Model Based Systems Engineering for Power Electronics Equipment

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ABSTRACT

The recent rapid progress of digitalization has led to the development of smart factories, where shorter development times are required to launch products in a timely manner. Fuji Electric is working on digitization and development process innovation as one of its initiatives for DX. We have applied model based systems engineering to the development process of power electronics equipment and confirmed that this enhanced process can be used to validate the system in the early stages of development by building a system simulation environment for, as a verification example, a door system used in railcars, which includes mechanisms, electrical circuits, and control software. As a result, it is expected to prevent rework, shorten development time, and improve reliability.

1. Introduction

Digitalization has recently been progressing rapidly, and with the introduction of Industrie 4.0 in Germany as a turning point, factories have become increasingly smart. As in the Society 5.0 concept proposed in Japan, initiatives toward the development of the Internet of Things (IoT) and digital transformation (DX) are accelerating around the world. Meanwhile, as customer demands become increasingly diverse, product variations are increasing, and development man-hours are also rising. Under these circumstances, launching products in a limited period of time in a timely manner requires development times to be reduced. To meet this demand, model-based development (MBD) and model-based systems engineering (MBSE), which makes use of MBD, are effective solutions that are increasingly being applied in the industrial world.

Fuji Electric is working on digitalization and innovation of development processes as one of its DX initiatives. In the past, we have made continuous efforts to improve the productivity of research and development, such as the innovation of design processes including front-loading design and concurrent design, the advancement of the technology and the expansion of the scope of applications in computer-aided engineering (CAE).[1]

For further evolution, with the aim of introducing model-based systems engineering, we have applied model-based development to a door system used for railcars as an example including mechanisms, electrical circuits and control software. In addition, we have built a system simulation environment for systems engineering to verify its effectiveness, which will be described below.

2. Model-Based Development and Systems Engineering

2.1 Model-based development

Model-based development refers to development in which a large number of models are prepared as parts to allow reuse in a simulation environment for electrical circuits and mechanisms, and these parts are combined for efficient product verification in advance.

We built a mechanism model for mechanisms, an electrical circuit model for electrical circuits, and a control software model for control software. We combined these to use as a system model and built a development environment for linkage and interaction simulation. Figure 1 shows an overview of a system model that uses the respective parts models.

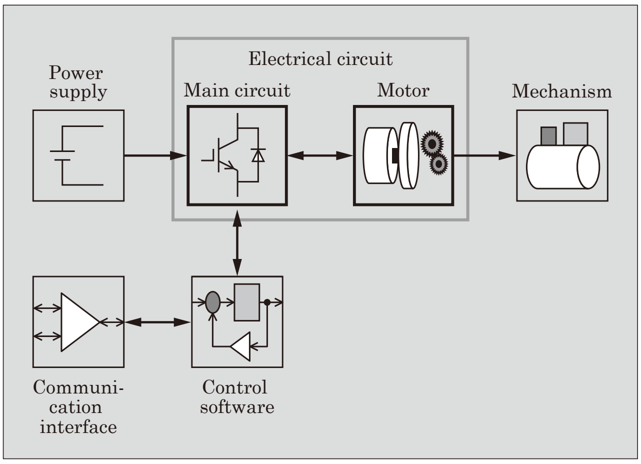

Fig.1 Outline of system model using parts models

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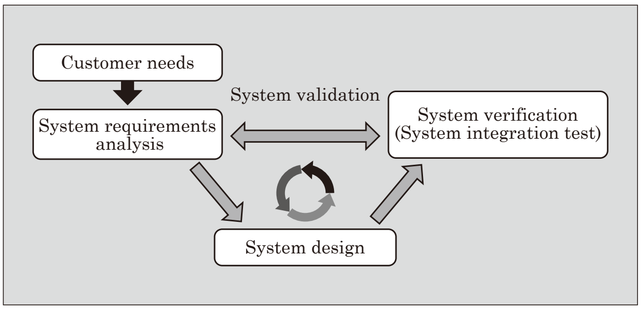

Fig.2 Outline of systems engineering

2.2 Systems engineering

Systems engineering first makes customer demands clear in the initial phase of the development cycle and translates them into functional requirements. Taking into consideration for the functional requirements spanning multiple fields, it confirms the validation of the requirements for the entire system (see Fig. 2).

3. Issues in Development Process

Figure 3(a) shows the conventional development process. Power electronics equipment often require hardware design that includes mechanism design, electrical circuit design and control software design. The process of hardware design that includes mechanism design was often carried out by repeating partial prototyping and verification multiple times, which tended to extend development times. Electrical circuit design and control software design are developed in parallel with hardware design, but any hardware design change causes rework, which often extended the period. In order to solve these problems to reduce development times, validation in an upstream process is effective by adopting model-based development and systems engineering.

In addition, inadequate initial definition of requirements or system study at the time of system design should cause major rework in order to deal with these issues. Even if no problems are found in verification of the respective units after hardware design and control software, problems may be found in integration tests in downstream processes or evaluation tests using the actual equipment. When the specification of a conventional product is used as the basis for design change to design variations, inability to identify the extent of impact of the design change may cause rework, resulting in extension of the development time. To meet the challenge of shorter development times, it is effective to use systems engineering at the time of system design to verify consistency and coordination of the entire system.

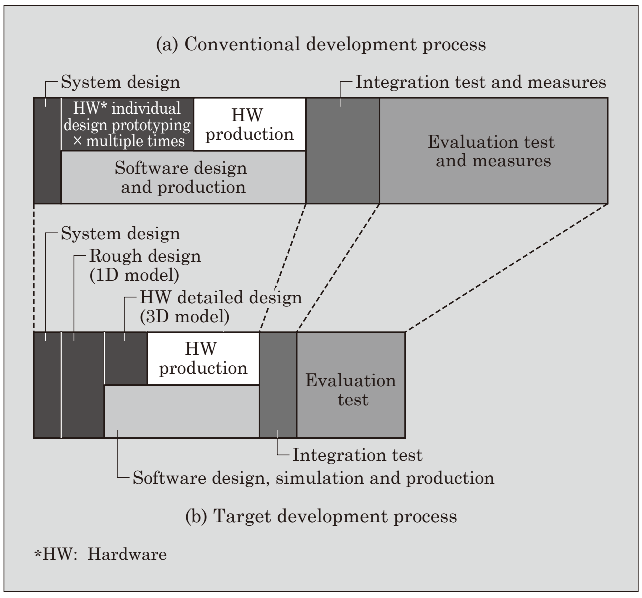

Fig.3 Conventional and target development processes

4. Fuji Electric's Goal of Model-Based Systems Engineering

As described in Chapter 3, many power electronics equipment products require mechanism design, electrical circuit design and control software design during development. Coordinated design of these to validate the system and subsequently designing each of them in detail allows elimination of the man-hours and rework for dealing with problems that occur in downstream processes, as shown in Fig. 3(b), preventing the extension of time taken for for integration and evaluation tests.

Figure 4 shows a development process using the model-based systems engineering we have implemented. In upstream development processes, requirement analysis is conducted based on customer de-

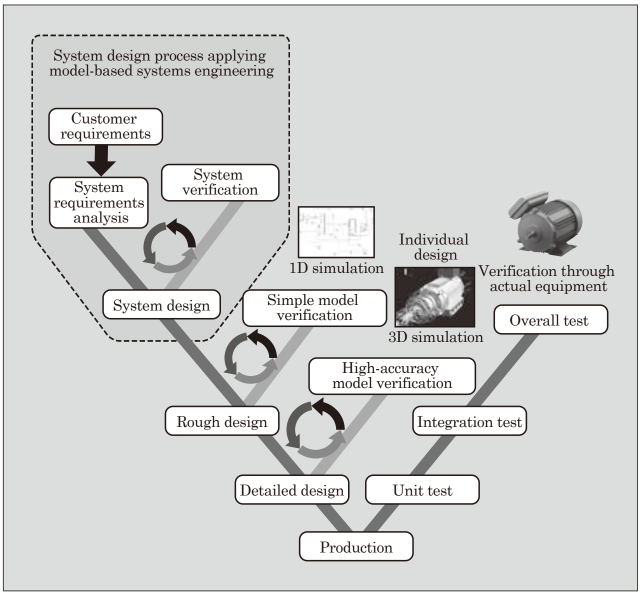

Fig.4 Development process through model-based systems engineering

mands to define the requirements and design the system, and models are used to verify the system. Based on system specifications determined in this way, the system is roughly designed and verified to determine the outline specifications, which is followed by detailed software and hardware design and verification. In model-based development, these verification processes are carried out by using models.

Employing model-based systems engineering will lead to high-reliability system design, and adopting front-loading design to validate the design in the early stages of the development will reduce the development time. In the development of variations, we are committed to determine the extent of the impact of specification changes and implement the required design changes and verifications to improve development efficiency.

5. Validation through Model-Based Systems Engineering

The door system for railcars (see Fig. 5) offered by Fuji Electric uses a motor to open and close doors and has been used widely in Japan and overseas.[(2)] Based on the standard specifications, we develop variations according to customer needs. We take this as an example to present system design in accordance with the model-based systems engineering technique and the results of validation through the use of system simulation.

We analyzed the customer needs and translated them into functional requirements to determine system specifications and validate the door system. For verification, we built a system model as shown in Fig. 6. We used MATLAB*1 and Simulink*2 for 1D modeling of the mechanism to conduct system simulation.

(1) Opening and closing operations of doors for railcars

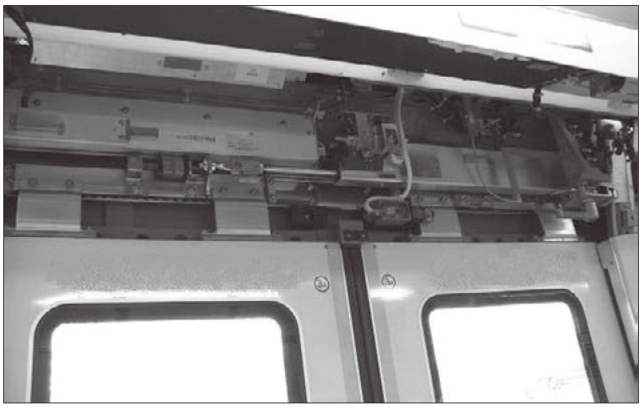

Fig.5 Door system for railcars

*1: MATLAB is a trademark or registered trade mark of The MathWorks, Inc.

*2: Simulink is a trademark or registered trade mark of The MathWorks, Inc.

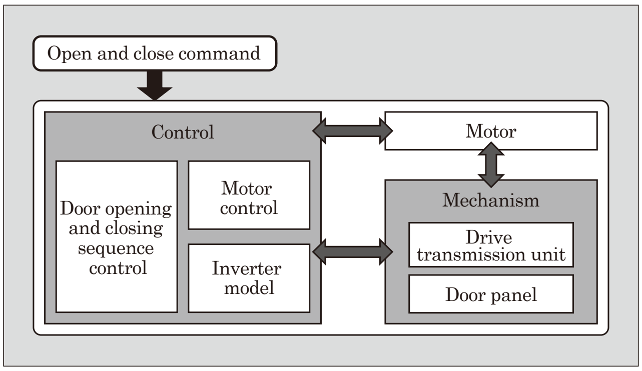

Fig.6 Door system model

Door systems are required to complete opening and closing operations within the specified time to meet the needs of scheduled railway services. Some requirements come from the perspective of ensuring the safety of railcars, such as the opening and closing speeds being lower than the specified speed to prevent the risk of injury caused by excessive impact or pressure in the event that a passenger's hand or body is caught between doors. It is important to implement coordinated design to satisfy the requirements and functional specifications of the control software, electrical circuit, motor and mechanism, such as the requirement that there be no problems in the speed patterns of opening and closing operations, door size and weight, or in the correlations between them.

(2) Coordinated design of door systems

The following is an example of coordinated design, which is the improvement of the trade-off between the maximum load of the door and the opening and closing time.

When the door is stationary, a load equivalent to the weight of the door panel is applied to the multiple rollers composed of hangers. When a door is opened or closed, moment is generated as the door panel moves according to the positional relationship between the hangers and the center of gravity of the door panel, and significant dynamic load corresponding to acceleration is generated on a specific roller. Therefore, increasing the acceleration to reduce the opening and closing time causes the dynamic load to increase. We determined an appropriate acceleration and maximum speed and used system simulation to verify that the maximum dynamic load during opening and closing operation did not exceed the design target value and that the opening and closing time met the customer need.

(3) Speed command pattern design and operation results

Figures 7(a)-(d) show the speed patterns and simulation waveforms of the initial design determined based on the conventional basic specifications. At this time, the maximum door opening time was set at 3 s.

Figure 7(a) shows the speed command pattern of the initial design. Reaching the maximum speed in a short period, the door moves for a certain time with the

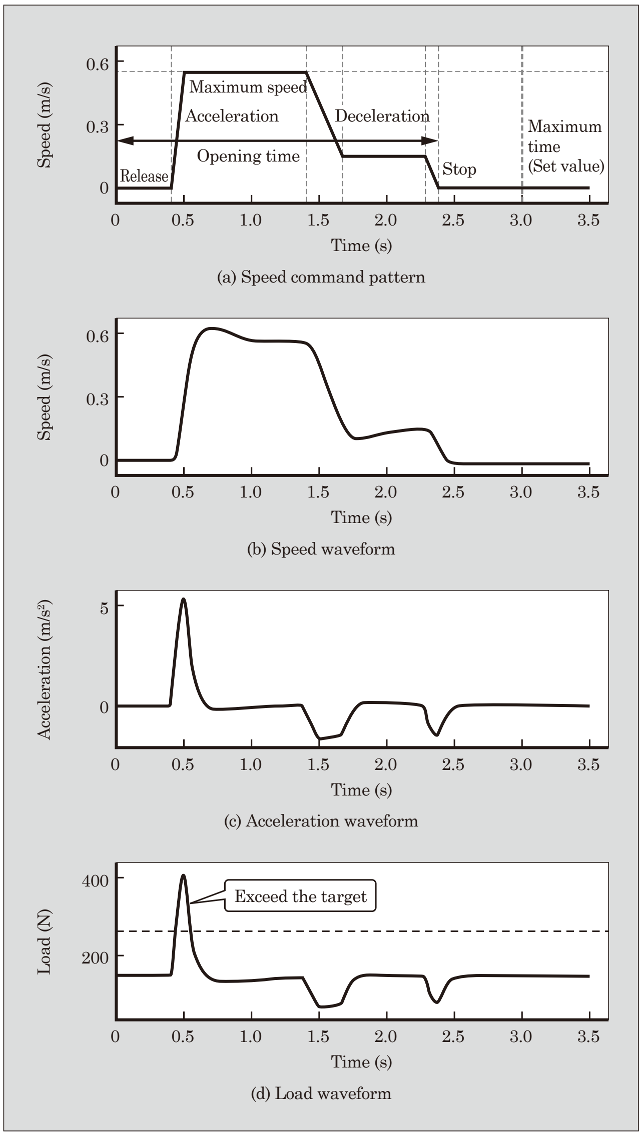

Fig.7 Speed command pattern and simulation waveforms of initial design

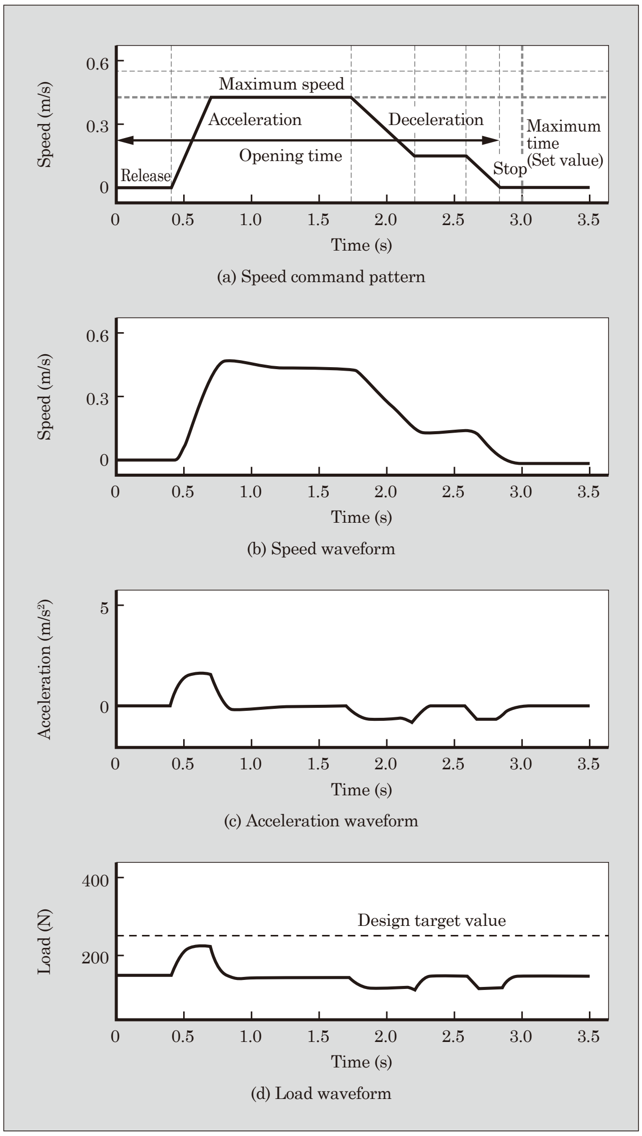

Fig.8 Speed command pattern and simulation waveforms after adjustment

maximum speed maintained, starts deceleration operation to slow down once, enters stopping operation, and then stops in approximately 2.5 s, which is shorter than the maximum opening time of 3 s. In response to this speed command pattern, the door response speed changed as shown in Fig. 7(b), along with which the acceleration changed as shown in Fig. 7(c). As a result, the maximum dynamic load exceeded the design target value as shown in Fig. 7(d). Accordingly, with this speed command pattern, the door opening time satisfies the functional requirement, but the maximum load does not, this speed command pattern therefore has not been adopted.

(4) Speed command pattern design change and operation results

To reduce the dynamic load, a door panel mass or acceleration need to be reduced. However, dealing with this issue by changing the design of the mechanism, including the door panel, leads to a large scope of impact that includes increased man-hours for design change and verification of the respective parts. Accordingly, we explored a speed command pattern that satisfies functional requirements of the maximum load and door opening time without changing the mechanism.

We determined the maximum speed and acceleration time within a range in which the door opening time satisfies the functional requirement and then changed the design so that the load during operation would satisfy the functional requirement. Figures 8(a)-(d) show the specific examples.

As shown in Fig. 8(a), the speed command pattern was changed to one that made effective use of the target time for opening and closing with the maximum speed and acceleration reduced. This made the actual speed change more gradual as shown in Fig. 8(b) and reduced the maximum acceleration as shown in Fig. 8(c). As a result, the maximum dynamic load at the maximum acceleration became lower than the design target value as shown in Fig. 8(d) to satisfy both functional requirements of the maximum load and door opening.

In this way, model-based systems engineering and model-based development have allowed the use of simulation in an upstream process of development to identify the extent of impact, determine the optimum conditions and implement efficient coordinated design. In addition, various conditions can be evaluated without using the actual equipment, leading to the realization of shorter times for evaluation tests and improved reliability.

6. Postscript

Fuji Electric is working on digitalization and innovation of development processes as one of its DX initiatives. This paper has described model-based systems engineering for power electronics equipment.

In the future, in addition to door systems for railcars, we will apply this methodology to the development and design of actual power electronics equipment such as drive systems, as well as the development of variations that meet customer needs. In this way, we will contribute to shorter development times and improved reliability.

Furthermore, through the repeated feedback of data using actual railcars and the improvement of sophistication and accuracy of analysis simulation, we intend to also make use of the developed system model as a digital twin in after-sales services, such as the optimization of operation and maintenance efficiency.

References

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(2) Fujita, K. et al. Passenger Door System for Series E235 Train of East Railway Company (Yamanote Line) Designed to Improve Transportation Quality. Fuji Electric Review. 2018, vol.64, no.1, p.44-48.

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