Variable-Speed Engine Generator With Supercapacitor: Isolated Power Generation System and Fuel Efficiency

Joon-Hwan Lee, *Member, IEEE*, Seung-Hwan Lee, *Member, IEEE*, and Seung-Ki Sul, *Fellow, IEEE*

***Abstract*—A variable-speed engine generator set for an isolated power system is investigated due to reduced fuel consumption and less emission. However, because of the sluggish dynamic behavior of the internal combustion engine, the power quality would be degraded during the sudden load power surge, where the power required by the load is not available by the engine because of the reduced engine speed. An isolated power system based on a variable-speed engine with a supercapacitor bank can improve the dynamic characteristics under such a sudden load change, and power quality, fuel consumption, and emission of pollutants can be improved remarkably. Furthermore, it is verified by the computer simulation and experimental results that the three-phase four-leg inverter is compatible to the isolated power system with an unbalanced load. In this paper, the feasibility of the system has been verified based on a 26-kW commercial diesel engine system.**

***Index Terms*—Diesel engines, power control, supercapacitor (SC), three-phase four-leg inverter.**

I. Introduction

FOR AN ISOLATED power generation system, a wound-rotor synchronous generator run by a constant-speed diesel engine (CSDE) has been widely used due to initial cost and simplicity for almost the last 100 years. However, if the engine and the generator are not severely oversized, then voltage and frequency dipping at sudden load power surge is inevitable in most cases. Hence, the sensitive electric load such as personal computers and other computer-based loads may malfunction with the generation system. Furthermore, the waveform of the generator would be distorted with unbalanced load and/or nonlinear load, and that is, again, the cause of malfunctioning of those sensitive loads.

As a necessity of constant output frequency, even at light load conditions, since the speed of an engine should be operated constant, the engine is not running at the optimal speed, where the fuel consumption at a given load power is minimum. Furthermore, emission characteristic at the constant speed is getting poor than that at the optimal speed. To reduce fuel consumption and improve the emission characteristics, the diesel engine speed can be varied according to the load condition. A system consists of the variable-speed diesel engine (VSDE), permanent-magnet synchronous generator (PMSG), and pulsewidth modulation (PWM) boost rectifier, dc link, and a constant-voltage constant-frequency (CVCF) inverter can be implemented to optimize fuel efficiency and emission characteristics. In the system, the mechanical power from the VSDE can be converted to variable frequency and variable voltage ac power. The power is transferred to a constant-voltage dc link via a PWM boost rectifier. Finally, the power at the dc link can be converted to CVCF ac voltage by a three-phase four-leg PWM inverter, which can provide high-quality electric power regardless of the load conditions such as nonlinear load and/or unbalanced load. However, because of the sluggish response of the speed of the engine, the output power of the generator cannot respond to the rapidly increasing load power, and the output voltage cannot be maintained even with the CVCF inverter. The power quality of the system can be enhanced with an energy storage system based on the supercapacitor (SC) bank against the sudden load power surge. Furthermore, the SC can supply additional power such as in-rush current of an electric load for a few seconds without any increase in the engine's power capacity.

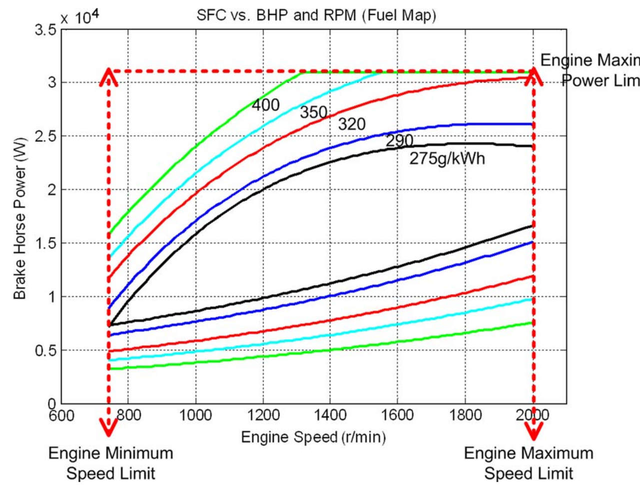

Fig. 1. Experimental results. SFC according to power and speed.

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TABLE I
PARAMETERS OF THE SYSTEM

P_{eng_rated}	26 [kW]	ω_{eng_rated}	1800 [r/min]	$f_{sAC\text{-}DC}$	8 [kHz]	L_f	250 [uH]
Fuel Injection	Direct In-line	J_{engine}	0.3 [kgm^2]	$f_{sDC\text{-}DC}$	16 [kHz]	C_f	50 [uF]
Number of Cylinders	4	Displacement Volume	3268 [cc]	$f_{sDC\text{-}AC}$	16 [kHz]	R_f	0.2 [Ω]
P_{mot_rated}	22.19 [kW]	ω_{mot_rated}	1814.3 [r/min]	f_{sout}	60 [Hz]	V_{xf}	220 [V_{rms}]
R_s	0.047 [Ω]	J_{motor}	0.0051 [kgm^2]	$L_{dc\text{-}dc}$	1 [mH]	C_{super}	2.7 [F]
L_{ds}	1.4 [mH]	T_{rated}	117 [Nm]	$R_{dc\text{-}dc}$	0.4[Ω]	R_{dc}	7.7 [Ω]
L_{qs}	1.4 [mH]	E_{phase}	261[V]	L_{dc}	9 [mH]	C_{dc}	800 [uF]
P	12	K_e	0.23 [V/rad/sec]				

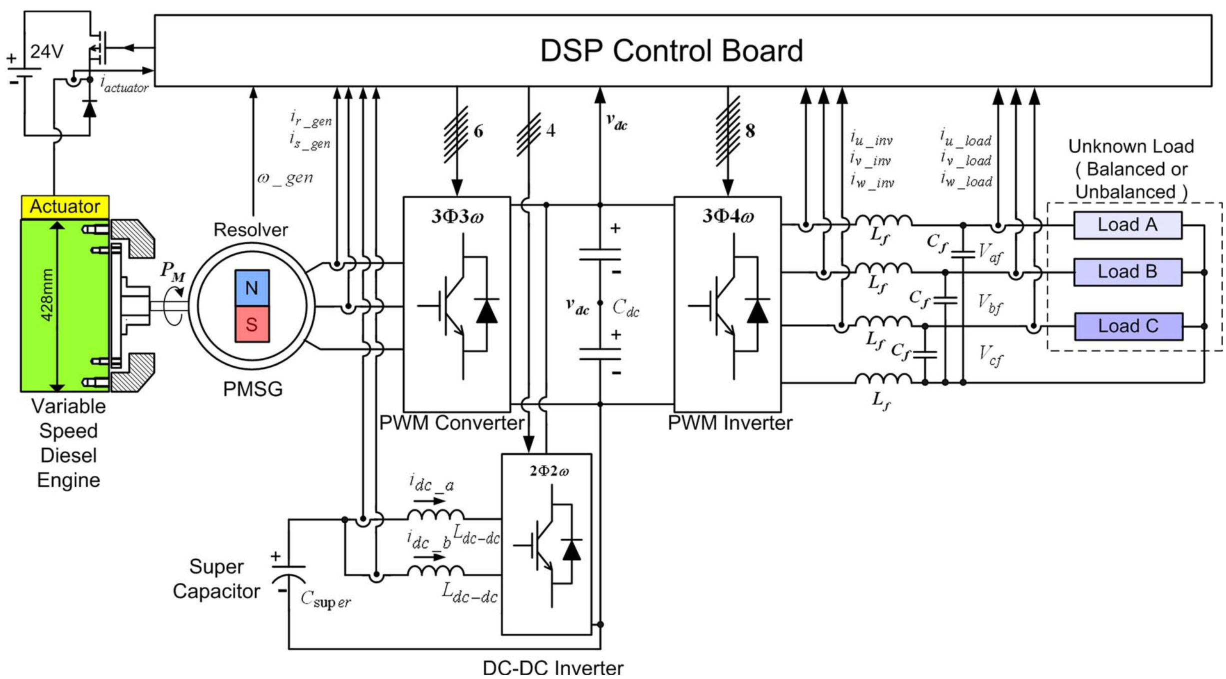

Fig. 2. Configuration of the overall system.

The effectiveness of the variable-speed diesel generator (VSDG) with an SC is verified in view point of fuel consumption and power quality by the computer simulation and experimental results. The actual fuel consumption data are listed, and they confirm the improved fuel efficiency.

II. Engine Characteristic

CSDEs, which have been widely used so far, are operated at a constant speed to generate CVCF regardless of the load condition. However, the fuel consumption under the same output power varies with the engine speed. A fuel consumption characteristic of the tested diesel engine that is called specific fuel consumption (SFC) is depicted on an engine-speed-versus-output-power plane in Fig. 1. The specification of the engine is listed in Table I.

To increase fuel efficiency and reduce pollutants, the diesel engine speed can be adjusted according to the load conditions. For example, in Fig. 1, the diesel engine which was generating 10 kW · h consumed 3.4, 3.6, 4, and 4.4 L in which the specific gravity of diesel oil is 0.8 kg/L at 1200, 1400, 1750, and 2000 r/min, respectively. As a result, a fuel cost of more than 21% can be saved if the engine speed is adjusted with the load condition as shown in Fig. 1. Furthermore, the fuel consumption under light load like as several hundreds of power can be reduced up to 40%. However, output power fluctuation may occur in the case of a sudden load change since the change of the engine speed is not as quick as the electrical load change. As a result, some sensitive electric devices may malfunction due to voltage fluctuation. Therefore, an SC bank is used to supply quickly varying load power.

III. Power Strategy

A. Power Control

A configuration of the system and the overall control system block diagram are shown in Figs. 2 and 3, respectively. The

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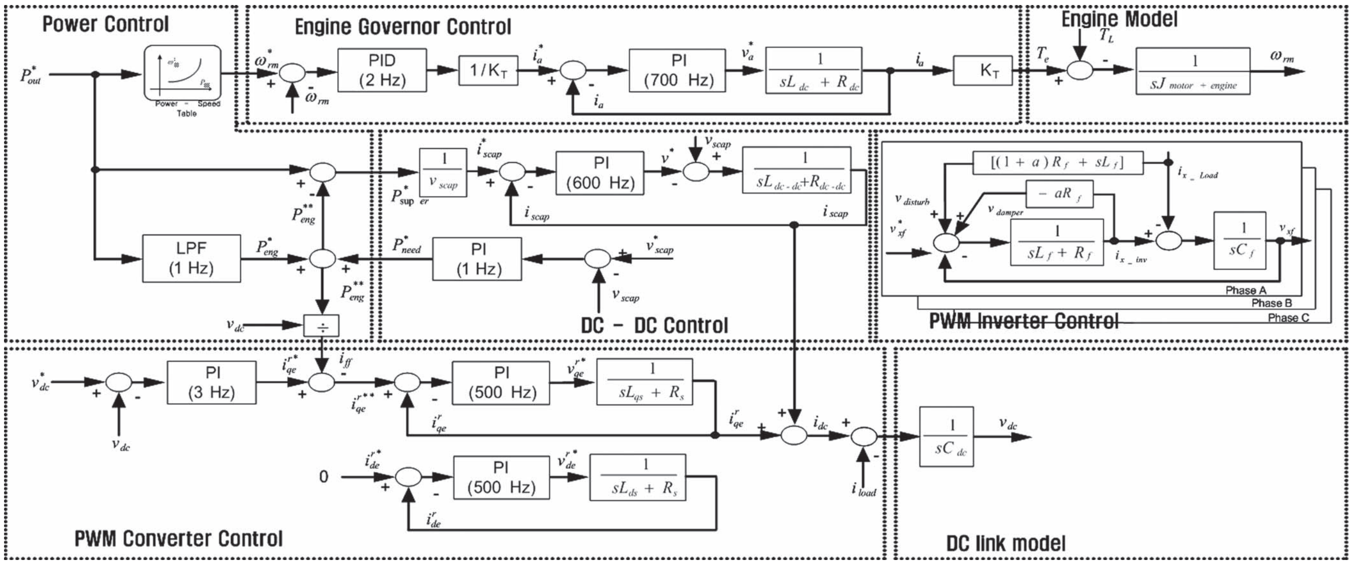

Fig. 3. Block diagram of the overall control system.

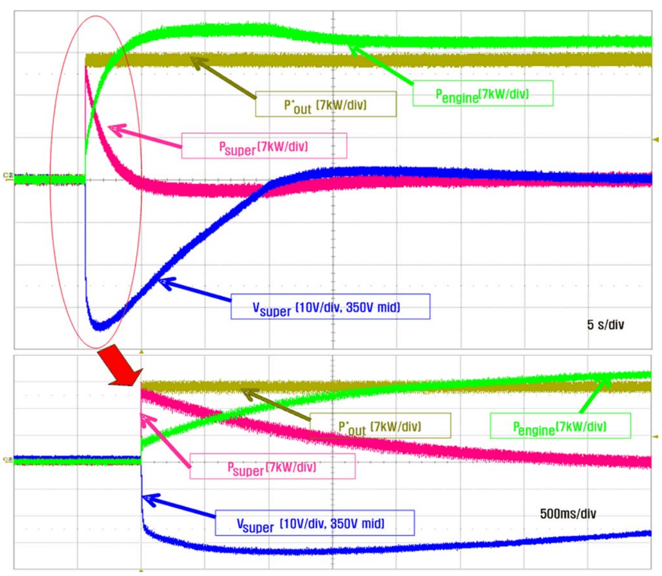

Fig. 4. Experimental result of power control.

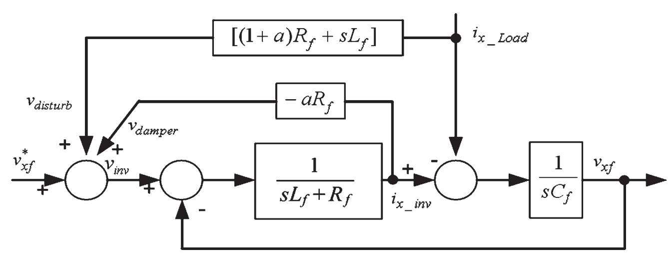

Fig. 5. Control of load disturbance.

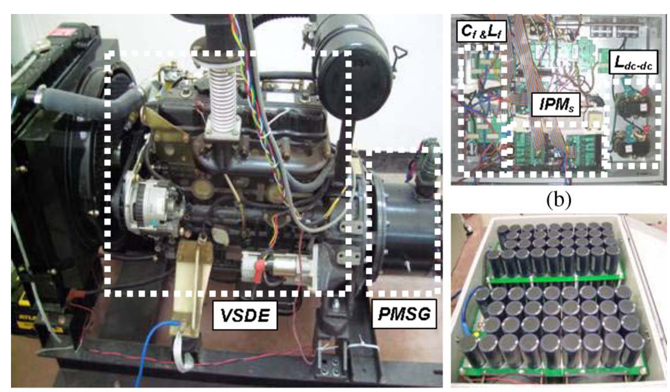

Fig. 6. Hardware structure of the system. (a) VSDE and PMSG. (b) Power stack. (c) SC bank.

system consists of a 26-kW diesel engine that is controlled by an electric governor with a dc actuator, a 22-kW PMSG, a three-phase three-leg PWM converter, a three-phase four-leg PWM inverter, and a two-leg PWM dc–dc converter. The required power (P^*_{out}) is calculated from the product of the reference output voltages and load currents. The reference of the engine speed (ω^*_{rm}) is referred to as the power-speed table that is obtained from the experiment as shown in Fig. 3 in order to achieve maximum fuel efficiency. The engine speed is regulated by an actuator. The PWM converter controls the dc link voltage to be 600 V by supplying the average power from the generator to the dc link. To improve the dynamic response of the dc-link voltage, the current feedforward (i_{ff}) is calculated from the reference (P^{**}_{eng}). To prevent power fluctuation due to sudden load change, the dc–dc converter supplies the power difference $(P^*_{\sup er})$ between the required power (P^*_{out}) and the generated power (P^{**}_{eng}) from the SC to the dc link.

The slow dynamics of the engine is modeled as a low-pass filter. Thus, the estimated engine output power (P^*_{eng}) is calculated from the low-pass filter. Since the SC voltage should be recovered after supplying the sudden load power, the reference of the SC (P^*_{need}) is added to the filtered output power reference (P^*_{eng}). Consequently, the power from the SC is followed as

$$P^*_{\sup er} = P^*_{\text{out}} - \{LPF(P^*_{\text{out}}) + P^*_{\text{need}}\}. \tag{1}$$

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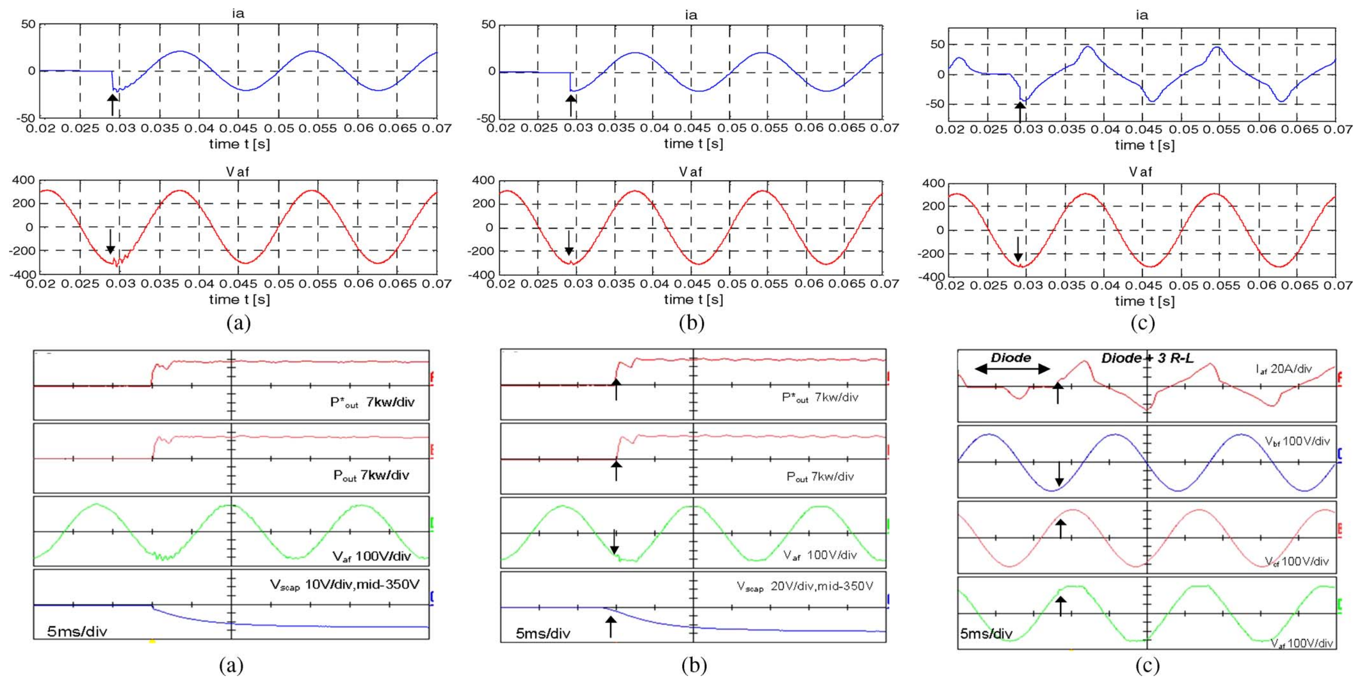

Fig. 7. (Upper) Simulation and (lower) experimental results. (a) RL balanced load (20 kW) without a controller. (b) RL balanced load (20 kW) with a controller. (c) RL balanced load (9 kW) and nonlinear load (2.5 kW) with a controller under mixed load.

Fig. 4 shows the experimental results about power control. The required power (P^*_{out}), the generated power (P_{engine}) by the engine, the power (P_{super}) of the SC, and the SC voltage in the case of a 20-kW step load change are depicted in Fig. 4. When the sudden load is burdened, the engine speed increases to optimal speed referred to the required power by the electric governor. While the engine speed is changing to generate the required power, the SC supplies the power difference between the required power and the generated power by the power controller. To regulate the dc-link voltage, the SC voltage decreases. As a result, the three-phase four-leg PWM inverter with constant dc link voltage supplies regulated three-phase voltages without any distortion under unbalanced load and/or nonlinear load. The SCs used in this experiment are 350 F, 2.6 V, and are connected in series. Their total energy is 165 kJ.

B. Three-Phase Four-Leg Inverter

A four-leg inverter which is capable of generating zero sequence voltage in order to handle the neutral current caused by unbalanced load or source was proposed. The extra leg of the four-leg inverter in the three-phase four-leg system provides not only a neutral connection but also controllability of the zero sequence voltage. Furthermore, the voltage modulation index is greater than that in the three-phase three-leg system. It is suitable for three-phase balanced load and single-phase unbalanced load due to controllability of the zero sequence voltage [5]. It is necessary to control each phase for generating output voltage under a stationary frame due to unbalanced load and/or nonlinear load. The active damping voltage and the disturbance voltage rejection are incorporated to produce a sinusoidal output voltage under balance and unbalanced load

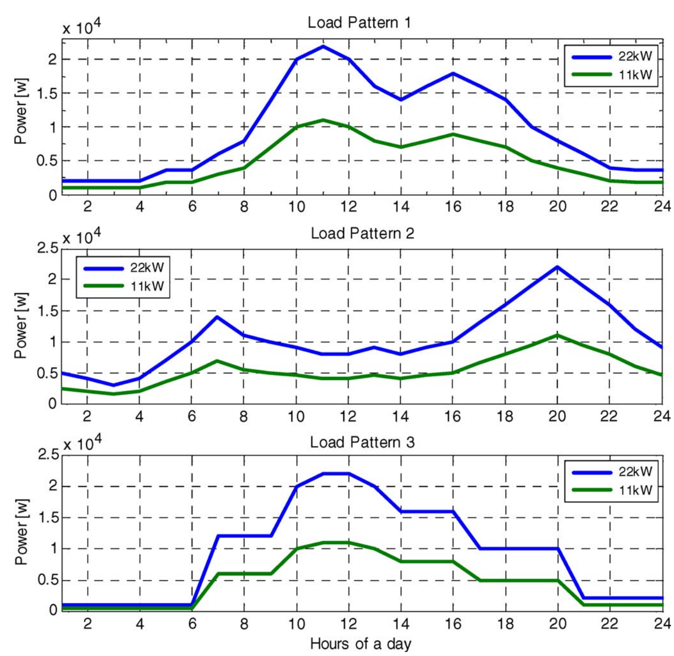

Fig. 8. Saving ratio of fuel consumption.

at sudden load [6]. v^*_{xf} is defined as a single-phase voltage command.

1) Active Damping Voltage (v_{damper})*:* The block diagram is described as follows.

The output of active damping of voltage is shown as

$$v_{\mathrm{damper}} = K_{\mathrm{damper}} \cdot i_{x\_\mathrm{inv}} = -aR_f \cdot i_{x\_\mathrm{inv}}. \tag{2}$$

The active damper can be assumed as an addition of the series resistance. The transfer function of the capacitance and active

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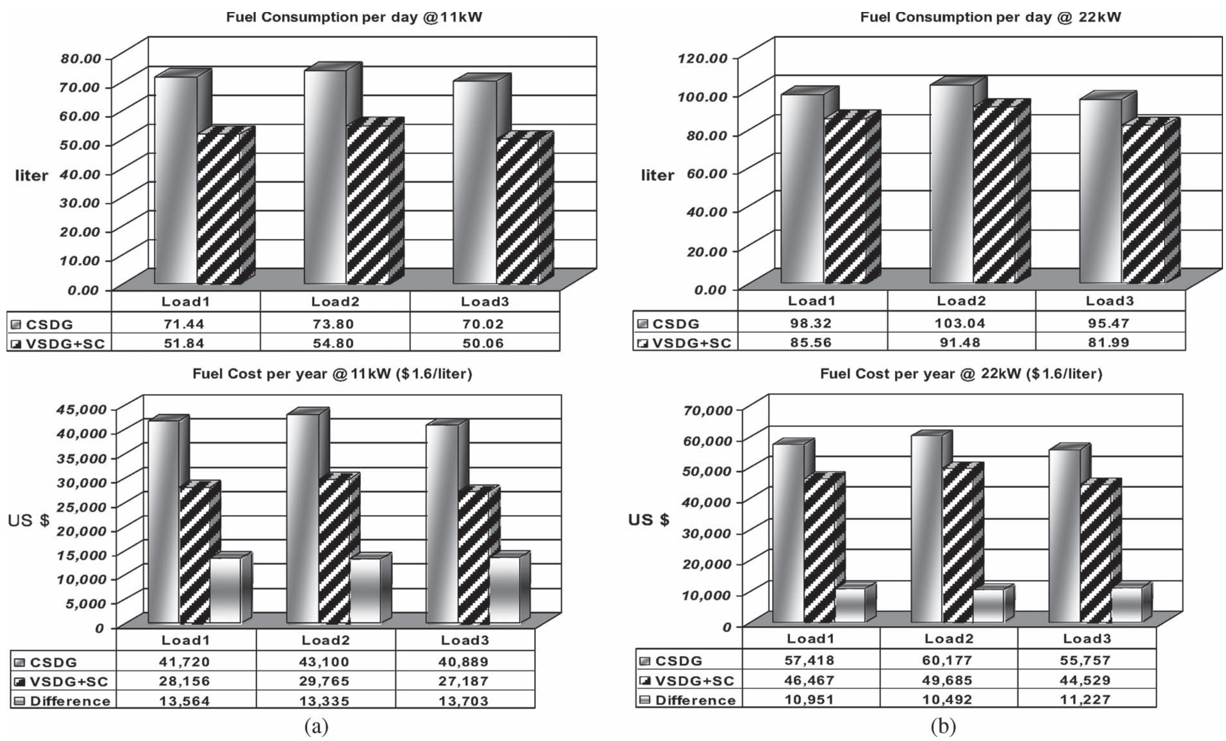

Fig. 9. Comparison of fuel consumption between CSDG and VSDG with an SC. (a) 11 kW. (b) 22 kW.

damping is obtained as

$$\frac{v_{xf}}{v_{xf}^*} = \frac{1/L_f C_f}{s^2 + (R_f + aR_f)/L_f + 1/L_f C_f} = \frac{\omega_f^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^2} \tag{3}$$

where $\zeta_c = [(R_f + aR_f)/2](\sqrt{C_f/L_f})$ and $\omega_f = 1/\sqrt{L_f C_f}$.

2) Disturbance-Rejecting Voltage (v_{disturb})*:* The compensation of the disturbance voltage is shown in Fig. 5. Since there are voltage drops due to active damping and filter inductance, the output voltage is distorted. However, the distorted voltage can be compensated by the disturbance-rejecting voltage.

The compensation voltage is obtained as

$$v_{\text{disturb}} = ((1+a)R_f + sL_f) \cdot i_{x\_\text{Load}}. \tag{4}$$

IV. Experimental Results

The parameters are given in Table I. Furthermore, the experimental result about power control is shown in Fig. 4. Fig. 7 shows the simulation and experimental results with the hardware structure of the system in Fig. 6. The sudden load with a three-phase balanced RL load that is about 20 kW is applied at 0.03 s. The output voltage is oscillated several tens of voltage by the sudden load condition as that in Fig. 7(a).

However, with active damping and rejecting disturbance voltage, there is no output voltage oscillation in Fig. 7(b). To verify the controllability of a zero sequence voltage under unbalanced load condition, simulations were carried out under mixed load condition.

Phase a: diode rectifier, $C_{\text{dc}} = 800\ \mu\text{F}$, $R_{\text{dc}} = 40\ \Omega R_a = 15\ \Omega$ will be added at 0.03 s.

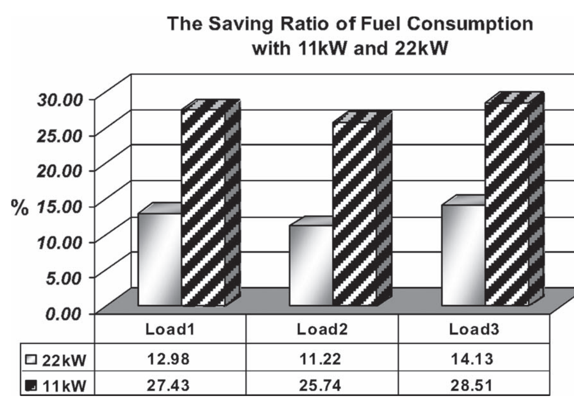

Fig. 10. Saving ratio of fuel consumption.

Phase b: $R_b = 15\ \Omega$
Phase c: $R_c = 15\ \Omega$, where all loads are line-to-neutral.

Even mixed with such a harsh nonlinear load and RL balanced load, the phase output voltage is well regulated like as that in Fig. 7(c).

V. Fuel Efficiency

Fuel consumptions of a conventional constant-speed diesel generator (CSDG) system and the proposed VSDG with an SC system were compared under three different one-day load patterns. The three load patterns [7] depicted in Fig. 8 represent a typical power demand for a day. The simulation results in Figs. 9 and 10 show the total fuel consumptions and fuel costs of the CSDG and the VSDG with an SC for a year. CSDGs for an isolated generation system are conventionally installed with twice capability due to reliability of the produced power in real site.

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Although the CSDE would be rarely operated in excess of 11 kW, it should be installed with twice capability due to the consideration of peak power. The sizing of the generator does not only depend on the required power but is also sensitive to voltage and current. However, the VSDG with an SC can supply excessive power for a few seconds without distortion of current and voltage.

Although the VSDG with an SC requires more components, increasing system losses, such as switches and passive components, a fuel cost of up to 25% can be saved under 11-kW load condition. Furthermore, the payback period of system installation is less than one year because a fuel cost of up to \$13 000/year can be saved under 11 kW and \$10 000/year under 22 kW.

VI. Conclusion

Although the CSDG has been widely used for distributed power systems, poor power quality and expensive running cost would not be affordable under much higher fuel price situation in the future. It is well known that the efficiency of a diesel engine depends on the operating speed and output power of the engine. To improve the fuel efficiency and reduce emission, the diesel engine speed can be adjusted according to the load conditions. As a result, a diesel fuel of more than 40% can be saved under light load condition if the speed of the engine generator is changed in accordance with the output power of the generator. A CVCF ac voltage can be generated from the dc link by a three-phase four-leg PWM inverter, which can provide high-quality electric power regardless of the load conditions such as nonlinear load and/or unbalanced load. The power quality of the VSDG with an energy storage based on an SC bank against sudden load power is superior to that of the CSDG. Moreover, the SC can supply excessive power for a few seconds, which is out of the engine capability. The validity of the VSDG with the SC for saving energy up to 25% under 11 kW was evaluated in the experimental and simulation results.

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