Technical Trends of Hydraulic-Electric Power Steering Systems

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A hydraulic-electric power steering system is in the spotlight as an energy-saving system which features both high output power and better steering comfort. Koyo has developed it for vehicles such as recreational vehicles (RV) and small trucks providing the maximum axial force of 13 000 N at a battery voltage of 12 V, which conventional electric power steering systems have been unable to cover technologically.

***Key Words**: energy saving, hydraulic power steering system, power pack, high efficiency motor*

1. Introduction

In 2003, Koyo's hydraulic-electric power steering (H-EPS) system (**Fig. 1**) was first adopted for a mass-produced standard passenger vehicle marketed in Japan. Herein, the development history and future technical trends of H-EPS are described.

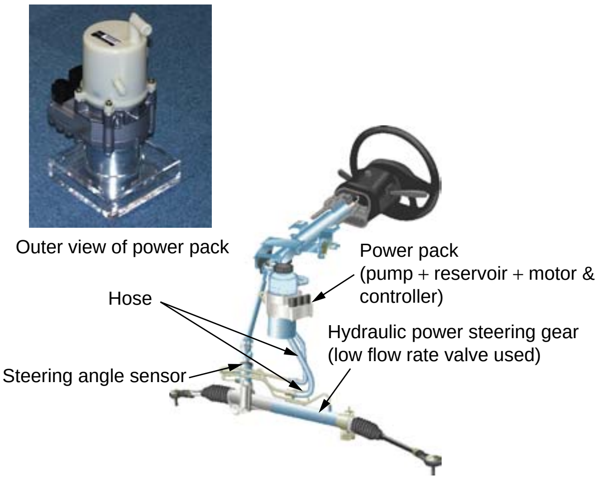


Fig. 1 Systemic structure of H-EPS

2. History of Development

In the1980s, application of H-EPS system expanded to various vehicles as a new generation energy-saving steering system, especially in Europe, thanks to the energy saving features and ease of installation. The Koyo Group's participation began in 1989 when European company H as a member of the group first adopted an industrial power pack for use in a vehicle as the 1st generation H-EPS.

In the 1990s, the power pack was steadily improved and developed into the 2nd generation power pack for automobiles which could be mass-produced at low cost. In the same decade, demand for further energy saving on the H-EPS system became so intensified that a separate electronic control unit (ECU) came to be employed for the first time to control the motor speed, thus enabling wasteful energy consumption to be reduced with less hydraulic oil flow rate while the steering wheel was not being turned. This was referred to as "stand-by control."

In late 1990s, when a major Japanese automaker released a hybrid car on the market first in the world, public interest in energy saving grew further. Accordingly, the Koyo Group started to develop the 3rd generation power pack. In this endeavor, an ECU-integrated brushless motor was newly developed to increase motor efficiency and make it possible to control motor speed precisely according to steering angular velocity and vehicle speed. As a result, the extent of energy savings was improved dramatically. Concerning steering feeling, it could be finely tuned so as to become lighter at lower vehicle speed and heavier at higher speed. Moreover, the endurance reliability of steering systems was drastically improved by use of brushless motor.

The improvement of hydraulic pumps was also carried out, resulting not only in the enhanced performance but also in reduction of the number of components, which contributed to reduction of the size and weight.

Despite such steady evolution of H-EPS system in response to needs especially in Europe, the use of this system in Japan has been limited to mid-size sport cars, electric cars and OEMs (original equipment manufacturing) of European automobile manufacturers. One reason for this might be that efforts have been done to install electric power steering (EPS) without a hydraulic system mainly in sub-compact vehicles. Another reason might be that a gasoline engine car has provided less limitation in layout of an engine-driven hydraulic pump.

3. Expansion of Demand

Global demand trends for various power steering systems are shown in **Fig. 2** (Koyo estimation). ("HPS" in this figure stands for the hydraulic power steering driven by the engine. Note that the demand for H-EPS shown in this figure does not include that for the super high-power motor version to be introduced in the following sections.) According to this figure, whereas the demand for EPS is expected to increase remarkably, the expected increase of H-EPS demand is comparatively small with the total staying around 4 million.

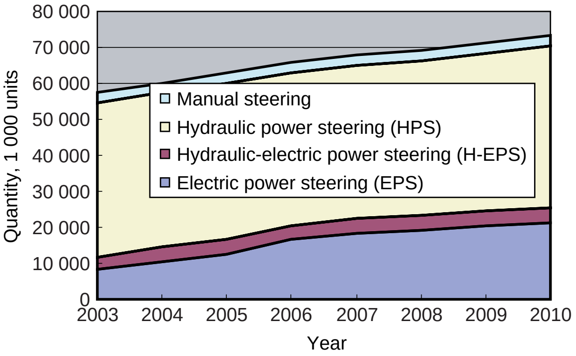


Fig. 2 Trend of demand on power steering systems

Figure 3 shows the features of various power steering systems. In this figure, C-EPS stands for column type, P-EPS for pinion type, RD-EPS for rack direct drive type and RC-EPS for rack cross type. This figure was prepared by Koyo engineers on the basis of their conception of each power steering system.

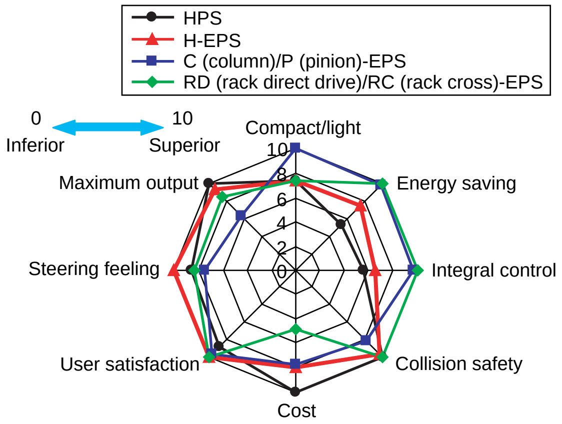


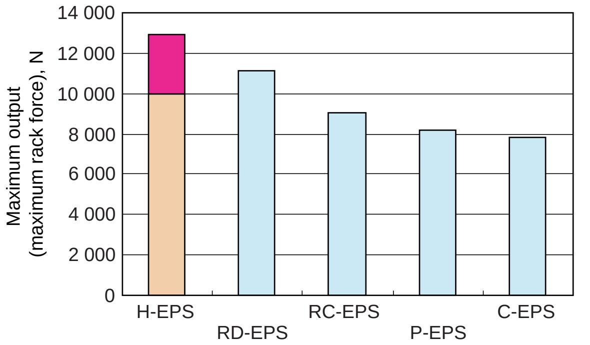
Fig. 3 Features of power steering systems

As shown in **Fig. 3**, H-EPS system is highly evaluated in aspects of steering feeling and maximum output. Regarding steering feeling, H-EPS is evaluated as being higher than HPS and much higher than EPS. The key to this lies in the fact that H-EPS, while basically remaining a hydraulic system, is capable of finely controlling the flow rate of hydraulic fluid according to steering conditions. Since the advent of HPS system, car drivers have been accustomed to steering feeling provided by the system for several decades.

In other words, we have enjoyed a natural, comfortable steering feeling through a fuzzy hydraulic medium between tires and steering wheel. While keeping this natural steering feeling, H-EPS has additionally succeeded in enabling system-tuning responding to the driving conditions by having the hydraulic oil flow controlled in accordance with vehicle speed and steering angular velocity. This explains why H-EPS systems are rated higher than HPS systems.

The maximum output force of a steering system is one of the most important factors, like cost, for automobile manufacturers to consider in selecting a steering system suitable for a given vehicle class. In this respect, EPS systems including H-EPS have a severe limitation on the maximum output force due to the limited supply of power from the battery, which is no more than 12 V and several dozen A. This is one of the reasons why EPS systems including H-EPS have not been successfully applied on the market dominated by HPS, in spite of better evaluation than HPS in most of the eight aspects shown in **Fig. 3**.

Figure 4 shows the results of a survey on maximum output forces of various EPS systems currently in mass-production or under development (the results may vary somewhat depending on parameters used in the study).



* ▇ shaded part represents super high power motor under development.

Fig. 4 Maximum output of power steering systems

Both C-EPS and P-EPS can provide the maximum output force no more than approximately 8 000 N, as seen in **Fig. 4**, because it is limited by mechanical strength due to structural reasons.

RD-EPS and RC-EPS have been developed with structural improvement to overcome this limitation. Nevertheless, even these improved EPS systems are still behind H-EPS system in terms of the maximum output force. The reason why H-EPS system has higher maximum output force despite the same input energy lies in the higher energy conversion efficiency of its components, especially its motor. Motors used in EPS systems and H-EPS systems are basically different in a way they are used. H-EPS systems enable the motor to be designed structurally more efficient. Concerning EPS systems, including H-EPS systems, it is important how to develop the systems with high efficiency.

4. H-EPS System Series

Figure 5 shows a series of the 3rd generation power packs currently mass-produced or under development. In this figure, the values are based on a stroke ratio of 50mm/rev. and on Koyo standard piston area (for each vehicle class) as the steering gear specifications. Power packs are classified into four levels of motor output, which are: normal power (NP) type for compact passenger cars, high power (HP) and boost high power (BHP) types for compact to middle-class passenger cars, and super high power (SHP) type. In further response to needs, SHP motors for large vehicles with efficiency improved to an extreme extent are being developed with a target of mass-production application in 2006.

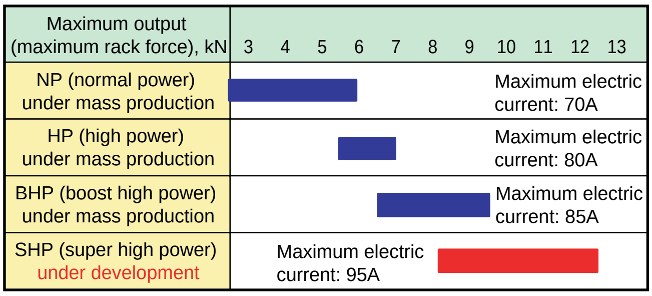


Fig. 5 H-EPS system series

5. Element Technology for Next Generation H-EPS Systems

In this section introduced are some of advanced technologies that are being developed for creating demands for H-EPS systems. Especially, development of higher output H-EPS systems would target on development of a motor capable of providing an axial force-steering responsiveness 20 to 30 percent higher than that of the conventional H-EPS systems (NP, HP, BHP) and EPS systems.

5. 1 Improvement of Motor Efficiency

Super high power (SHP) motor itself has targeted at 30% increase in its output force. On the other hand, the electric current from the battery, although limited from the vehicle side, has been designed to come up to max. 95 A (approx. 10% higher than the conventional 85 A). Energy flow diagram of a brushless motor and its loss are shown in **Fig. 6 (a)** and **(b)**, respectively. Improvement of motor efficiency is likened to a battle against motor loss, therefore SHP motor has adopted the following three technologies.

1) Control of current conduction angles and phases
2) Reduction of ECU internal resistance
3) High-density motor coiling

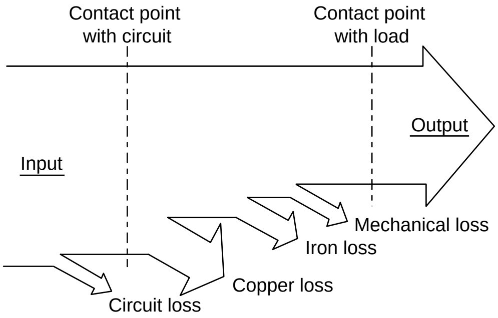


Fig. 6 (a) Energy flow of brushless motor

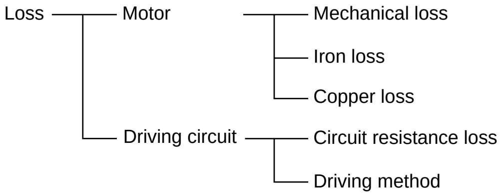


Fig. 6 (b) Energy loss of motor and ECU

5. 1. 1 Control of Current Conduction Angles and Phases

Brushless motors are generally driven at a current conduction angle of 120° as applied on NP and HP series motors of H-EPS systems. BHP motors were the first to employ a current conduction angle of 180° to increase the output force as shown in **Fig. 7 (a)**. When greater output force is required, pulse with lead angle of 60° (fixed) is added to the ordinary current conduction at 120° and the entire pulse amplitude is PWM-controlled. However, PWM control is accompanied by a problem of switching-loss increase. In SHP motors, the additional pulse's lead angle is adjusted between 0° and 60° in accordance with required output force (control of current conduction angles and phases) (**Fig. 7 (b)**). For instance, at the maximum rated output force, the maximum motor efficiency, or the minimum battery current, can be obtained at a conduction angle of 150 to 160° and at a lead angle of 30 to 40° (phase at the beginning of conduction). **Figure 8** shows the relationship between the conduction angles, the phase at the beginning of conduction, and the motor efficiency in isogram. At the maximum output of 1 028 W (3 N·m, 3 265 min^{-1}), a motor efficiency of 83% was obtained with a conduction angle of 160° and a lead angle of 45°, requiring battery current of 91.5 A.

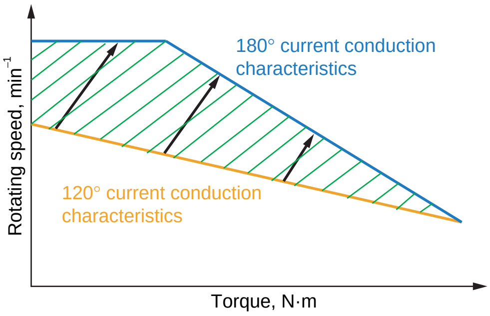


Fig. 7 (a) Higher output realized by 180° conductivity method

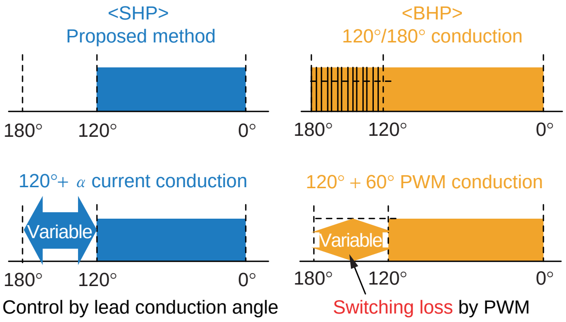


Fig. 7 (b) Conductivity method for BHP motor and SHP motor

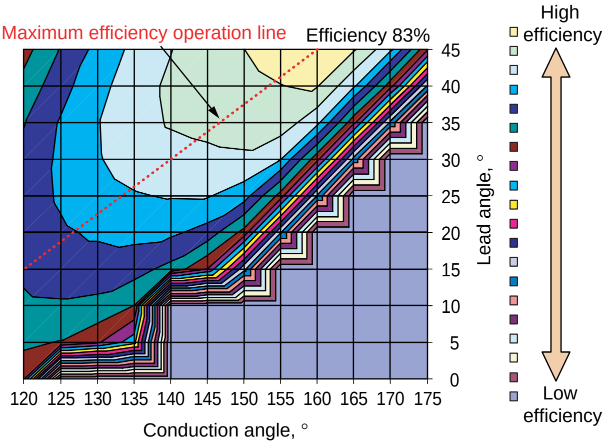


Fig. 8 SHP motor efficiency contour line

Control of conduction angles and phases is advantageous from the standpoint of EMI (electromagnetic interference) protection. The conventional PWM control allows EMI to rise up to the maximum when the motor output is maximal (at maximum electric current), thus requiring an EMI filter to be designed against such maximum noise, which is inevitably very large in size. On the other hand, the conduction angle/phase control enables the constant of the filter to be smaller without PWM control at the maximum motor output. As a result, the EMI protection equivalent to that by conventional series coil insertion type can be provided by simply inserting such a magnetic core as a ferrite core into the battery supply line (**Fig. 9 (a), (b)**).

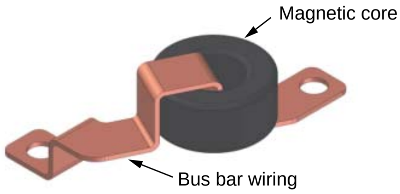


Fig. 9 (a) EMI noise filter by magnetic core

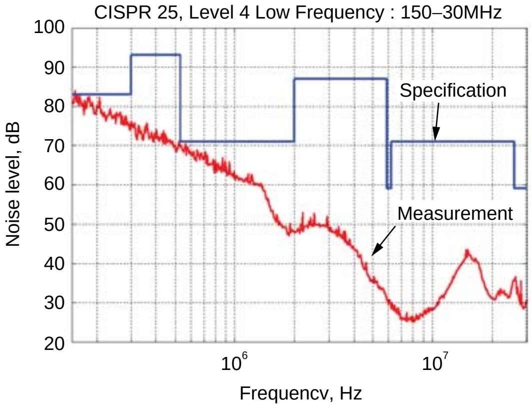


Fig. 9 (b) Effect of EMI noise filter

5. 1. 2 Reduction of ECU Internal Resistance

An inverter with MOS-FET is used in a driving circuit (for switching current to the coil) of SHP motor (low-voltage heavy-current type brushless motor) (**Fig. 10 (a)**). Because resistance in the ECU causes copper loss ($i^2 \times R$), that resistance value must be reduced to improve the efficiency of the motor inclusive of its driving circuit. The ECU resistance value for the motor came to be reduced to 6.4 mΩ by reducing a resistance value of MOS-FET and improving a bus bar wiring (**Fig. 10 (b)**). For instance, the current supplied from the battery reaches the maximum of 100 A or so, with loss of approx. 60 W. As ECU resistance for BHP motor is 15 mΩ, its loss reaches about 150 W. Supposing that ECU for conventional BHP motors is used, additional loss would be 90 W, equivalent to approx. 7 A of battery current (difference of loss: 90 W (13.5 V, 7 A)), which needs to be covered.

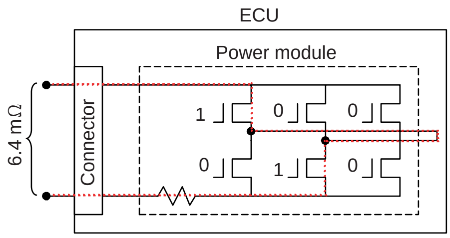


Fig. 10 (a) Driving circuit of low-voltage & large-current type brushless motor

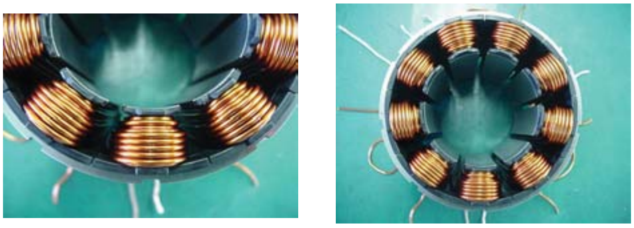
	Electric current, A	ECU resistance value, mΩ
BHP	85	15
SHP	95	6.4

Fig. 10 (b) ECU internal resistance

5. 1. 3 High-Density Coil Winding

12 V-series brushless motors for EPS are of low-voltage & heavy-current types, which generally incorporate straight core (divided core) as the motor stator structure to minimize copper loss. However, since H-EPS motors, in particular SHP motors, rotate at very high speed, it is required to take account of iron loss in addition to copper loss. In order to minimize the iron loss, a low-iron-loss material (magnetic steel sheet with silicone content adjusted to reduce hysteresis loss) has been used, and high-density coil winding with the conventional ring core structure (**Fig. 11**) has been chosen to reduce the resistance of coil for the motors.

[SHP motor coil winding]



[Conventional coil winding]

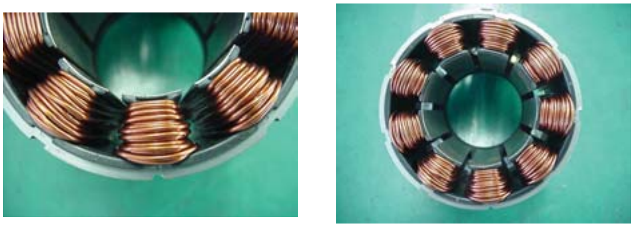


Fig. 11 High-density windings for SHP motor

The characteristics of SHP motors and BHP motors are compared in **Fig. 12**. With a 10 A increase of the input (battery) current, a 30% increase of motor output has been achieved.

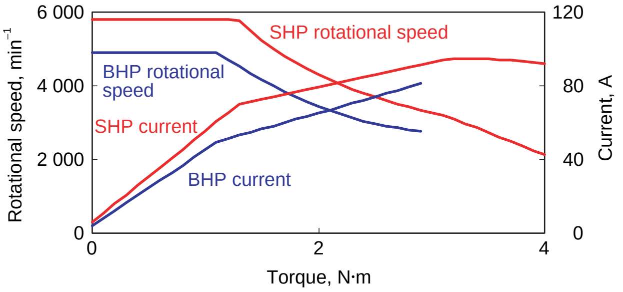


Fig. 12 Comparison of motor characteristics

5. 2 Hydraulic Pump

5. 2. 1 Development of High-Performance Bearings

Bearings for H-EPS systems are required to have sufficient durability under such severe conditions as oil temperatures of –40 to 120℃, rotational speeds of 1 000 to 6 000 min^{-1}, and maximum loads of approx. 12 MPa. To improve the durability, such solutions as a bearing design with optimum oil film formation, low-friction bearing materials, contamination-resistant bearing materials, and environmentally friendly lead-free bearing materials have been developed.

5. 2. 2 Noise Reduction

The most important point in designing H-EPS systems, including other EPS systems, is countermeasures against noise. In case of H-EPS systems, the pump operates at low rotational speed even when the steering wheel is kept stationary, while the pump speed increases when the steering wheel is turned. Thus the systems usually involve some noise generation. The pump operation noise varies depending on the pump rotational speed, and the higher the pump rotational speed, the larger the noise. Also, the change of pump rotational speed by motor control leads to change in tone of the noise. In order to solve these problems, a new torque-type power pack combining a pump with increased basic discharge (same modules) and high-torque type motor is being developed.

The increase of basic discharge would not only allow the rotational speed to be reduced for the same quantity of hydraulic fluid, but also diminish the difference between the minimum and maximum rotational speeds, thus improving the noise tone change. To confirm the effect, an operating noise was measured on power packs with basic pump discharges of 1.50 cm^3/rev. and 2.00 cm^3/rev., with the result as shown in **Fig. 13** (on the premise that both pumps had the same flow rate, and overall values are compared). The measurement was conducted at high and low rotating speeds. In both cases, the 2.00 cm^3/rev. pump was found better in noise characteristics.

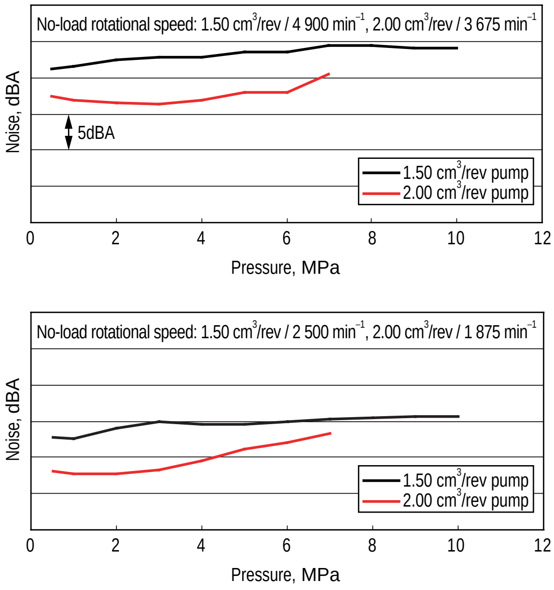


Fig. 13 Noise data

5. 3 Summary

(1) Control of current conduction angles and phases, (2) reduction of ECU internal resistance and (3) high-density coil winding (adoption of low iron-loss material) enable a 30% improvement in output force with 95 A input current (10 A higher than the conventional 85 A). Since this range of application (thrust force and responsiveness) can hardly be achieved by EPS, the advantage of H-EPS (SHP series) is expected to last for several years down the road. In addition, since the higher output of H-EPS is demanded in large and luxury cars, quietness is also a vital requirement. To cope with such requirement, technological development has been completed in response to customer's needs.

6. Future Perspective

In accordance with recognition of the high-output-force performance of H-EPS with SHP motors, inquiries about the application mainly for heavy vehicles have been increased both in Japan and Europe. Today, under increasing concern for environmental protection, it is imperative to promote urgently energy-saving on heavy vehicles including RVs and light trucks. Accordingly, product development taking into account such vehicles is becoming indispensable.

With increasing recognition of the superiority of SHP motor specifications and new understanding of the demand for heavy vehicles and light trucks, it is expected that the H-EPS market in 2010 will be at the maximum 30% more than that shown in **Fig. 2**.

In order to achieve this forecast, it is necessary not only to further improve the merits, but also to overcome any existing demerits. As shown in **Fig. 3**, H-EPS systems are still rated behind EPS systems in the aspects of energy-saving and integral control. Further improvement will be targeted in these areas.

Now that the first mass-production of H-EPS in the Japanese market has been realized, positive development efforts will continue with hope for increased demand.

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