temperature thus increases continuously. However, if the temperature curve of scenario (III) is analyzed, it is qualitatively very similar to that of scenario (I). The temperature curve shown thus also reaches the steady state. This demonstrates that the use of the thermal coupling system results in a temperature curve that is similar to the original assembly situation, despite the spatial separation of the subsystems. However, it can also be seen that there is an offset between scenario (I) and (III).

For this reason, the temperature difference of the measuring points 1 to 4 between scenario (I) and (III) is shown in Figure 8. This figure shows that the temperature difference of each single measuring point does not exceed 2.1 K at any time. The behavior of all measuring points is very similar. A negative temperature difference means that scenario (III) is colder than scenario (I). Initially, there is a quick increase in the temperature difference. This is due to the inertia of the thermal masses of the thermal coupling system and the control system. Thus, the temperature differences at the measuring points 2 and 3, which are located directly at the thermal coupling system, are larger than at the measuring points 1 and 4, which are located further away. Another influence of the thermal coupling system can be seen at the temperature measuring points 2 and 3. Due to the two-point control for acclimatization of the Peltier devices, the corresponding heating and cooling devices are switched on or off when the temperature exceeds or falls below the set barriers of ±0.5 K. A static state is established after approx. 400 seconds. The temperature differences between scenarios (I) and (III) are constant at about 1.7 K from then on. This means that the temperature distribution in the subsystems A and B of scenario (III) is qualitatively the same as in scenario (I). In quantitative comparison, the temperature distribution is only 1.7 K colder throughout the subsystems. This difference is quite small, but cannot be compensated by the described concept of the thermal coupling system.

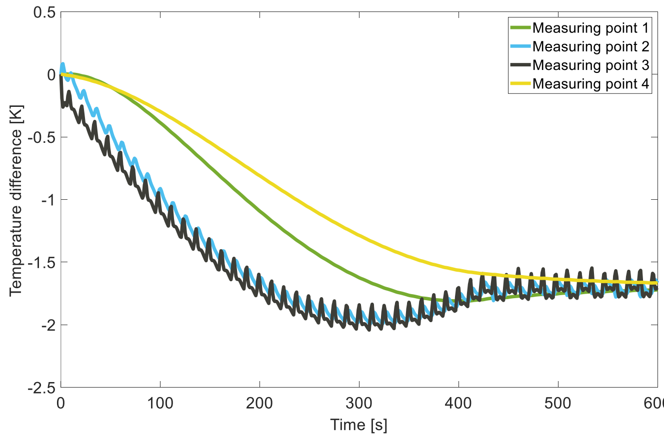

FIGURE 8: TEMPERATURE DIFFERENCE BETWEEN SCENARIO (III) AND (I) OF THE INDIVIDUAL MEASUREMENT POINTS WITH THE FIRST LOAD CASE

4.2 Behavior of Permanent Unsteady State

The unsteady state is considered as the second load case. Figure 9 shows the temperature curve of sensor 2 of all three scenarios. It can be seen that the temperature in scenario (I) increases continuously since a constant heat flux is also applied. Scenario (II) has a much faster increase than scenario (I) due to spatial separation of the systems. After already 400 seconds the temperature difference is more than 100 K. Between scenarios (I) and (III), a deviation of the temperature curves can also be seen. It is much smaller but also increases continuously. For long runtimes with a permanent unsteady state, larger deviations occur despite the use of the coupling system.

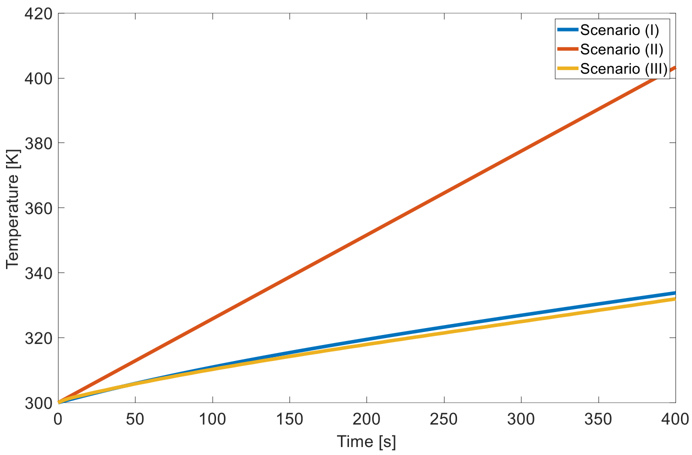

FIGURE 9: TEMPERATURE CURVE OF TEMPERATURE SENSOR 2 WITH SECOND LOAD CASE TO DEMONSTRATE A PERMANENT UNSTEADY STATE

4.3 Discussion

The results show that by using the thermal coupling system, the temperature curve is represented much better than when it is not used. However, an influence of the coupling system itself, as expected, cannot be completely prevented. Once the steady state is reached, the resulting temperature difference does not increase, but for unsteady states it does. Regarding this aspect, further investigations should be carried out to optimize the controller to fully comply with the thermal coupling condition. The offset should not be increased by unsteady states, if possible. However, the deviations can already often be accepted, since the accuracy requirements in the early stages of product development are not particularly high. This is the case because in most of the considered systems a steady state is established and the temperature differences do not increase according to the results of the simulation.

However, the investigations conducted so far have certain limitations. The contact resistance between the subsystems should be considered in a further step and examined in detail. Deviations caused by the change of the contact resistance could be compensated by calculation and implemented in the controller. In addition, the robustness of the control due to specific disturbances should be investigated by using e.g. fault injection. For future steps, the system should be physically built and tested.

Due to the selected concept with Peltier devices, high heat flows can be transferred locally. A combination of several of these modular thermal coupling systems allows the use for larger contact areas. The resulting setup of a parallel arrangement of these modules, should be investigated in more detail in the future with regard to its influence.

The concept of the thermal couling systems can be extended by connecting not only two spatially separated subsystems but also physical ones with virtual ones. This type of coupling is often used on XiL test benches but requires further investigation. Additionally, the described thermal coupling system can be modified to transfer thermal interactions by thermal radiation or convection.

5. CONCLUSION

This paper describes a concept of a thermal coupling system that can transfer thermal interactions by heat conduction between spatially separated subsystems as they would be connected in the original assembly. The results demonstrate the feasibility of the concept. It is therefore to be continued in the future because it is able to improve the product validation by using it on X-in-the-Loop test benches.

ACKNOWLEDGEMENTS

The project upon which this publication is based was funded by Federal Ministry for Economic Affairs and Energy under the funding number 20Y1910E. The authors of this publication are responsible for its contents.

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