

Development of the Lightweight, Compact Sine Wave Inverter-Equipped EU16i Generator

Toshifumi KOUCHI* Motohiro SHIMIZU*
Tadafumi HIROSE* Yukio SUGIMOTO*

ABSTRACT

The EU16i sine wave inverter-equipped generator was developed as the most lightweight and compact generator in the 1.6 kVA-rated output class. This generator has both superior portability and output capable of powering household appliances with their large power consumption. It also provides a low noise level, low fuel consumption, low exhaust emissions, and high-quality electrical performance with low waveform distortion and frequency variation. The efficient and lightweight high-speed multi-pole alternator and sine wave inverter system enables the engine to achieve higher speeds with a smaller displacement. With a frame that is fully covered with lightweight resin, this generator achieves a weight approximately one-half that of conventional generators. It also employs an electronic governor with automatic load-dependent speed control, together with an efficient generating system and a two-tiered noise dampening system. These allow this generator to achieve a reduction in noise level of 6 - 8 dB (A) over the practical load range and an improvement in fuel consumption of 20 - 40% compared to conventional generators. The EU16i generator meets the requirements of the EU Noise Directive, Stage II, as well as the CARB Tier II/EPA Phase II exhaust emission regulations. The EU16i is marketed worldwide though it is only marketed as the EU16i domestically. It is sold in North America as the EU2000i and as the EU20i when exported to other regions.

1. Introduction

Because they provide a convenient source of electricity, portable generators are becoming increasingly popular around the world for use by private individuals in leisure activities or as a backup power system for the home, and as a power supply for commercial and emergency applications.

In recent years, electrical equipment operating under advanced electronic control (microcomputer control), such as computers, has been coming into widespread use. In

conjunction with this development, generators are now needed to provide quality electrical performance suitable for a wide variety of equipment.

Furthermore, due to society's continuing concern about the environment, demands for low noise levels, low fuel consumption and low exhaust emissions is being applied even to generators, with countries around the world enacting increasingly strict regulations designed to protect the environment. In regards to noise, the EU Noise Directive Stage I will go into effect in 2002, and Stage II will go into effect in 2006. In regards to emissions, following the

*Asaka Higashi R&D Center

EPA (Environmental Protection Agency) Phase II regulations that were implemented in 2001, the CARB (California Air Resource Board) Tier II regulations will go into effect in 2002.

Because conventional generators are equipped with a double-pole field rotational generating system, the engine speed is limited to 3000 rpm for a 50 Hz system and 3600 rpm for a 60 Hz system. This is due to the synchronous relationship that exists between the engine speed and the output alternating-current frequency. As a result, engines and generators both become larger in terms of volume and weight; in addition, the generated electrical output is approximately 15% lower in a 50 Hz system when compared with a 60 Hz system. Consequently, conventional generators, including those manufactured by other companies in the 1500 to 1800 VA output class that are capable of powering household appliances that consume large amounts of power, weigh as much as 30 or 40 kg, making them too heavy for one person to carry. Furthermore, Honda has offered no portable generators in this class.

This article introduces the EU16i Generator, a portable generator that is the lightest in its class due to the adoption of a lightweight, high efficiency inverter generating system and a full-cover and two-tiered noise dampening resin structure.

2. Development Concept

The development concept behind the EU16i was to produce a portable generator capable of generating enough output to power large electric appliances used in the typical home while still keeping the generator light and small enough to be portable by using the same sinusoidal inverter technology that was adopted in the EU9i (1)(2) (which has been in mass production since 1998). Furthermore, in order to enhance the competitive product strength of the generator, low noise level, low fuel consumption, low

exhaust emission and quality electrical performance were also established as design goals.

The development targets were as follows:

- (1) The generator must produce output capable of powering large electric appliances used in the typical home, while still being of a size and weight that allows it to be carried easily.
- (2) The generator must offer quality electrical performance with minimal waveform distortion and frequency modulation so that it can also power electronic equipment such as computers.
- (3) The generator must be made suitable for use in a variety of circumstances, such as at night or at a campground by reducing the noise produced by the generator and by reducing the fuel consumption of the generator in order to permit operation for extended periods.
- (4) The generator must satisfy environmental regulations.
 - CARB Tier II/EPA Phase II Emissions Regulations
 - EU Noise Directive Stage II

3. Main Specifications and Basic Construction

The EM1500X, a conventional generator of the same class as the EU16i, had a pipe-frame construction that required two people, or one person using both hands, to



Fig. 1 External view of EU16i and EM1500X

Table 1 Comparison of specifications with EM1500X

Model			EU16i	EM1500X	
Engine	Type		4-stroke OHC	4-stroke OHV	
	Displacement (cm³)		98	163	
	Speed (rpm)		* 3 000-5 000	3 000	3 600
			☆ 4 300-5 000		
	Operating noise level (dB (A) at 7m)		* 53-59	63	64
☆ 59					
Generator	Type		Multi-pole field rotary	Double-pole field rotary	
	Excitation method		Magneto	Field current regulation	
	Voltage regulation method		※ PWM	# AVR	
	AC frequency (Hz)		50/60	50	60
	Max. AC output (VA)		2 000	1 500	1 800
	Rated AC output (VA)		1 600	1 300	1 500
	Voltage variation rate		Momentary	10% max.	
			Stability	15% max.	
	Frequency variation rate		Momentary	6% max.	
			Stability	7% max.	
	Waveform distortion		Momentary	1% max.	
Stability			15% max.		
Generating efficiency		5% max.	7% max.		
		81%	25% max.		
Dimensions	Dimensions L × W × H (mm)		81%	78%	
	Dry weight (kg)		21	41.5	

* : ECO-THROTTLE ON

☆ : ECO-THROTTLE OFF

※ PWM = Pulse width modulation

AVR = Auto voltage regulator

carry it. The EU16i, however, is fully covered with a plastic shell and has a narrow construction that allows it to be easily carried with one hand. Fig. 1 shows the appearances of the EU16i and the EM1500X, and Table 1 shows a comparison of the major specifications.

The EU16i employs an inverter system that does not cause the output alternating-current frequency to be limited by the engine speed. In addition, the engine itself was made smaller and lighter compared to conventional models by increasing the engine rpm, thus increasing the power output and reducing the required engine displacement. Further, in consideration of enhancements in cooling performance, noise insulating performance and the lighter weight of the engine, a cooling fan and an outer rotor-type high-speed multi-pole alternator that also serves as the flywheel are located in the position where a conventional flywheel would be located. The alternator and the fan are enclosed in an aluminum diecast fan cover and a plastic shroud. The engine unit is attached to the frame by vibration damping mounts at three points, one on the top of the engine unit and two on the bottom of the engine unit. The two-tier noise dampening structure is achieved by enclosing the unit in a plastic outer cover.

Each component (the power receptacle, the inverter unit, the alternator, the engine and the muffler) is arranged vertically in order, starting with the component that is coolest and radiates the least heat, which keeps the overall width of the unit to a minimum. This arrangement was designed to enhance cooling performance and portability. In addition, an effort was made to greatly reduce noise and fuel consumption by reducing the engine speed in the frequently used service load range, and a load-dependent speed control-type electronic governor that automatically controls the engine speed in accordance with the load of the electrical equipment being powered was adopted.

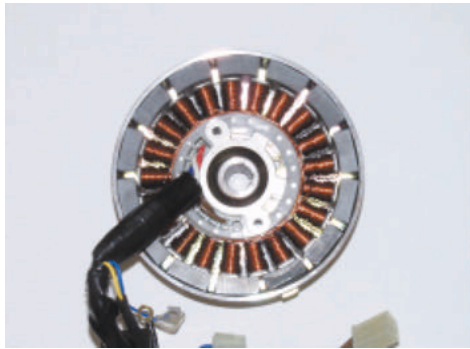


Fig. 2 Alternator

4. Component Technologies

4.1 High-speed Multi-pole Outer Rotor-type

Alternator

As shown in Fig. 2, the alternator that is used in the EU16i is an outer rotor-type magnetic alternator with a three-phase multi-pole stator. This alternator generates three-phase high-frequency alternating current and supplies that current to the inverter. Commercially available strontium ferrite, a material with a very high magnetic flux density is used for the magnetic material, which further improved the high output/lightweight characteristics of the system.

Fig. 3 shows a comparison of the weight of the EU16i generating system (maximum output: 2 kVA), the weight of mass-produced (EU9i, EU24i, and EU28is) inverter generating systems (inverter unit + alternator) and the weight of conventional generating systems (alternator + flywheel). Table 2 shows a standalone performance comparison of the alternators.

As shown in the figure, the EU16i is less than 1/3 the weight of a conventional generating system, and approximately 20% less than a mass-produced inverter generating system (including the reduction in the weight of the inverter unit as described later).

4.2 32-bit CPU Control System Inverter Unit

Compared with the mass-produced EU9i (maximum output: 1 kVA), the output of the inverter unit that is incorporated in the EU16i (maximum output: 2 kVA) was doubled while minimizing any increase in weight and size by reviewing the system configuration in its entirety.

Fig. 4 shows a comparison of the inverter units in the EU16i, the EU9i, and the EU28is. 16-bit processors were

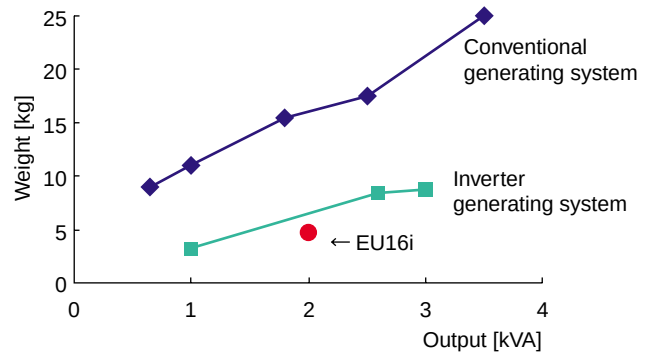


Fig. 3 Max. output and weight of the power-generating system

Table 2 Comparison of generation-system performance

Model		EU16i		EU9i		EU28is	
Alternator	Revolution (rpm)	4300	5000	5500	6000	3500	3800
	Max. output (W)	2500	3000	1350	1500	4100	4500
	Generating efficiency	88%	88%	88%	88%	87%	87%
	Weight (kg)	2.8		1.8		5.4	
Inverter	Max. output (VA)	2000		1000		3000	
	Rated output (VA)	1600		900		2800	
	Efficiency	92%		90%		90%	
	Weight (kg)	1.9		1.4		3.3	

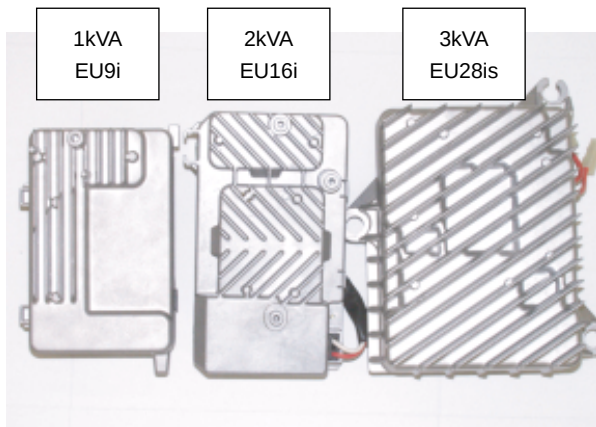


Fig. 4 Inverter unit

used for the CPUs in the EU9i and the EU28is, but a 32-bit processor is used in the EU16i to control the inverter section and the electronic governor section. By implementing most of the analog arithmetic circuitry that was used in the EU9i and the EU28 inverter through software in the EU16i's CPU, the number of control circuit components has been greatly reduced, which also contributes to keeping the system small and light. In addition, reducing the power loss in each section also results in enhanced conversion efficiency. Fig. 5 shows the block diagram for the system, and Table 2 shows a comparison of inverter performance.

4.2.1 Inverter section control

In the inverter section, the high frequency alternating-current from the alternator is rectified to a direct current, and is then converted into the sinusoidal alternating current that is output.

The control section can be broadly divided into the following four sections.

(1) Output waveform control

A precise 50Hz or 60Hz sine wave is created in the CPU as the basis for the output waveform. The inverter is driven by a PWM (Pulse Width Modulation) signal on a carrier wave of approximately 20 kHz. In addition, the output voltage and current waveforms are fed back to the CPU, which suppresses waveform distortion caused by the effects of the load equipment so that a precise sine wave and suitable voltage can be maintained.

(2) Protective function section

The inverter has functions that protect against overcurrent, overvoltage, and overheating. A breaker function protects against overcurrent by starting a timer and stopping output after a prescribed length of time has passed if the CPU determines that current above a prescribed level is being output. A peak current control function blocks overcurrent from being applied to ICs by means of an overcurrent protective circuit that protects against sudden overcurrent due to an output short, etc. Because the internal direct current voltage may increase under the effects of the load or during parallel operation, the CPU protects against overvoltage by suppressing voltage increases and by stopping output if the voltage is above a prescribed level. The overheating protection function stops output if the temperature of the power elements that make up the inverter rises above a prescribed value when operating under harsh environmental conditions.

(3) Rectification control

This section controls the continuity angle of the SCR (Silicon Controlled Rectifier) and converts the alternator output to a suitable direct current voltage. If the direct current voltage drops below a stipulated value due to a load that requires large starting power, for example, this section suppresses the inverter output and prevents an excessive

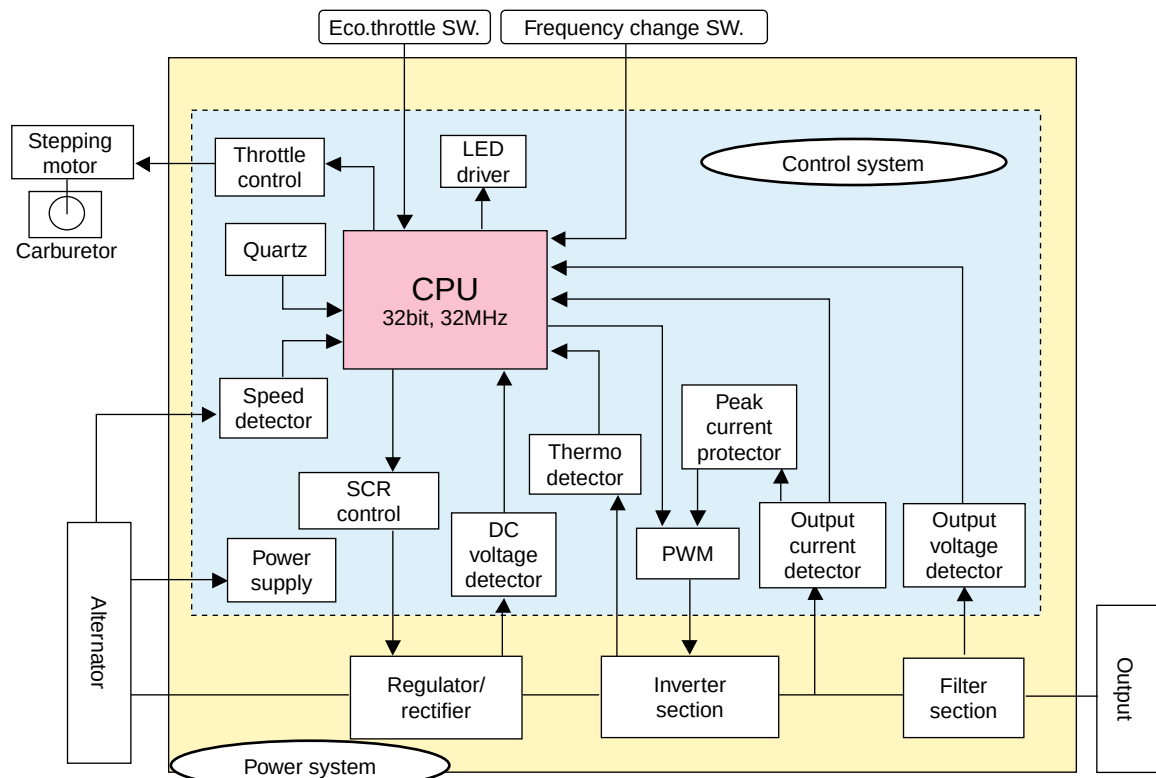


Fig. 5 Block diagram of inverter and speed-control system

drop in the direct current voltage, increasing the load starting capacity of the generator by always using a range where the alternator is efficient. This section also has a function that adjusts the direct current voltage up or down in accordance with the engine speed, which contributes to an expanded variable rotation speed range.

(4) Parallel operation control section

The generators in the Inverter Generator Series include a parallel operation function that allows the user to obtain twice the output simply by using a special cord to connect the outputs of two generators. In order to implement parallel operation, it is essential to match the phase and frequency of the two generators, as well as matching the voltage.

In order to match the phase and frequency, the CPU makes fine adjustments to the frequency in real time, based on the phase difference in the voltage and current. Next, in order to match the voltage, the CPU makes fine adjustments to the dropping characteristic and the voltage in order to prevent a load imbalance on the generators due to voltage differences.

4.2.2 Electronic governor section control

The electronic governor is of the load-dependent speed control-type, and it automatically controls the engine speed at a level suitable for the amount of power being used. The engine speed is kept at a level that matches the effective power by calculating the rotation speed on the basis of the load rate of the alternator. By enhancing the basic performance of the rotation speed control method and the rectification control, the variable range for the rotation speed has been increased by 15% compared with the mass-produced EU9i and EU28is. Incorporating this electronic governor made it possible to lower the engine rotation speed in the practical load range, reduce fuel consumption and reduce noise. Fig. 6 shows the effect on fuel consumption in comparison with conventional generating systems, while Fig. 7 shows the effect on noise. Note that the effect on noise also includes the effects of the two-tiered structure of the cover.

The electronic governor consists of the inverter unit, which handles throttle control, and a stepping motor positioned on the same shaft as the throttle.

(1) Determining the rotation speed

Fig. 8 shows the relationship between the engine speed and the generated output of EU16i. The SCR continuity angle is used as a parameter. The target speed is calculated such that the SCR continuity angle is maintained at a suitable value.

The SCR is an element that is used to rectify high-frequency alternating current from the alternator to a stipulated direct current voltage. If the load is large, the voltage drops and the SCR continuity angle widens; conversely, if the load is small, the SCR continuity angle closes. Therefore, it is possible to determine how much margin there is in the alternator output on the basis of the SCR continuity angle. Because the alternator output is proportional to the rotation speed, the SCR continuity angle can be increased to increase the rotation speed and maintain the alternator within the stipulated margin. Conversely, if the SCR continuity angle decreases and the alternator margin increases, the engine speed drops. This type of control is aimed at maintaining the alternator margin at a stipulated level to determine the optimal engine speed that is best suited to the power load that is being consumed.

(2) Rotation speed control

The engine speed is detected through the alternator subcoil. Because there are 14 magnetic poles in the

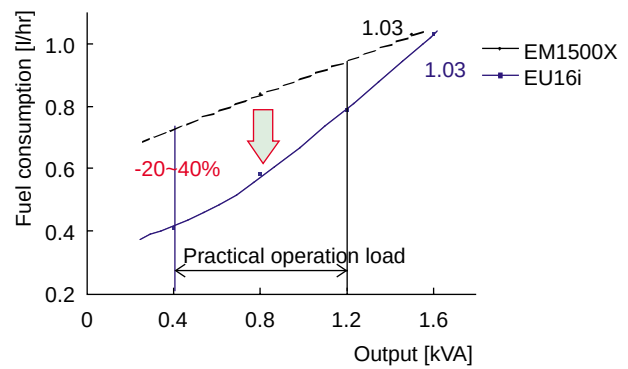


Fig. 6 Fuel consumption

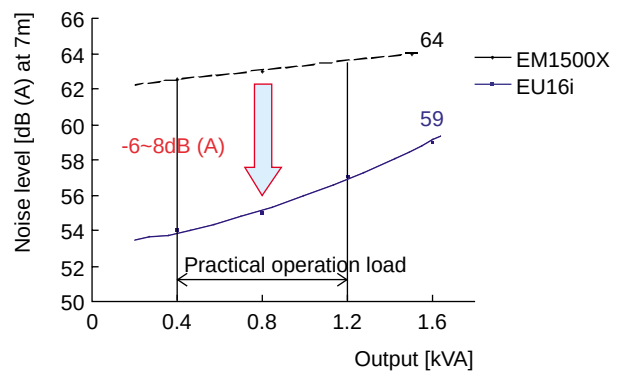


Fig. 7 Noise level

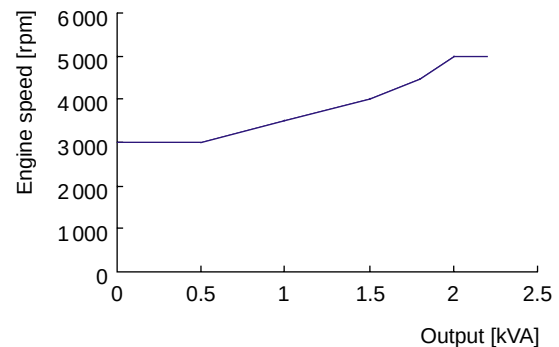


Fig. 8 Engine speed and output

alternator, the subcoil generates seven pulses per engine rotation. Because the combustion cycle occurs every two rotations in a single cylinder engine, an engine rotation is recognized every 14 pulses.

The rotation speed is determined at a prescribed interval, and the calculations are processed in order to derive the target speed which is then output to the stepping motor. The throttle position is recognized in the CPU at all times, and if a load that exceeds the capability of the engine is applied, the CPU suppresses the inverter output voltage to prevent the engine from stalling. This function makes it possible to use the engine to its maximum capacity for generating power, and contributes to increased output.

(3) Stepping motor

The EU16i uses the same stepping motor as in the mass-produced EU9i. The stepping motor is combined with the carburetor. Deceleration is achieved by means of a

reduction gear in the stepping motor, which is connected to the throttle shaft of the carburetor by means of a plastic linkage. The deceleration ratio is set to a value such that the throttle will be at the full extent of its stroke when motor operation is at 100 steps. The stepping motor is driven by the CPU through two-phase excitation via a motor driver. In order to enhance the following characteristics of the motor, the drive signal varies the rate of acceleration or deceleration. The value stored in the CPU after the throttle is set to wide open during the initial startup period is used for detecting the throttle position.

4.3 Engine

The engine used in the EU16i (the GX100) was developed by focusing on the following points to fully achieve the advantages of a portable inverter generator:

- Improved output at high engine speeds
- Smaller size, lighter weight
- Reduced noise
- Satisfaction of CARB/EPA emission requirements

The primary technologies that were adopted in order to meet these needs include: (1) uni-block cylinder, (2) built-in timing belt and high-speed valve system, and (3) emission reduction technologies.

4.3.1 Uni-block cylinder

In order to achieve a small size and light weight, a uni-block cylinder construction, in which the cylinder head and the cylinder block are one piece, was adopted for the GX100. Unlike the typical construction with a separate head, the uni-block cylinder does not require additional thickness at joints and does not require head bolts or gaskets. In conjunction with its higher rotation speed and

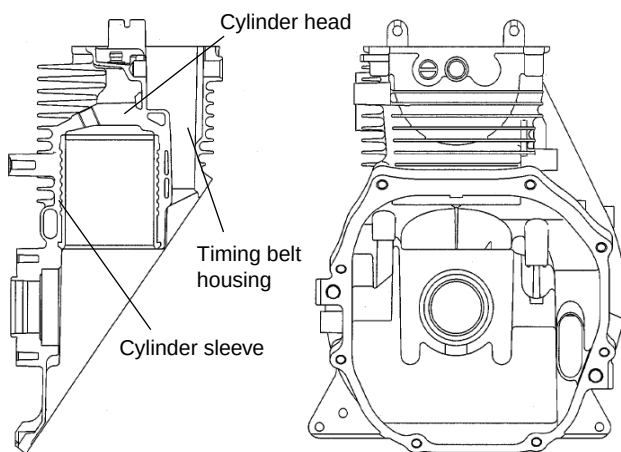


Fig. 9 Cylinder block section

lower displacement, the weight of the head and the cylinder block in the GX100 was reduced by approximately 40%. This construction eliminated the effects of forces along the tightening axis of the head bolt, which is one of the causes of cylinder distortion, and also produced benefits in terms of oil consumption and in degradation of emissions over time. Furthermore, while a sleeveless aluminum cylinder was used in the conventional uni-block cylinder⁽³⁾, a cylinder cast in a thin cast iron sleeve is used in the GX100, which also reduces the degradation in emissions. The construction of the GX100's cylinder block is shown in Fig. 9.

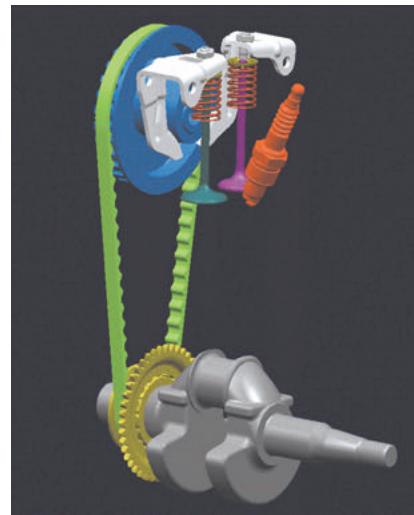


Fig. 10 Valve train

4.3.2 Built-in timing belt mechanism

The OHC construction that has been proven in the GC/GCV 135/160⁽³⁾, shown in Fig. 10, was adopted in the GX100. By adopting a component configuration consisting of a built-in timing belt, a resin single cam pulley, and an L-shaped rocker arm, noise, size, weight, and cost could be reduced.

In addition to the OHC construction described above, the reduction in the equivalent valve weight by reducing the stem diameter of the intake and exhaust valves and the optimization of the rocker arm, the cam profile, and the belt size have realized a suitable valve system for engine speeds of up to 5000 rpm, a necessity in an inverter generator, as opposed to the 3600 rpm of a conventional generator.

4.3.3 Emission reduction technologies

The following technologies were adopted in order to satisfy the CARB Tier II/EPA Phase II emission regulations:

- Change to center plug by using a small spark plug
- Optimization of the shape of the combustion chamber, including minimization of the quenching area around the combustion chamber

Due to the effects of these technologies, the EU16i achieved the best emission values in its displacement class, as shown in Fig. 11.

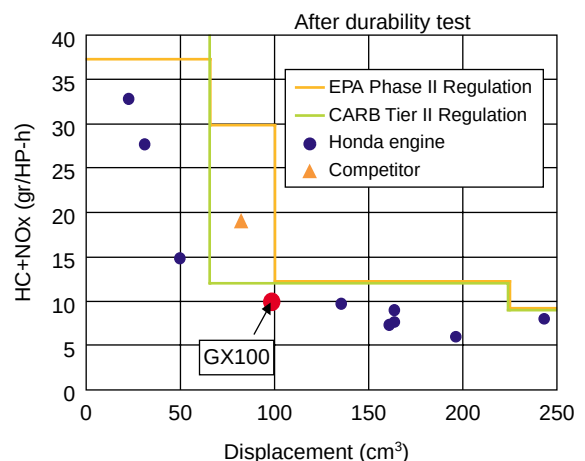


Fig. 11 Emission performance

4.4 Frame Construction

In order to attain the required cooling performance while remaining light and reducing noise in the EU16i, component placement was optimized and a full-cover, two-tiered noise dampening resin structure was adopted. Fig. 12 shows the construction of the EU16i's lightweight resin full-cover.

In the EU16i, an inverter system was adopted in which the output alternating-current frequency is not limited by the engine speed. A light multi-pole alternator that also serves as a flywheel was located at the position that would normally be occupied by a conventional flywheel. As a result, the weight of the components that are supported by the frame, including the engine and the alternator, was reduced by approximately 53% compared to earlier systems.

In addition, by using aluminum diecast components for not only the engine bracket but also the head cover and the fan cover, the engine itself could be used to support these components through their respective mounts on the rear portion of the carrying handle on the outer cover and a portion of the under cover. In addition, the high-strength plastic subframe that supports the large plastic fuel tank was connected to the front portion of the carrying handle on the outer cover and to the under frame. A feature of this construction is that the carrying handle directly bears the weight of the engine, the alternator and the fuel tank when the generator is being carried.

Reducing the weight of these components and adopting this support structure made it possible to switch to plastic while still retaining adequate strength and rigidity in the outer cover, the under frame, and joints between them, resulting in a large reduction in the weight of the generator as a whole.

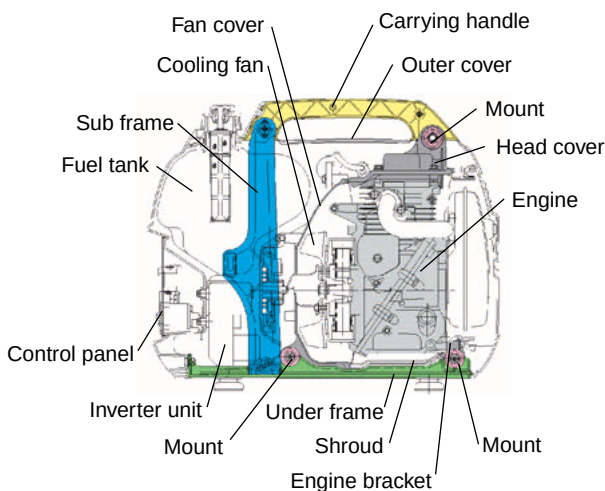


Fig. 12 Lightweight resin full-cover structure for EU16i

The under frame was created from plastic and its shape was optimized in order to ensure that it provided adequate strength and rigidity while the generator is in operation. The shape of the stress concentration areas was optimized by using simulation to analyze the distribution of stress in the under frame. Fig. 13 shows the results of this simulation and analysis.

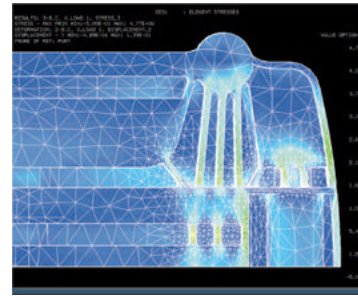


Fig. 13 Analysis of simulated under frame

Taking the cooling efficiency of each component into consideration, the alternator, the engine, the muffler and the inverter were arranged in a line, starting from the inverter unit, which produces little heat. The flow of cooling air was made unidirectional, and by causing the cooling air to flow over the components that produce the least heat first, the volume of cooling air needed was reduced. The alternator, the engine, and the muffler, which all produce significant heat, were enclosed by a sealed fan cover and a shroud in order to prevent warm air from recirculating over them. In addition, a two-tiered structure was adopted, with these components also covered by the outer cover. As a result, while conventional models had two fans, one to cool the engine and one to cool the alternator, the EU16i only needed one fan, contributing to the lighter weight and smaller sized generator. In addition, placing an intake opening in the rear of the outer cover creates a flow of cooling air from the rear portion inside the cover, which helps to prevent the temperature of the outer cover from rising due to heat radiated by the engine, and also serves to cool the carburetor. Fig. 14 shows the cooling system of the completed machine.

In order to reduce noise in the completed machine, fan noise was reduced by placing the inverter unit in front of the fan. In addition, a large air cleaner with a silencer nose, a large muffler, an electronic governor, and a variable pitch cooling fan were all adopted.

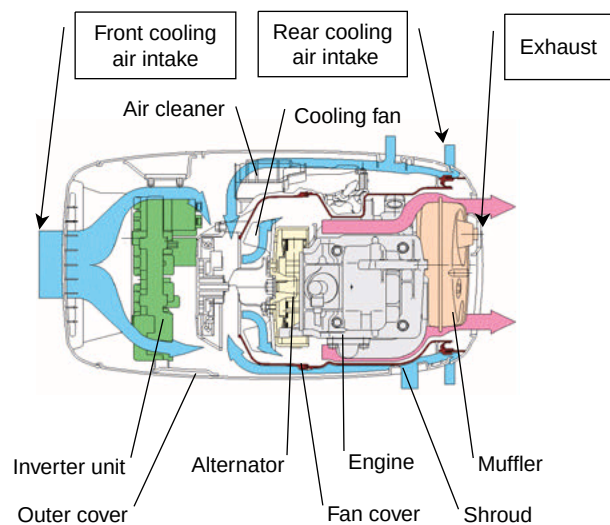


Fig. 14 Cooling system of the completed machine

The result of this structure was to reduce noise by 6 to 8 dB (A) under a practical load in comparison with the conventional EM1500X, which is sufficient to satisfy the EU Noise Directive Stage II scheduled to go into effect in 2006. This structure also resulted in approximately a 50% weight reduction. Fig. 15 shows a comparison of component weights between the EM1500X and the EU16i.

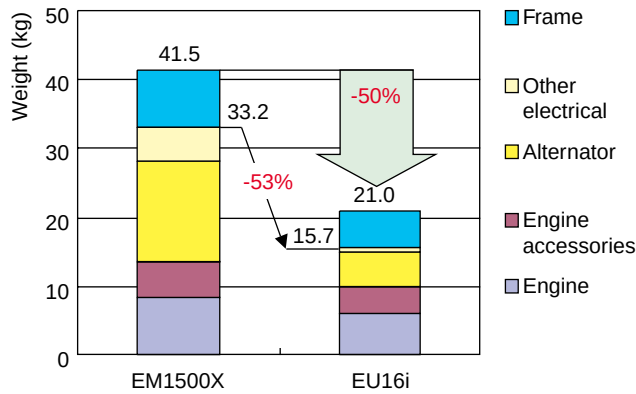


Fig. 15 Comparison of weight between EU16i and existing EM1500X

5. Conclusion

Rather than applying a conventional general-purpose engine, a small, high-speed, 4-stroke engine was combined with a high-speed multi-pole outer rotor-type alternator that also serves as a flywheel. Further, a sinusoidal inverter control and a lightweight plastic full-cover structure were adopted to develop the EU16i generator. This new EU16i generator is portable, produces output capable of powering large home appliances, and it provides quality electrical performance suitable for electronic equipment such as computers.

- (1) Excellent portability was achieved with a dry weight of 21 kg, which is only half that of conventional models, and with a comparatively narrow suitcase style design.
- (2) With waveform distortion of less than 2.5% and frequency fluctuation of less than 1%, electrical performance equivalent to that of commercial power supplies was achieved.
- (3) Compared with conventional models, noise was reduced by 6 to 8 dB (A) and fuel consumption was reduced by 20 to 40% under practical loads.
- (4) The EU16i satisfies EU Noise Directive Stage II (to be implemented in 2006) and CARB Tier II (2002)/EPA Phase II (2001) emission regulations.

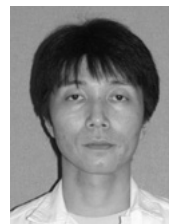
The EU16i is the version being marketed in Japan. The EU2000i is the version being marketed in North America, and the EU20i is the version being marketed in other export markets. The development team is confident that customers around the world will find all of these to be excellent products.

The development team would also like to express their thanks to all who helped in the course of the development of these products.

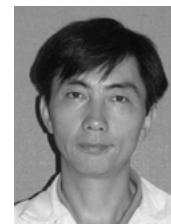
References

- (1) Tanaka, Y., Kouchi, T., Ito, K., and Nakamura, M.: Development of the Lightweight and Compact Portable Generators-GENE21 Series, HONDA R&D Technical Review, Vol. 11 No. 2, p.15-22 (1999)
- (2) Kouchi, T., Ito, K., and Nakamura, M.: Development of Lightweight and Compact 1kVA-class Portable Generator, SAE Paper 1999-01-3304
- (3) Suzuki, T., Hojo, H., Inoue, S., Moriyama, H., Fujinaga, Y.: Development of General Purpose OHC Engine with Built-in Timing Belt, HONDA R&D Technical Review, Vol.10, p.122-127 (1998)

■ Authors ■



Toshifumi KOUCHI



Motohiro SHIMIZU



Tadafumi HIROSE



Yukio SUGIMOTO