# Hitachi Electric Drive Solutions that Contribute to Global Environment

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*OVERVIEW: The trend in automobiles, servo machine tools, and similar products is to replace engine, hydraulic, and other mechanical drive systems with electric drive systems that utilize an electric motor in anticipation of significant energy savings and improvements in system performance. It is expected that this shift to electric drive will become widespread in industry and social infrastructure over the coming decades. The adoption of electric drive involves more than just using an electric motor as the power source, it also requires techniques for making effective use of energy across the entire system. To promote the wider adoption of electric drive, Hitachi intends to supply solutions that meet diverse requirements for electric drive including motors, batteries, and other key components, and also new control techniques that are in harmony with the overall system.*

## INTRODUCTION

ELECTRO-MOTORIZATION means replacing a mechanical system powered by an engine or hydraulics with a motor system comprising an electric motor, inverter, and batteries or power supply. Features of electric drive include superior environmental performance as measured by things like energy efficiency and lower greenhouse gas emissions, and better performance of the mechanical load when driven by a motor.

The technology is becoming steadily more widespread and, in addition to HEVs (hybrid electric vehicles) which are a well-known example of electric drive, it is also finding applications in industry and social infrastructure such as servo machine tools (presses, injection molding machines, etc.), hybrid locomotives, and electrically operated construction machinery. Whereas applications that have traditionally used an electric motor have sought to improve efficiency when running under constant conditions, a feature of replacing existing systems with electric drive is that it enables large changes in output torque to be made rapidly when operating under continuously varying conditions. It also allows energy efficiency to be improved through cyclic energy use. One specific example is regenerative power generation whereby electric energy is recovered from the kinetic energy of the mechanical load during braking and used to charge a battery.

Electric drive systems require each component to be custom-made for the application. For example, motors are designed for specific applications and the chassis made as small as possible, taking account of ease of installation.

This article describes solutions for future electric drive systems proposed by Hitachi and the new control techniques that realize them.

## HARMONIOUS MOTOR SYSTEM

The transition from engine or hydraulic power to

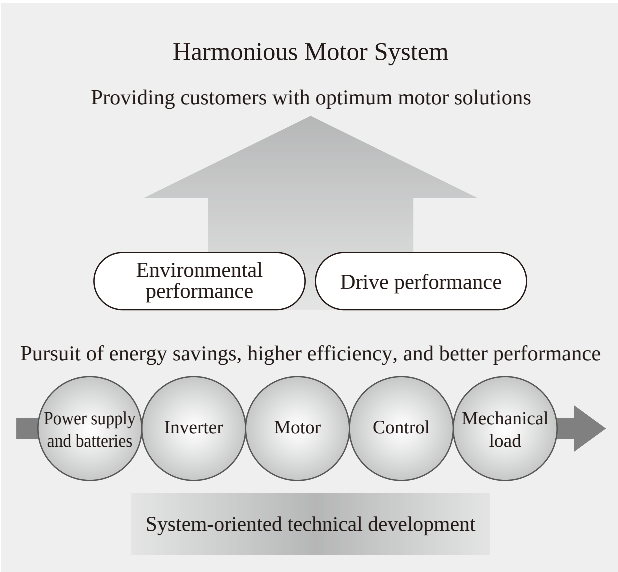
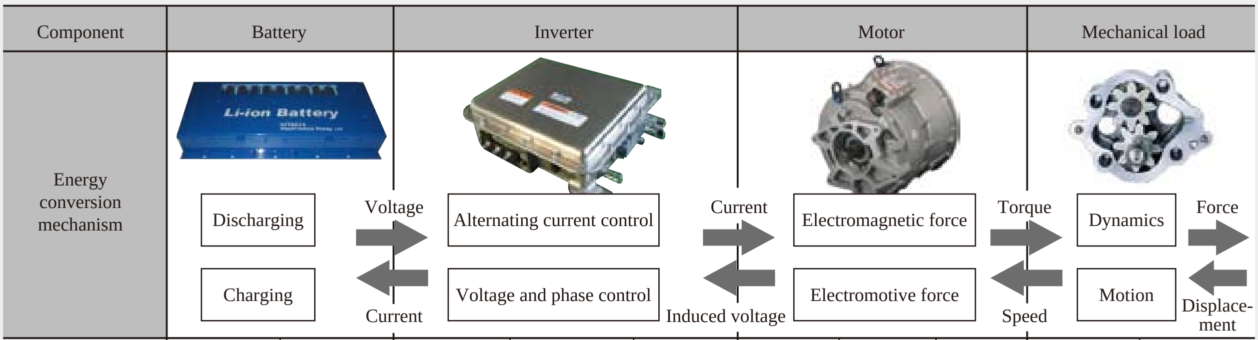



*Fig. 1—Harmonious Motor System Concept.*
*The concept seeks to supply customers with the motor solution that best suits their needs by delivering both environmental and drive performance.*




| Constraint | Current | Resistance | Control delay | Pulse modulation | Device | Volume | Magnet | Ripple | Friction | Vibration |
|---|---|---|---|---|---|---|---|---|---|---|
| Environmental requirement | ● | ● | | ● | ● | ● | ● | ● | ● | |
| Drive performance requirement | ● | | ● | ● | | ● | | ● | | ● |

*Fig. 2—Interrelationships between Components in Electric Drive Applications.*
*Harmonious control of the electric drive system is achieved by considering the interrelationships between the battery, inverter, motor, and mechanical load based on their respective energy conversion mechanisms.*

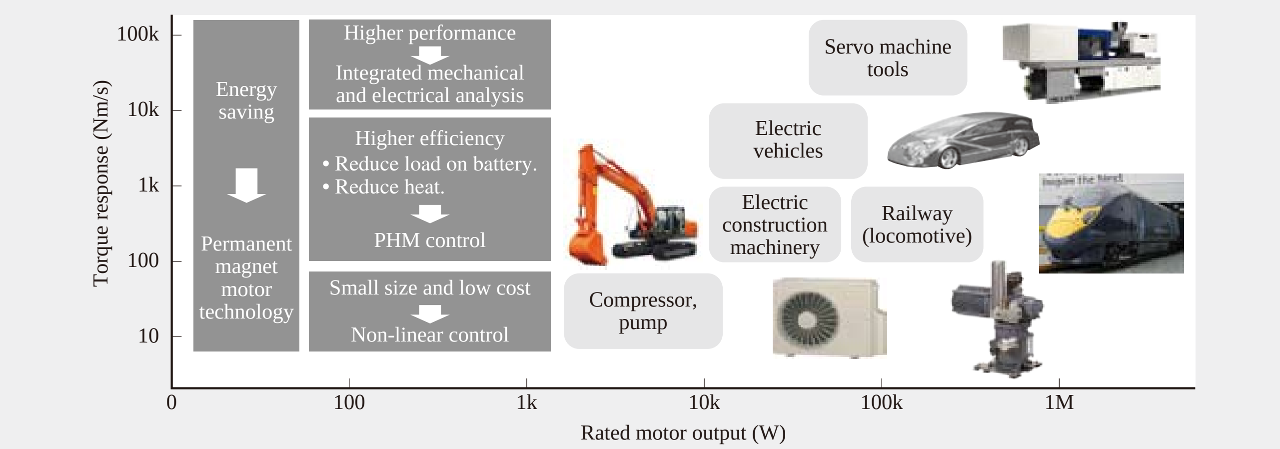
electric drive presents an opportunity to incorporate advanced functions and make energy efficiency improvements that were not possible on previous mechanical systems. Hitachi is promoting the Harmonious Motor System concept as a solution to the various requirements and challenges faced when adopting electric drive (see Fig. 1). The Harmonious Motor System concept recognizes environmental performance and drive performance as being the two key issues for electric drive and seeks to offer system-oriented solutions by harmonizing the operation of the power supply and batteries, inverter, control system, motor, and mechanical load.

Measures for the harmonious integration of the components in an electric drive system start from a consideration of the interrelationships between the batteries, inverter, motor, and mechanical load based on their respective energy conversion mechanisms. Fig. 2 shows examples of these interrelationships. The charging and discharging characteristics of a battery are determined by chemistry and the battery's voltage and current parameters characterize its connection to the inverter. The inverter performs AC (alternating current) control (including frequency conversion) and voltage/phase control based on external commands. The motor uses the AC output of the inverter to generate electromagnetic force and produce torque. The motor applies this torque to rotate the mechanical load which determines the speed. If the motor is made to rotate by an external power source, it generates electromotive force which is applied to the inverter as a voltage. Finally, the motor torque and speed determine the power and displacement of the mechanical load.

Although the energy conversion mechanisms of each component are different, there is continuity in that the input and output of each can be physically characterized in terms of power (or work). The Harmonious Motor System performs quantitative analysis of the operation of the system in the design stage by modeling the physical characteristics of each component and studying these in an integrated simulation.

Fig. 2 also shows which of the constraints (main design parameters for each component) play a part in satisfying the environmental and drive performance requirements of the system. Constraints that affect both the environmental and drive performance are the current in the case of the battery, the pulse modulation for the inverter, and the volume and level of ripple for the motor. Hitachi is working on obtaining harmonious solutions by solving the control problem for the batteries, inverter, motor, and mechanical load with reference to these constraints.

Fig. 3 shows the recommended technologies for different application fields. For applications such as compressors and pumps that use motors with comparatively low output and slow torque response, Hitachi has developed non-linear control for permanent magnet motors[1]. For battery-equipped vehicles such as electric cars or construction machinery, Hitachi is currently developing highly efficient PHM (pulse harmonic modulation) control[3]. For applications such as servo machine tools that require instantaneous control of several tens of thousands of Nm of torque,




PHM: pulse harmonic modulation

*Fig. 3—Core Technologies for Electric Drive Systems.*
*These systems are based on electric drive of a permanent magnet motor and feature new control techniques and effective analysis techniques for system design.*

Hitachi has devised analysis techniques that treat the mechanical and electrical parts as a single system and which are used for tasks such as system design and improving equipment performance[4]. By applying these core technologies, Hitachi is able to supply motor solutions that are optimized for a wide range of different needs.

## NON-LINEAR VECTOR CONTROL TECHNOLOGY FOR REDUCING MOTOR SIZE AND IMPROVING RESPONSE

### Motor Non-linearity

Two important factors in the adoption of electric drive are improving the efficiency and reducing the size of the electric motor. This is why motor design can be thought of as a process of optimizing the motor's efficiency and size. However, because the motor is only one part of the system, how the motor is to operate within the system, specifically its response performance, is also very important. The main determinant of this response performance is the control technique.

As shown in Fig. 4, flexible torque response can be achieved by incorporating a control model into the controller based on the motor characteristics (represented in the figure by the transfer function *G*, with the control model being the inverse transfer function $G^{-1}$). The typical way in which this is done is called "vector control."

Permanent magnet synchronous motors are part of the impetus behind the current trend toward the adoption of electric drive but are more difficult to control than previous types of motor. The reason for this difficulty is the motor's non-linear response shown

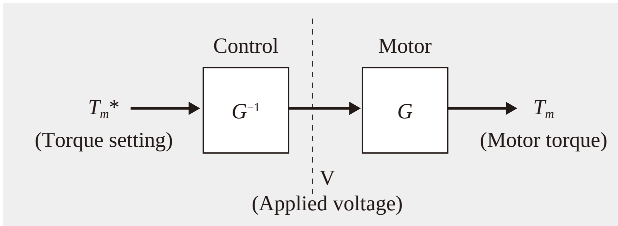



*Fig. 4—Relationship between Motor Characteristics and Control.*
*Flexible motor torque control can be achieved by implementing a control system based on an inverse model of the motor's transfer function (G).*

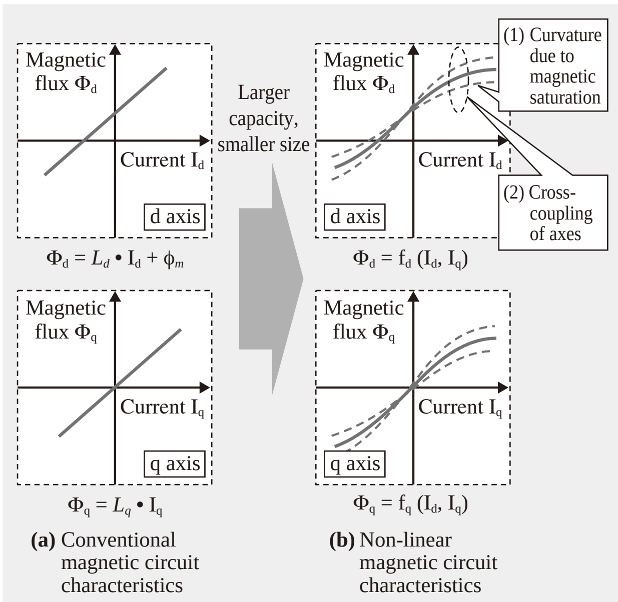



*Fig. 5—Magnetic Circuit Non-linearity of Flux in Motor.*
*The relationship between current and magnetic flux is a curve (non-linear) rather than a straight line (linear), and cross-coupling also occurs between the d and q axes.*

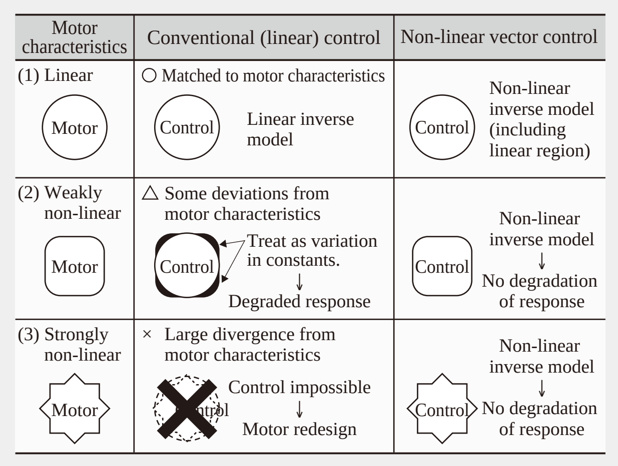



*Fig. 6—Concepts of Linear and Non-linear Control Based on Motor Characteristics.*
*Optimum control can be achieved without loss of response performance by adopting a control scheme appropriate to the motor characteristics.*

in Fig. 5. Previously, the magnetic circuit in the motor could be treated as behaving linearly and the control system designed based on linear control theory. For motors that use permanent magnets, however, the more the output density is increased the more the behavior diverges from linearity, with the appearance of non-linear effects such as magnetic saturation and cross-coupling between axes. This degrades the response and means a large amount of time needs to be spent tuning the system to achieve the desired response. This has a particularly large impact when using sensorless control (a control technique that does not use a sensor to detect rotor position), an approach that has been used in a growing range of applications in recent years, making the treatment of non-linearity a major challenge.

### Non-linear Vector Control

Currently, the standard way of dealing with non-linearity is to use linear control but vary the motor constants. In some cases, measures such as de-tuning the motor design are used to achieve the desired control performance (see Fig. 6).

As an alternative, non-linear vector control was developed by mathematically modeling the motor's non-linearity(1) and redesigning vector control(2). Because non-linear vector control incorporates the non-linearity of the motor into the control model, the motor design is no longer constrained by the control method. This means the motor can be made as small as possible.

Fig. 7 shows the waveforms produced by a simulation of the response to an impact load applied to a motor that has been made as small as possible. Although the advantages of this method vary widely depending on factors such as the mechanical characteristics of the motor load and the load status, results have demonstrated the potential to reduce motor size by around 20% compared to before. As the problem of motor non-linearity is expected to become increasingly evident in the future, Hitachi believes that use of non-linear vector control will become essential.

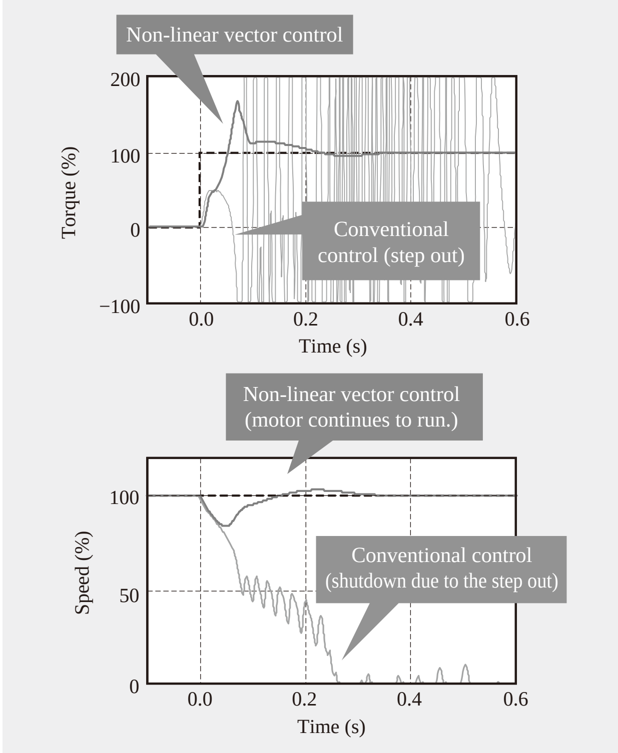



*Fig. 7—Comparison of Responses to the Out-of-range External Impact Load by Motor with Highly Non-linear Characteristics (Simulation).*
*The response performance when subject to a load disturbance can be improved by having the control system take account of the non-linearity.*

## NEW CONTROL TECHNOLOGY THAT HARMONIZES MOTORS, INVERTERS, AND BATTERIES

To implement an efficient integrated control system that harmonizes the motor, inverter, and battery, Hitachi is developing a new modulation method called PHM control(3) that is suitable for AC motor drive and a wide range of other applications.

### PHM Control

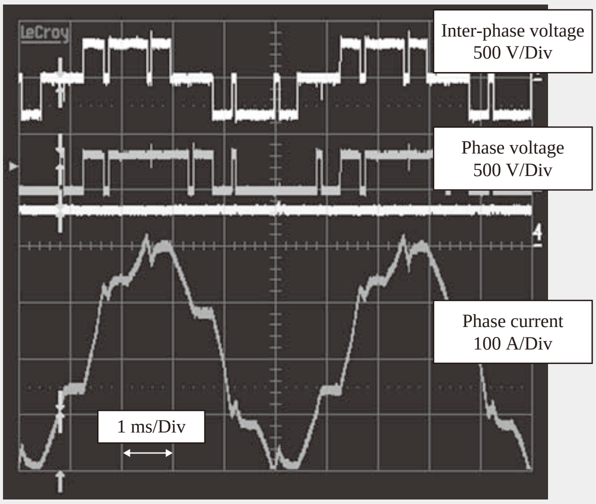
PHM control is a new modulation method that reduces inverter losses. The losses in an inverter are the sum of conduction loss and the switching loss in the IGBTs (insulated-gate bipolar transistor) or other devices. This control technique targets switching loss by reducing the number of switchings without increasing the distortion in the motor current.

A motor is an inductive load and the attenuation of the $n_{th}$ harmonic component of the motor current by the impedance is given by the formula $1/(n\omega L)$. Accordingly, when considering the effect that harmonics in the inverter output voltage have on the motor current waveform (motor current harmonics), the lower components of the harmonics have a greater influence than the higher components and therefore are responsible for more motor current distortion. This makes it is desirable to suppress lower order components in the inverter voltage output.

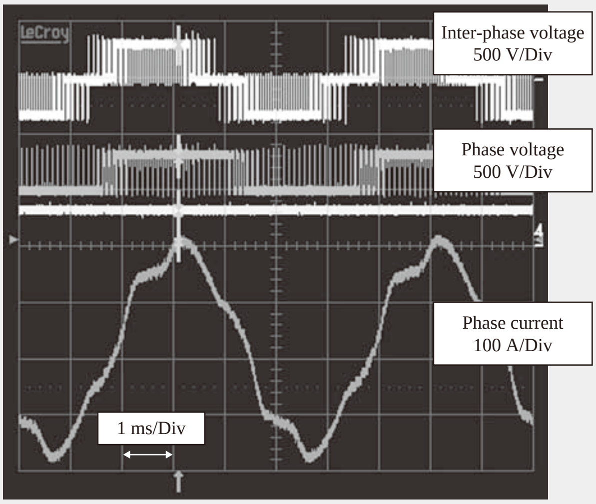
The standard sinusoidal PWM (pulse width modulation) control technique used for AC motor control reduces the harmonic component of the inverter voltage other than the fundamental by increasing the carrier frequency to perform more frequent switching, but this has the effect of increasing switching loss.

PHM control uses a simple algebraic formula to determine the minimum switching pattern to eliminate specific harmonic components by using the Fourier series expansion to establish a formula for the relationship between harmonics and the switching phase in the pattern of inter-phase motor voltages under specific conditions.

Fig. 8 shows an example comparing PHM and PWM control. PHM control does not need to perform the rapid switching used in sinusoidal PWM control. Using only about one-tenth as many switching events, PHM control can eliminate specific lower harmonics from the inverter output voltage while reproducing roughly the same motor current. Also, increasing the level of modulation in PHM control lengthens the widths of the inter-phase voltage pulses such that the inter-pulse interval disappears at a modulation level of 1.27 and the output changes seamlessly to a square wave (with no elimination of harmonics).




**(a)** PHM control (drive control technique using harmonic modulation and fewer pulses)




**(b)** PWM control

PWM: pulse width modulation HEV: hybrid electric vehicle

*Fig. 8—PHM Control (Elimination of 5th Harmonic) and PWM Control (10-kHz Carrier).*
*In a comparison using a prototype Hitachi motor with an electrical angle frequency of 250 Hz, the number of switching events per one cycle in electrical angle was five for PHM control and 50 for PWM control. This corresponds to 14.5% total current distortion for PHM control and 11.4% for PWM control.*

## Harmonious Integrated Control System

PHM control not only reduces inverter losses, it also helps improve the system efficiency of the motor, inverter, and battery.

PHM control has the flexibility to select a higher level of modulation than PWM control, primarily in the weaker magnetic field region. This makes it possible to use a high level of modulation, increase the output voltage to the motor, reduce the weak field current (reactive current), and reduce the motor current without diminishing the output. This helps reduce the motor copper loss and battery current (suppressing a drop in the charging capacity).

The motor characteristics change depending on the design of the magnetic circuit and the required total current distortion depends on the motor operating point. With PHM control, the higher harmonics in the motor current tend to be attenuated by the inductive

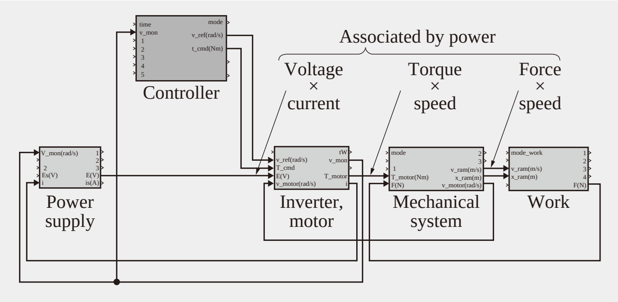



*Fig. 9—Overview of Integrated Simulator.*
*Coupled calculations are performed to investigate the operation of entire product systems by using power and intermediary variables to associate the calculations for the control, electrical, and mechanical systems.*

load impedance of the motor. However, if this attenuation effect is insufficient, the optimum voltage harmonics to be eliminated can be adjusted to suit the AC motor drive conditions by, for example, changing from elimination of the 5th harmonic to elimination of the 5th and 7th harmonics.

## INTEGRATED SIMULATION TECHNOLOGY FOR TOTAL DESIGN OF MECHANICAL AND ELECTRICAL SYSTEMS

### Overview and Benefits of Integrated Simulation Technology

In many products that use electric motors, the operations of the control, electrical, and mechanical systems are interdependent. Accordingly, designing the optimum motor unit or control logic, for example, needs to take account of these interactions and consider the overall product system. To this end, Hitachi has developed an integrated simulator that can perform analyses of the entire system (see Fig. 9).

The integrated simulator contains computational blocks representing the control, electrical, and mechanical systems which it associates primarily in terms of power to perform a coupled computation for the entire system. The calculations performed in the computational blocks include control calculations with accurate timings based on interrupts, motor characteristics calculations using magnetic field analysis, and mechanical efficiency calculations that take account of the load, speed, and other factors, and are able to predict the typically non-linear product characteristics with a high level of accuracy.

Fig. 10 shows an example of an integrated simulator calculation representing a forming operation performed by a press using a servo motor. The figure shows how the motor speed and torque are calculated accurately.

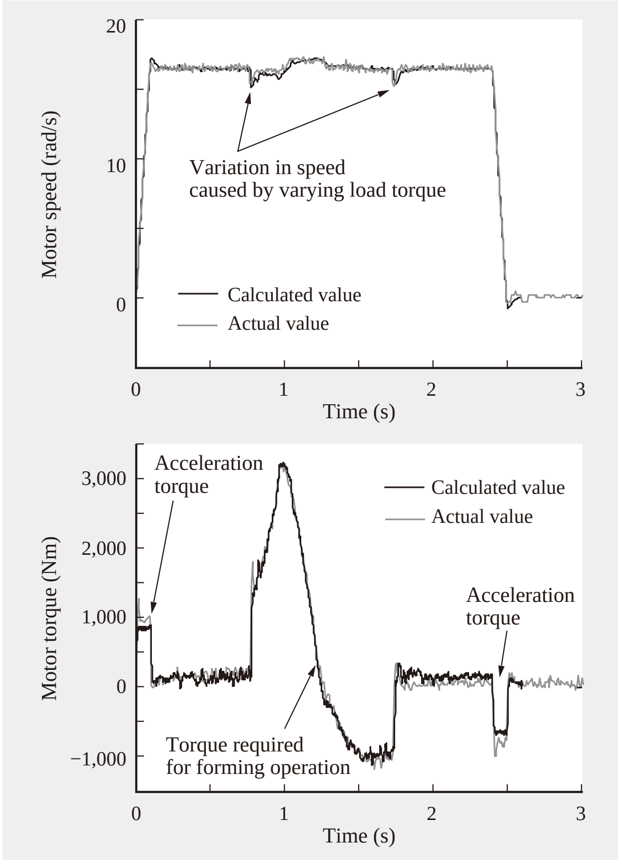



*Fig. 10—Example Calculation Using Integrated Simulator.*
*The graphs show comparisons of actual and calculated data for a forming operation performed by a press driven by a servo motor. The simulation accurately calculates the acceleration torque required to bring the mechanical system up to speed, the torque required for the forming operation, and the variation in speed caused by the varying load torque. These results simulate a forming operation performed by a servo-press using a low-speed, high-torque servo motor and were obtained in cooperation with Aida Engineering, Ltd.*

Another use for the integrated simulator utilizes its ability to perform quantitative analyses of the effects of design changes. This method performs parameter optimization in a way that treats the control, electrical, and mechanical systems as a coupled system, with trial calculations used to identify what are in effect optimum values.

### Analysis of Motor Drive System Taking Account of Mechanical Characteristics

The models of the mechanical system used in the integrated simulator are constructed with a high degree of precision to ensure that calculations of the mechanical load imposed on the motor are performed accurately and especially to identify problems in practical operation such as resonance or points where

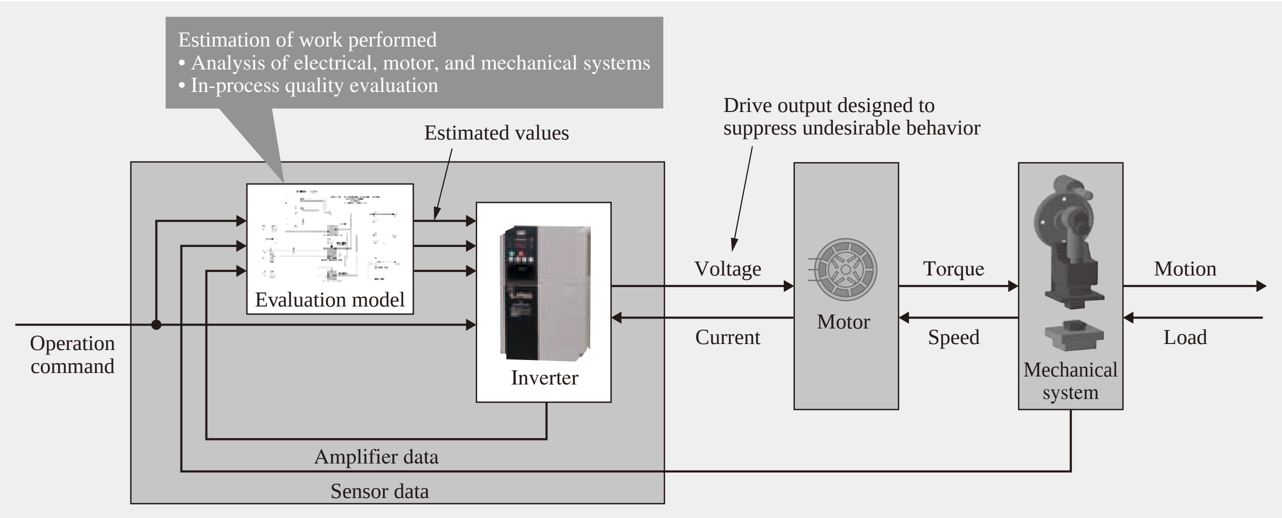



*Fig. 11—Use of Evaluation Model of Mechanical System to Enhance Control Performance.*
*The evaluation model is used to estimate the work performed by the motor, analyze individual components, and review the quality of machining operation. This information is used when operating the motor to enhance the drive unit by making changes such as varying the drive torque and switching operation mode.*

the load increases.

In addition to their use as simulators, Hitachi is also looking at using these models to develop more advanced motor drives. The way this works is that the model is initially used to understand undesirable behavior in the mechanical system and identify the inputs associated with this behavior.

Next, the logic needed to modify the motor output in a way that will prevent this undesirable behavior is derived and incorporated into the control program in the drive unit (see Fig. 11). Also, to allow the adjustment program to respond to a wider range of phenomenon, the form of the model can be modified to create an evaluation model that can calculate the desired estimation values and the system structured so that it can track various different changes quickly by changing the model parameters.

Hitachi has also embarked on development of an advanced form of the evaluation model in which the model of the mechanical system is modified to classify and collate characteristic variables including speed, load, square of speed, and product of load and speed. This is called a “universal model” because it can be adapted for use with many different mechanical systems simply by adjusting the variation coefficients. A feature of the universal model is that by collating each variable the calculation volume can be significantly reduced compared to detailed models used in the past while still maintaining the quality of the computation. This makes it possible to run the model at high speed and perform tasks such as model identification rapidly. Hitachi’s objective for the future is to incorporate the motor into the inverter unit and create a motor drive system with high added-value that is capable of functions such as performing realtime evaluation of the mechanical load or revising the operation of disturbance suppression functions in realtime.

Hitachi will begin using the integrated simulation for industrial applications this year.

## CONCLUSIONS

This article has described solutions for future electric drive systems advocated by Hitachi and the new control techniques that realize them.

It seems likely that improvements in energy efficiency will be made obligatory in the future as a way of responding to the problem of global warming and by promoting the adoption of electric drive Hitachi aims to supply solutions that combine better energy efficiency with advanced functions that add value to systems.

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