Development of CRAMAS Motor Board

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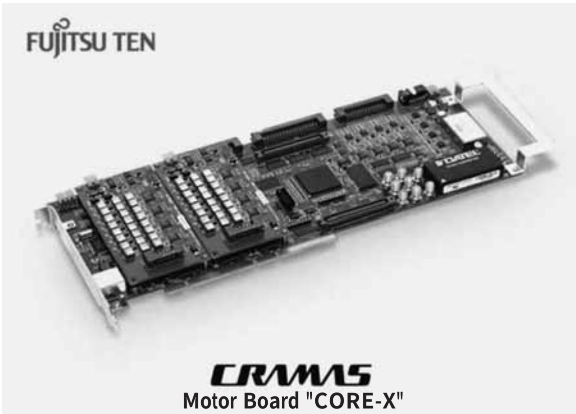

Abstract

In recent years, the demand for motor control has been rising due to the computerization in vehicles. Recent motors require an advanced control system and must handle high current flow. Therefore, in terms of motor control development, verification of motor-controllers through a simulator system has become more important to avoid dangers involved in actual vehicle testing, and having to prepare large scale facilities for this purpose.

CRAMAS is a unique simulator developed by FUJITSU TEN. It is now being widely utilized in the automotive industry as a solution in their development process. Now we have succeeded in developing a new CRAMAS Motor Board in response to increased demands in motor control systems and succeeded in producing a motor simulator with the highest class precision in the industry.

1 Introduction

1.1 Rise in demand for motor control

In recent years, the demand for motor control has been rising due to the computerization in vehicles. Motors, which have been used mainly for power windows, sunroofs, and other body related components, are now extending into the field of basic automobile functions such as "driving, turning, and stopping", and their numbers are continuing to grow (Figure 1). In regards to the "Driving" function, electric vehicles and hybrid vehicles (EHVs hereafter) using electric motors for their driving force are already in actual use. Introduction of motors in "Turning", has started with electric power steering, and now a lane keeping assist system is in use, that augments the steering operations of the driver to prevent a vehicle from deviating out of a traffic lane. These motors that are utilized for basic driving functions, require an advanced control system and must handle high current flow in comparison to motors used in body components. Therefore, in terms of motor control system development, verification of motor-controller through a simulator system has become more important to avoid dangers in actual vehicle testing, and having to prepare large-scale facilities for this purpose.

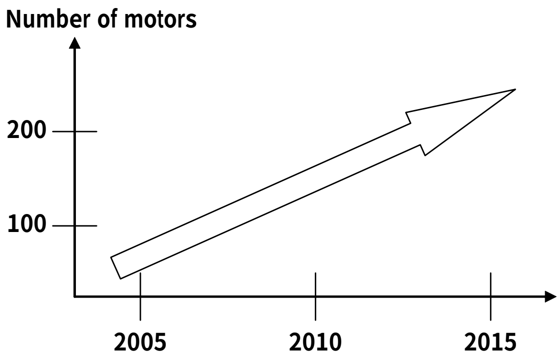

Fig.1 Number of motors per vehicle (estimate)

1.2 CRAMAS

CRAMAS is a unique simulator developed by Fujitsu Ten.

Fig.2 External view of CRAMAS

The most significant feature of CRAMAS is that it can simulate a target controlled system in real time. It is classified typically as a HILS (Hardware In-the-Loop Simulator). Initially, it was being utilized as a tool for evaluating our own ECUs (Electronic control Units), but it is now being used widely in the automotive industry as a solution to their development process. By introducing a solution utilizing CRAMAS, it is possible to perform all processes on the desktop, from the development of control system to the evaluation and debugging of various ECUs. It has been proven to have an effect in reducing development times and reducing cost.

Now we have succeeded in developing a new CRAMAS Motor Board in response to increased demands in motor control systems and succeeded in producing a motor simulator with the highest-class precision in the industry. This report describes the content and results of Motor Board development.

2 Characteristics of motor simulation

2.1 High precision simulation

The accuracy of a simulation depends on how precisely the target controlled system, i.e. actual system, is simulated. Higher accuracy means that there is less behavioral difference with the actual system, and the possible field of simulator application is broadened. However in order to improve precision, the calculating performance of the simulator needs to be substantially high, but attaining that level is limited by the price range of a simulator targeting automobile manufacturers. That is why instead of depending solely on calculating performance, we have developed a unique method of motor simulation that utilizes cooperative control of a hardware macro and software.

2.2 Simultaneous simulation of multiple motors

There are many systems in which motors are controlled simultaneously, such as EHVs. If a simulation is performed in series individually for every motor, the model processing performance must be increased according to the number of motors. However, there is a limit to the performance improvement that is possible. Therefore in the developed Motor Board, we have utilized a method of simulating multiple motors in parallel. In this method, the number of Motor Boards can be increased according to the number of motors that are going to be used, to achieve a high precision simulation that is equivalent to a 1-motor system.

2.3 Other functions

To improve their usefulness in control system development, the following functions were added to the Motor Board.

<New features of the Motor Board>

- Phase voltage measurement function at neutral point of motor.
- Measurement function for element current flow through the IGBT (Insulated Gate Bipolar Transistor)
- Inverter DC current measurement function

3 The Motor Board

3.1 System configuration

The CRAMAS allows flexible compatibility with any targeted system through combination of optional boards. For types of optional boards, there are CORE Boards that handle special signals of automobiles (described in Chapter 4) and various communication boards.

Motor Boards are supplied as one of the optional boards for CRAMAS. The most significant feature of the Motor Board, is that the series of motor simulation operations are concluded within the Motor Board itself. The configuration example of a CRAMAS system is shown in Figure 3. In this example, a motor control feature is added to a simulator for engine control development. By adding a Motor Board to an unused slot of a CRAMAS system, it is easy to add motor simulation features.

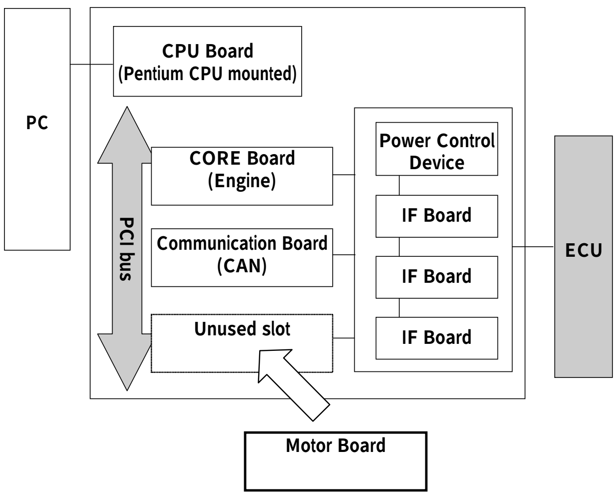

Fig.3 Additional implementation of the Motor Board

3.2 Cooperative control of hardware macro and software

In order to raise precision and perform parallel processing in the simulation, a hardware macro and software cooperative control technology was introduced into the Motor Board. The software processes data in order, and the hardware macro instantly performs circuit calculations of multiple input signals, and converts the results into data that the software can process. While the software can be altered, the hardware macro is a fixed circuit that cannot be changed after it is equipped.

In CRAMAS, the hardware macro is equipped on a FPGA (Field Programmable Gate Array) for flexibility so that it can be compatible with variations and changes in specifications.

The Motor Board is a "CORE-X Board" equipped with a motor model. Refer to Chapter 4 for the "CORE-X Board", and Chapter 5 for the modeling of a motor model.

4 The "CORE-X Board"

In order to achieve cooperative control of hardware macro and software - the key to raising motor simulation precision, we have developed the new "CORE-X Board". This board is the flagship product of the CORE Board series.

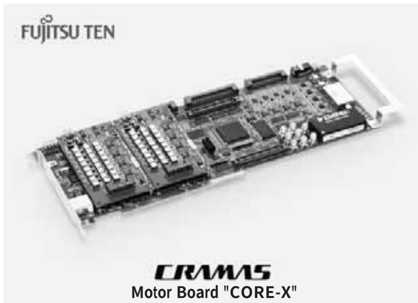

Fig.4 External view of the Motor Board

4.1 CORE Board

The CORE Board is a board combining a microprocessor and large scale FPGAs, to provide the required interface according to the application of CRAMAS.

4.2 CORE Board (previously released product)

The previously released CORE Board combines multiple devices such as microprocessors and FPGAs to provide required functions as shown in Figure 5. The software is implemented in the microprocessor, and the hardware macro is implemented in the FPGAs, but in the cooperative control of the hardware macro and software, the data communication speed among them becomes of utmost importance.

The previously released CORE Board uses a total 4 devices including a microprocessor and three FPGAs, and in this configuration, a performance drop due to the bottleneck in communication speed is unavoidable when dealing with large scale models such as motor simulations, where the model is cooperatively controlled by the hardware macro and software.

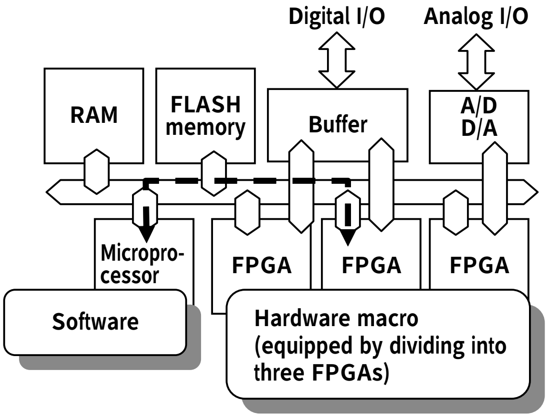

Fig.5 CORE Board (released product)

4.3 "CORE-X Board"

The main feature of the "CORE-X Board" is that a CPU- integrated large capacity FPGA was newly adapted.

As shown in Figure 6, the high speed microprocessor and large capacity FPGA are combined into one device, as opposed to the previously released CORE Board. As a result, the hardware macro and software was connected through high-speed internal device communication, and the system bottleneck, which was the obstacle in high accuracy of motor simulation, was solved.

In addition, by expanding FPGA capacity, we were able to adopt a high level synthesis tool that, although still considered inferior to hardware programming language in implementation efficiency, is expected to raise design efficiency.

High-level synthesis is a technique for designing a hardware macro through C language that is used mainly in software industry. This design method is best suited for the cooperative control between hardware macro and

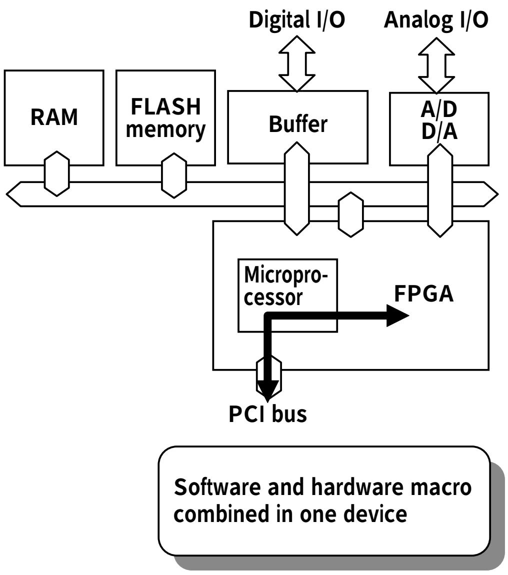

Fig.6 CORE-X Board

software, and we hope to expand its range of application in the future.

In addition, some special slots for adding sub-boards were equipped on the "CORE-X board". By using these slots, it has become possible to equip physical interface circuits required for hardware macros by the sub-board development only. It is also possible to add standard communication functions such as CAN (Controller Area Network).

We are also evaluating the possibility of allowing hardware macro design and physical interface design at the sub-board to be performed freely by CRAMAS users themselves in the future.

5 Modeling

Previously, motor models were software processed, so there was a limit to improving processing speed, and it was difficult to achieve parallel processing of multiple motors. To enable parallel processing and high-speed calculation, we have now equipped the main circuits onto the "CORE-X Board" as a hardware macro. By the software implementation, model parameters that require alteration during its execution can be handled with flexibility for different variations and changes in specifications.

5.1 Inverter modeling

The inverter model used to calculate the output voltage vector from the IGBT switching combinations per calculation cycle, and a time-mean model, which calculates a 3-phase voltage, was being used. The overview of this model is shown in Figure 7.

However in an actual inverter, there is an effect from dead -time control (shortage prevention control) which prevents DC current power short caused by two IGBTs connected in series in each phase turning on simultaneously. Therefore especially in a low revolution range in this model, the motor current waveform will be disrupted, and a torque ripple will occur. Because the time-mean model which ignores the ON/OFF logic of series-arranged, IGBTs cannot simulate this effect from dead-

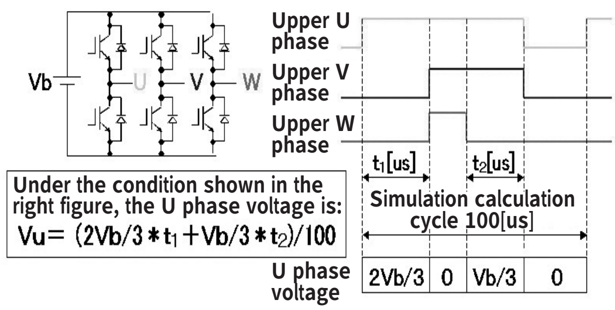

Fig.7 Inverter time-mean model

time, a lack of precision occurs in evaluation of dead-time compensation algorithms.

In order to simulate this dead-time effect, individual IGBTs were newly modeled as ideal switches. The phase voltage based on the DC power hypothetical neutral point becomes Vb/2 when the upper IGBT turns ON, and becomes -Vb/2 when the lower IGBT turns ON. The dead-time phase voltage when both upper and lower IGBTs are OFF, will be Vb/2 because the upper diode is powered at current<0 according to the polarity of the phase current and will similarly be ?Vb/2 when current >0. (Figure 8)

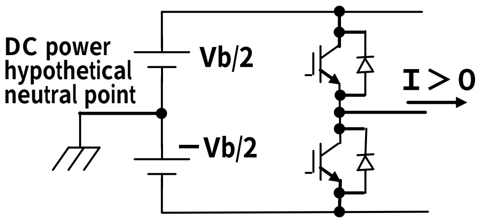

Fig.8 Inverter ideal-switch model

Furthermore, a device characteristic model is required when simulating inverter loss, etc. and an even higher accurate simulation ability is still required. We plan to continue to work in raising precision, by considering the coordination and coupling between circuit simulators and CRAMAS.

5.2 Motor modeling

The motor can be divided mainly into electrical characteristics and mechanical characteristics. The voltage to current conversion part of the electrical characteristics requires high-speed calculation, and because this part in itself is not changed very often, it has been made into a hardware macro. On the other hand, the torque to revolution conversion part is a mechanical characteristic so it can be software processed, and because this part is necessary to change frequently according to the targeted system, it was written in MATLAB/Simulink. Thus, the cooperative control structure was adopted between hardware macro and software. Now, the model that was converted into a hardware macro is described below.

A dq-axis coordinate model based on voltage equation(1) was utilized for the motor model.

$$\begin{pmatrix} Vd \\ Vq \end{pmatrix} = \begin{pmatrix} R+pLd & -\omega Lq \\ \omega Ld & R+pLq \end{pmatrix} \begin{pmatrix} id \\ iq \end{pmatrix} + \begin{pmatrix} 0 \\ \omega \Phi \end{pmatrix} \cdots (1)$$

Here, Vd/Vq are d-axis/q-axis voltages, R is armature resistance, p (=d/dt) is the differential operator, Ld/Lq are d-axis/q-axis inductance, ω is angular velocity, iq/id are d-axis/q-axis current, and Φ is armature flux linkage.

In the dq-axis coordinate model, if the parameters such as inductance are assumed as a fixed value, the effect of higher harmonic element cannot be simulated, so there will be a problem in simulation accuracy. Therefore, these were made so that the model parameters can be handled as variables. A pattern signal edit window is useful for the setting of these variable parameters. For example, as shown in Figure 9, the parameter of inductance influenced by rotor position can be set easily by plotting with a mouse.

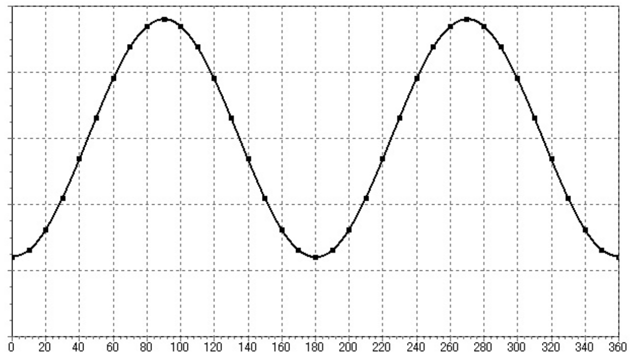

Fig.9 Pattern signal edit window

However, in order to accurately simulate the effects from motor structure and steel core material properties, a precise motor model is required. We will continue hereafter working in electromagnetic field simulators and also the coordination/coupling between CRAMAS and them.

6 Simulation results

The results of the actual simulation is summarized below.

6.1 Improvement in precision

The effect of dead-time shows up as a distortion near 0A in a 3-phase current waveform. This is especially noticeable at low revolution ranges.

Figure 10 shows the comparison results among the measurement data of actual motor and the motor simulation data from the new method and the old method. The old method could not simulate this distortion because the inverter model was a time-mean model, but the new developed high accurate method has replicated this distortion.

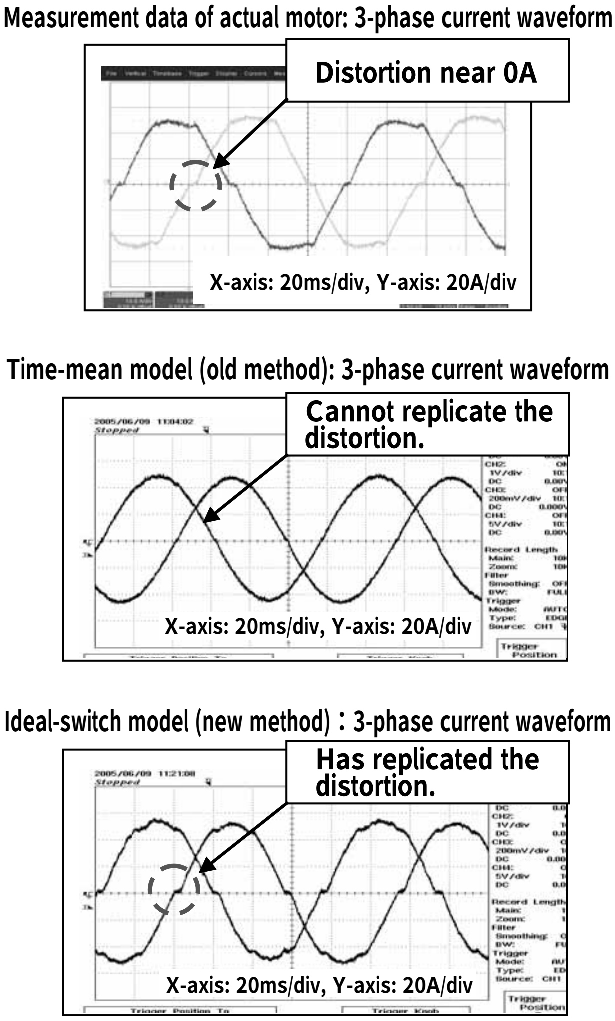

Fig.10 Dead time effect

6.2 Additional new features

A function to measure the phase voltage at the motor neutral point that is not possible to measure in an actual system was also newly added. Figure 11 shows the measurement examples of phase voltage and phase current.

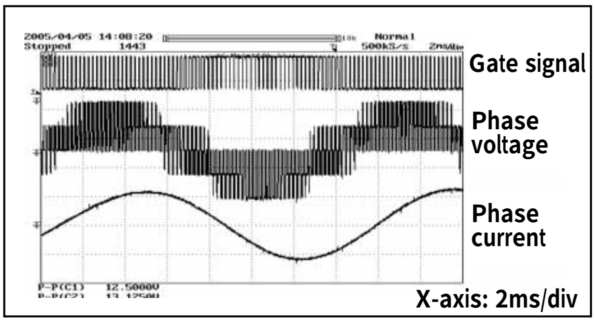

Fig.11 Example measurement data for phase voltage

Furthermore, a current measurement function at upper and lower IGBTs' elements, for each U, V, and W phases of inverter, was newly added. This function makes it possible to use the simulator for the evaluation of fail-safe algorism (Ex. gate drive signal malfunctions). For example, gate malfunction locations can be set by selection through the GUI (Graphical User Interface) of CRAMAS, and the behavior of element current during a fault occurrence can be monitored in real time. This method allows various evaluations that would normally be dangerous in an actual vehicle or system. The measurement data of the element current waveform is shown in Figure 12.

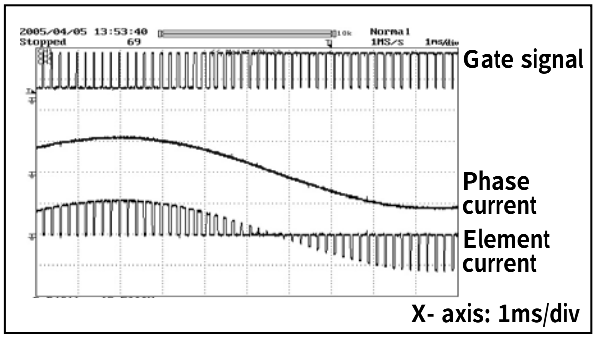

Fig.12 Example measurement data for element current

By utilizing motor simulations, it is possible to evaluate and verify EHVs and other motor control systems in an environment with no actual vehicle or system, without using large amount of electrical power.

Furthermore, an inverter DC current measurement function was added to be compatible with the latest sensorless motor control. The overview of sensorless motor control is shown in Figure 13. This function simulates current flow at the shunt resistance for inverter over-current protection, and the ECU calculates a 3-phase current based on this signal through an algorithm. Through this function, it is possible to utilize the simulator in cost down evaluations using current sensorless motor control.

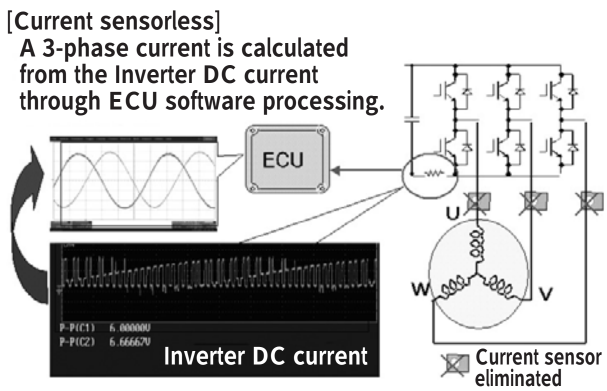

Fig.13 Sensorless current control

All of these functions described above comprises the newly developed motor simulator for motor control system development.

7 Conclusion

Our development described herein has succeeded in creating a high precision motor simulator. The outline view of this motor simulator is shown in Figure 14.

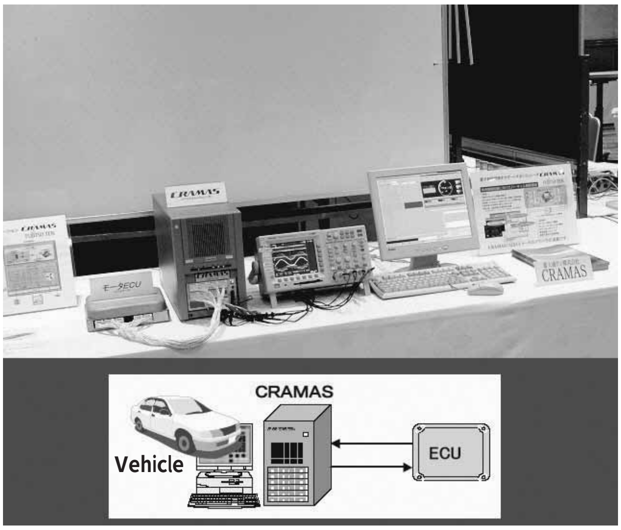

Fig.14 External view of the motor simulator

In automotive related fields, the number of motors being used is rising, and it is expected that the demand for motor simulation will be increasing hereafter. In the market, miniaturization and creation of higher speed motors is expected to continue, and motor control is likely to rapidly become even more complex. Therefore we will try to continue our efforts to further improve precision of simulations.

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