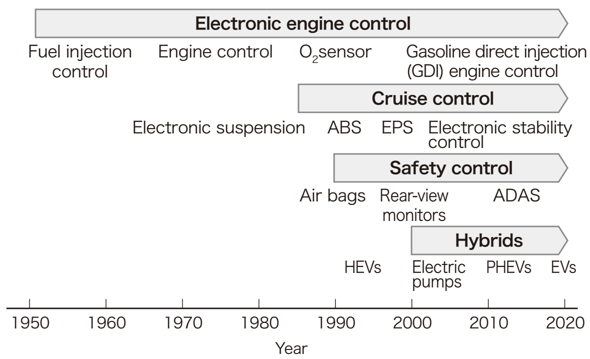
High-Speed, High-Accuracy Simulation Technique to Evaluate Thermal Performance and EMI Noise of Automotive Power Semiconductors

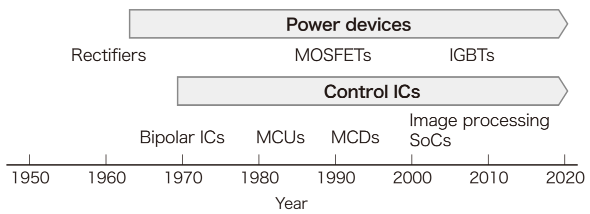
In line with the recent trend toward the electrification of automobiles, demand has been increasing in the automotive field for power semiconductors as key devices of in-vehicle systems. With the increasing use of electronic components, the introduction of simulation technologies using model-based development (MBD) methods to verify the functions and performance of overall systems has been rapidly expanding in order to efficiently develop in-vehicle systems.
Toshiba Electronic Devices & Storage Corporation has been promoting the deployment of power semiconductor products including metal-oxide-semiconductor field-effect transistors (MOSFETs) in response to customers' requirements for in-vehicle systems, and supplying not only devices but also device models of MOSFETs for such simulations. Moreover, we have been carrying out simulations of in-vehicle systems using our device models with the objective of offering optimal device models for system-level simulations. We found during this work that it was necessary to resolve the tradeoff between accuracy and calculation time. To achieve a balance between high accuracy and high speed, we have now developed the Accu-ROM (accurate reduced-order modeling) technique focusing on the evaluation of thermal performance and electromagnetic interference (EMI) noise in switching operations and confirmed the effectiveness of this approach using the Accu-ROM technique when selecting an optimal MOSFET device and switching speed.

1. Introduction

There was a time, not so long ago, when automobiles were manufactured as mechanical systems powered by an internal combustion engine. In recent years, automobiles have progressed remarkably, incorporating a host of electronic control units (ECUs). For example, in order to tackle the environmental issues caused by exhaust gas, automobile manufacturers have employed electronic control, achieving higher engine efficiency and thereby improving fuel economy. Automatic transmission (AT) systems, anti-lock braking systems (ABS), electronic stability control (ESC) systems, and electric power steering (EPS) systems have also improved the running, braking, and turning performance of automobiles. In addition to the enhancement of the inherent performance of automobiles, recent automotive innovations include advanced driver assistance systems (ADAS) coupled with braking and other mechanisms as well as electric vehicles (EVs) that do not have an internal combustion engine. In this way, electrification is spurring a once-in-a-century revolution in the automobile industry. Power semiconductor devices suitable for automotive applications, including metal-oxide-semiconductor field-effect transistors (MOSFETs), insulated-gate bipolar transistors (IGBTs), and motor control drivers (MCDs), are of critical importance to the success of this revolution.
Toshiba Electronic Devices & Storage Corporation has been improving the performance of semiconductor chips and developing products tailored to customer needs by using its long-cultivated semiconductor device technologies (**Figure 1**).



(a) History of electrification of automobiles



(b) History of automotive semiconductor devices developed by Toshiba Electronic Devices & Storage Corporation

O_2: oxygen
HEV: hybrid electric vehicle
PHEV: plug-in HEV
MCU: microcontroller unit
SoC: system-on-a-chip

Figure 1. Histories of electrification of automobiles and automotive power semiconductors developed by Toshiba Electronic Devices & Storage Corporation

In line with the progress of automotive electrification, we have developed optimal power semiconductor devices.

Automotive systems are becoming increasingly sophisticated and complicated while international competition in the development of new automobiles continues to intensify. Conventionally, automobile manufacturers have developed ECUs by iterating the prototyping process using hardware components provided by semiconductor vendors. However, such an approach could cause an enormous waste of resources when a failure to meet system specifications necessitates a design iteration. It is therefore imperative to establish a framework in which automobile and semiconductor manufacturers collaborate on ECU development in order to improve the development efficiency.

In Japan, SURIAWASE 2.0 is currently recommended by the Ministry of Economy, Trade and Industry (METI). Compiled based on the results of meetings held by the Study Group for Ideal Approaches to Model Utilization in the Automotive Industry, SURIAWASE 2.0 provides guidelines for a future approach whereby automobile manufacturers will enhance harmonization (*suriawase* in Japanese) of their own development processes by taking advantage of a model-based development (MBD) process that uses virtual simulations. In order to facilitate MBD, we are currently preparing SPICE (Simulation Program with Integrated Circuit Emphasis) models for our general-purpose discrete semiconductor devices to make them available for download from our website. In addition to functional and performance verification, applications of MBD are expanding to include thermal and electromagnetic interference (EMI) noise management.

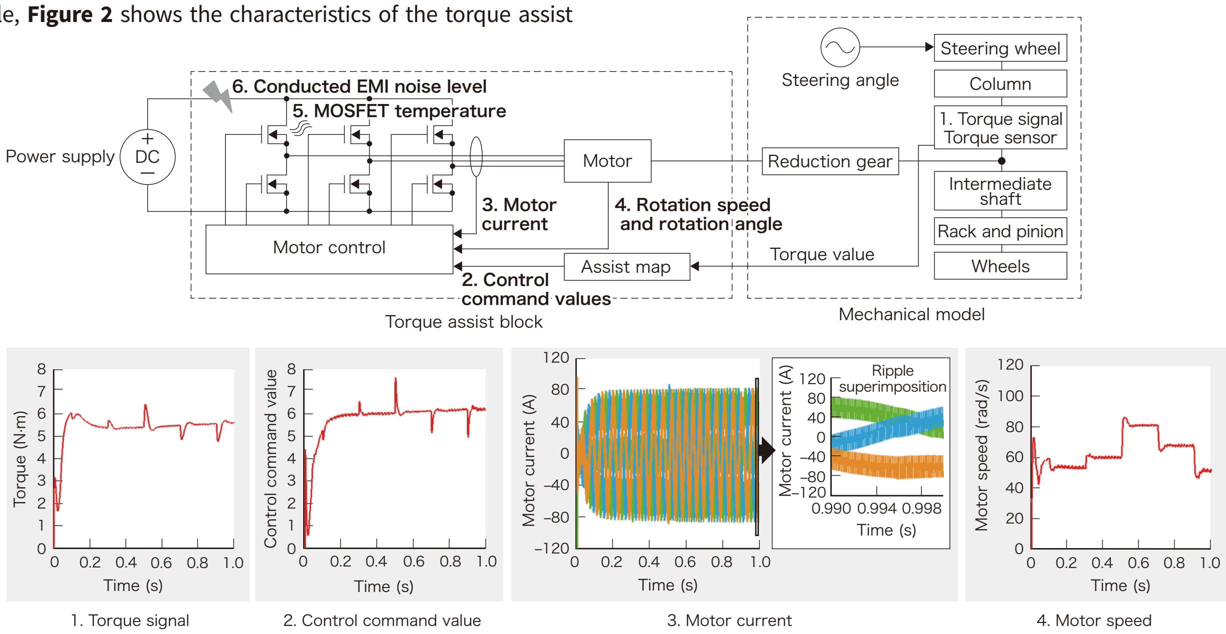
Under these circumstances, it is crucial to provide not only hardware components but also software device models. We have now developed the Accu-ROM (accurate reduced-order modeling) technique, which will change the approach to system development and help reduce the simulation run-time without compromising accuracy. This article provides an overview of the Accu-ROM technique and describes the results of performance evaluation of Accu-ROM-based simulation.

2. High-accuracy simulation technique using MBD

MBD is a development methodology using software employed in the conceptual design phase, which divides the constituent functions and units of a system into blocks, represents the operation of each block with mathematical expressions or table models, and links them together to verify the functionality and performance of the entire system. Generally, the fitness of the entire system is evaluated based on the results of MBD-based simulation in order to determine the specifications required for each block.

In the detailed design phase, each block is designed according to these specifications. To verify that a given block satisfies its specifications, its model is replaced with detailed design data. For example, **Figure 2** shows the characteristics of the torque assist block simulated after replacing it with detailed design data of a three-phase inverter circuit model. If it satisfies the specifications, the overall simulation results become similar to those obtained in the conceptual design phase. However, Figure 2 indicates that a ripple is superimposed on the output current from the inverter (i.e., the motor current) as the inverter switches on and off.

As demonstrated by this example, the MBD technique allows individual models in a block to be replaced with more detailed ones as the design process proceeds. This makes it possible not only to verify the functionality and performance of the block but also to obtain detailed simulation results closer to its real-world operation.



DC: direct current

Figure 2. Block diagram of EPS system and its simulated characteristics in detailed design phase

When the torque assist block is replaced with a three-phase inverter circuit model, a simulation indicates that a ripple generated by switching operations is superimposed on the motor current.

3. Reduced-order modeling technique for high-accuracy and high-speed simulation

Increasing the level of model detail of all blocks causes a substantial increase in simulation run-time. This is attributable to two factors. The first factor is a difference in latency among different blocks. For example, the EPS system shown in Figure 2 consists of a mechanical block consisting of such mechanical components as a reduction gear and an intermediate shaft and an electronic torque assist block. The mechanical components have a latency on the order of milliseconds whereas the inverter in the torque assist block has a latency of nanoseconds because of MOSFET switching operation. Suppose that the EPS system is simulated with a time step tailored for the inverter operation. Then, the same calculation is unnecessarily repeated for the mechanical components even when the inverter is not switching.
The other factor is the computation time required for MOSFET SPICE models. Typically, SPICE computation is extremely complicated and time-consuming because each SPICE model consists of 100 to 200 parameters.
It is generally necessary to simulate several tens of seconds to several minutes of circuit behavior in order to verify system operation. However, a single simulation sometimes takes several days because of the above-mentioned factors. To reduce the simulation run-time without compromising the computational accuracy, we have developed the Accu-ROM technique.

3.1 Model order reduction of the mechanical model

There is a substantial difference in latency between the mechanical model and the inverter, as described above. Since the detailed switching operation of the inverter does not affect the simulation results of the mechanical model, a simplified on-off switch model can be used for the inverter when you need to focus on the circuit behavior of the mechanical model alone. In this case, the inverter on-off conditions can be tracked with a coarse simulation time step. On the other hand, it is necessary to reduce the simulation time step to a small value when verifying the circuit behavior of the inverter. It should be noted, however, that the inverter exhibits the same behavior regardless of the contents of the mechanical model as long as the load torque connected to a motor is constant. Therefore, the Accu-ROM technique is designed to reduce the computational complexity by breaking a simulation into two phases.
In the first phase, the SPICE models for the MOSFETs of the inverter are replaced with simplified switch models, and a simulation is performed with a coarse time step. Since the inverter shown in Figure 2 has a simulated switching frequency of 6.5 kHz (i.e., a cycle period of 153.85 µs), we set the simulation time step to 15 µs, or one-tenth of the inverter's cycle period. The simulation in this phase provides the characteristics of the entire mechanical model.
In the second phase, the mechanical model is deleted as shown in **Figure 3**, and the torque source is connected to the motor so that it is fed with the characteristics of the mechanical model obtained in the first phase. For the feedback signals from the mechanical model to the motor control model, we used the control command values obtained in the first phase. The resulting mechanical model makes it possible to simulate the inverter behavior at high speed.

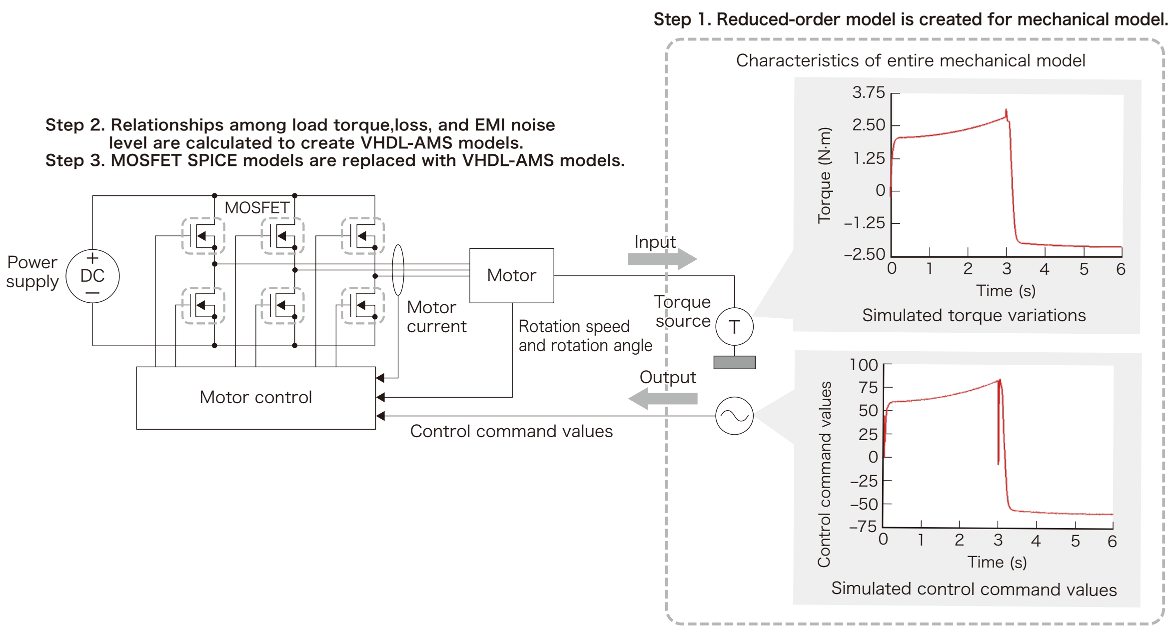


Figure 3. Flow of processes for calculation using Accu-ROM technique

A simulation using the Accu-ROM technique consists of steps 1 to 3 and verifies not only the functionality and performance of a system but also its heat generation and EMI noise at high speed.

3.2 Reduced-order modeling for the MOSFET

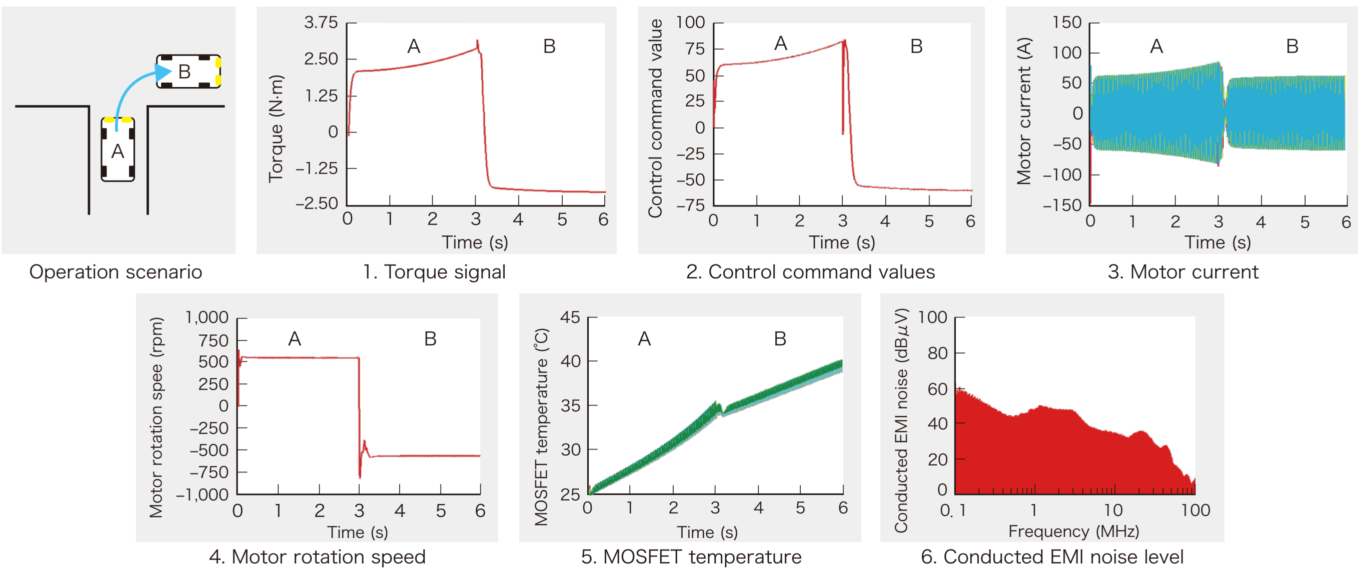
In order to reduce the computation time of the MOSFET model, we have developed its reduced-order model specifically designed for heat and EMI noise evaluation.

In Figure 3, a motor is connected to the torque source as described above. We replace the MOSFETs in this circuit with their SPICE models and set the simulation time step to a value small enough to simulate their switching characteristics. This circuit is used to calculate the amounts of switching loss and EMI noise beforehand while changing the load torque over the motor's specification range.

Next, we create VHDL-AMS (Very-High-Speed IC Hardware Description Language-Analog and Mixed Signal) models that incorporate a table or a regression equation representing the relationship among switching loss, EMI noise, and load torque. These VHDL-AMS models are used to replace the MOSFET SPICE models. During system verification, the VHDL-AMS models are referenced according to the load torque produced by system operations, eliminating the need for SPICE calculations. This makes it possible to calculate the amounts of switching loss and EMI noise at high speed.

3.3 Reducing the computation time using the Accu-ROM technique

Figure 4 shows the results of analysis using the Accu-ROM technique. These results represent the operation of an EPS system while an automobile is turning right. The motor current and the motor rotation speed shown in Figure 4 match the results obtained using non-reduced-order SPICE models while a MOSFET temperature (junction temperature) and EMI noise have an error of only 1.18°C and less than 0.5 dBμV, respectively. This demonstrates that the Accu-ROM technique enables high-accuracy system verification. Here, we calculated the amount of heat generated based on the current and voltage flowing through the MOSFETs and used them as heat sources to obtain the MOSFET junction temperature by means of peripheral thermal circuit models. We also connected a line impedance stabilization network (LISN) to the power supply in accordance with CISPR 25 (Comité International Spécial des Perturbations Radioélectriques 25; English: International Special Committee on Radio Interference 25) and calculated the resulting conducted EMI emissions by monitoring the voltage across the LISN terminals using the voltage method[1]. A simulation using the Accu-ROM technique took only 3 hours and 27 minutes (10 minutes to calculate the characteristics of the mechanical model and 3 hours and 27 minutes to perform a detailed analysis) whereas a simulation using non-reduced-order SPICE models took 32 hours and 51 minutes. So, the Accu-ROM technique reduced the simulation run-time by roughly 90% without compromising the accuracy.



Technique used	Detailed modeling	Accu-ROM technique
Analysis time required	32 hrs. 51 min.	3 hrs. 27 min.

Figure 4. Results of verifications of EPS system using Accu-ROM technique

A simulation using the Accu-ROM technique indicated the same behavior as a simulation using SPICE models in terms of motor current, MOSFET temperature, and EMI noise.

4. Verification of a trade-off between heat generation and EMI noise

Generally, there is a trade-off between the heat and EMI noise generated by switching operations. Increasing the switching speed helps reduce the switching loss, but causes an increase in EMI noise because of ringing. Conversely, reducing the switching speed helps reduce ringing, but causes an increase in switching loss and thus heat generation. It is therefore necessary to repeat simulations under various conditions in order to find the optimal conditions that satisfy both heat and EMI noise specifications. So, we performed verifications using the Accu-ROM technique described in Section 3.

Figure 5 shows the results of verifications of MOSFET temperature and EMI noise while changing the switching speed. At high switching speed, the EPS system generated less heat, but did not satisfy the EMI noise level required by CISPR 25 Class 5. At low switching speed, the EPS system satisfied the EMI noise requirement, but generated more heat.

The MBD and Accu-ROM techniques make it possible to simulate the generated heat and EMI noise at high speed. These techniques are effective for choosing the right MOSFET and the MOSFET switching speed. Even when it is difficult to satisfy both the heat and EMI noise specifications, these techniques provide guidelines for creating a thermal design with less heat generation while reducing the parasitic inductance of a printed circuit board to reduce EMI noise.

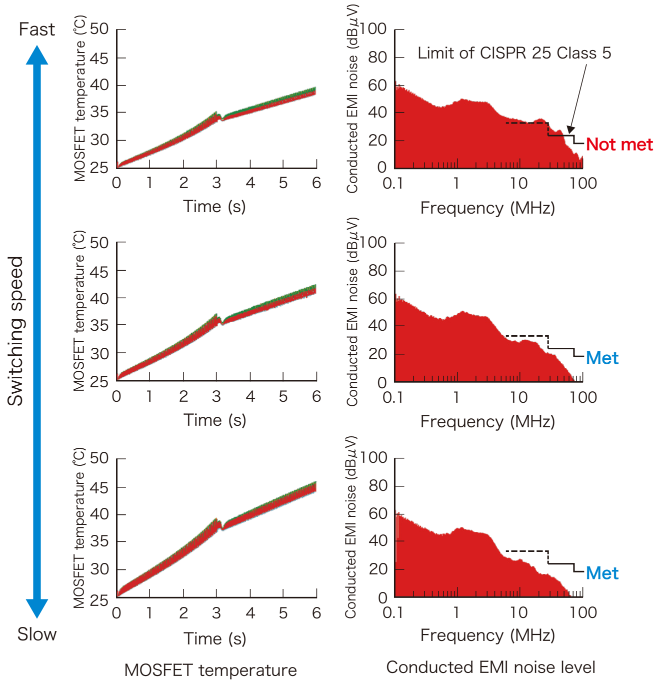


Figure 5. Results of verifications of heat generation and noise when changing switching speed

Increasing the switching speed helps reduce heat generation, but makes it difficult to satisfy the EMI noise limit specified by CISPR 25 Class 5. Conversely, reducing the switching speed helps satisfy the EMI noise limit, but causes an increase in heat generation.

5. Conclusion

We have developed the Accu-ROM technique that makes it possible to simulate the generated heat and EMI noise at high speed and with high accuracy. This technique enabled us to expand the applications of MBD because of the reduced simulation run-time.

We will employ the Accu-ROM technique to develop low-noise MOSFETs with high heat dissipation performance as well as control ICs with a slew rate control driver that helps reduce both heat generation and EMI noise. We will use this technique not only to develop semiconductor products but also to assist customers in developing excellent ECUs with high heat and EMI noise tolerance.

References

(1) CISPR 25 Ed. 4.0: 2016. Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers, IEC.