J Electr Eng Technol Vol. 8, No. 1: 137-143, 2013
http://dx.doi.org/10.5370/JEET.2013.8.1.137

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

A Study on Variable Speed Generation System with Energy Saving Function

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Abstract – This paper presents development of variable speed generation (VSG) system with energy saving function. The rubber tyred gantry crane (RTGC) requires the power from diesel-engine. Significant fuel savings by reducing the engine speed can be achieved, because all of operation modes except hoisting are required lower power than rated value of engine. When low speed operation output voltage of generator is decrease until acceptable range of motor driver inverters and auxiliary load supplier. According to power demand engine speed is varying from 20 to 60Hz, and voltage is varying between 210Vac and 480Vac. When idle mode or low power operation dc/dc converter operates by constant output voltage control and inverters dc site voltage is compensated by it. This paper proposed 3-phase interleaved boost converter which has the same structure as the commercially available 3-phase inverter and current sharing capability. 400kW interleaved converter is designed and a performance of converter is evaluated through several experiments with a RTGC system. Energy saving VSG system can cut down fuel consumption by 36% and 21.3% at idle and unidirectional load operations.

Keywords: Variable speed generation system, Energy saving, High power converter

1. Introduction

RTGC systems are used at container terminals and container storage yards to straddling multiple lanes of rail/road and container storage, or when maximum storage density in the container stack is desired [1]. RTGC has rubber tires like the bus or truck. It moves around on the yard. That's the reason why it is difficult to be supplied the electric power from the utility grid. Therefore a diesel-engine generator (GENSET) is used as its power source [2]. Diesel engines have encountered environmental and energy problems, such as air pollution caused by exhaust gas and global warming caused by CO_2 emissions. According to world bank commodity price data the price of a barrel of crude oil increased by 33% for last 12 months, 63.5% for last 5 years, and 331.5% for last 10 years respectively [3]. A hybrid RTGC using a super capacitor-based energy storage system can reduce the rated power of GENSET lower than conventional one about 60% [2]. This system has drawbacks such as high cost of super capacitors and hence its total cost becomes too high.

RTGC load profile is varying over wide range: when hoisting, it requires several hundreds of kW power rating. But under idle or low power operating conditions, uses several kW rating. In this case we can reduce the generators operation speed for decrease fuel consumptions. At low speed operation output voltage of generator decreases lower than acceptable range of motor drive inverters and auxiliary load supplier. According to power demand engine speed is varying from 20Hz to 60Hz, and voltage is varying between 210Vac and 480Vac. However, the generator output voltage and frequency is proportional to engine speed, in the low speed operation system can't operate because voltage dropping. In this paper, to resolve this problem, the inverter dc-link voltage compensated through the boost dc/dc converter and the system can operate in safety under low-power operating mode allows for low speed operation and fuel savings can be achieved. When idle mode or low power operation dc/dc converter operates by constant output voltage control and inverters dc site voltage is compensated by it. The predictive analysis of the fuel consumption was carried out during various operation mode of RTGC and fuel consumption per one cycle is reduced 28% in improved system. In lowering mode fuel consumption is reduced by 91% because regenerating energy is used to auxiliary loads an no demand from GENSET. At peak load condition, the dc-dc converter needs to handle a several hundred current.

In this paper proposed is 3-phase interleaved boost converter (IBC) which has the same structure as the commercially available 3-phase inverter and current sharing capability. IBC has been much studied due to its merits, such as (i) ripple cancellation both in the input and output waveforms to maximum extent; (ii) lower value of ripple amplitude, high ripple frequency in the resulting

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Received: March 6, 2012; Accepted: August 17, 2012

input and output waveforms; (iii) small component capacity etc [4-8]. IBC plays a role to compensate dc bus voltage during all operation of RTGC. Therefore an IBC is considered a good solution with respect to efficiency and current distribution. In section II focused to interleaved converter design and in section III a performance of converter and improved RTGC system is evaluated through several experiments. IBC is installed in real RTGC and operation of improved system is verified by rated and maximum load as 40ton load test. Improved system can cut down fuel consumption by 36% and 21.3% at idle and unidirectional load operation.

2. Improved RTGC System

2.1 RTGC system

In Fig. 1 is presented the electrical configuration of both conventional and proposed RTGC, respectively. In the conventional system main loads composed of hoist, gantry, trolley motors are supplied through rectifier and inverters from GENSET. Also CVCF (constant-voltage constant-frequency) power source is used to supply the power to auxiliary loads of a cooler and heater, system control power, etc. And the energy is to dissipate at DBU (dynamic breaking unit) when regenerating from motors of lowering mode to DC link side. The proposed system of Fig. 1(b) slightly different structure: the step-up converter is added to control the input DC voltage level for inverters, and the CVCF inverter is linked to DC output side of step-up converter. This structure can make all loads be operated over wide range even under the idling mode of the GENSET (the AUX loads can be operated only if the GENSET is operated at 1800RPM(60Hz) in the conventional one of Fig. 1(a)) use regenerating power to auxiliary load, because CVCF is connected to the DC link. If more energy regenerated than demand of AUX loads, rest energy is burning through DBU. Improved system was performed in RTGC and the detailed specification of the crane is shown in Table 1.

To analyze the RTGC system of Fig. 1, the exact diesel fuel consumption is needed but it is dependent of many variables, including ambient and engine temperature, operating conditions, etc. Generally the diesel fuel consumption was carried out during various operation mode of RTGC. Suppose the approximated fuel consumption Q_h with the unit of liters per hour, the effective specific fuel consumption per revolution S_T and then these are expressed as

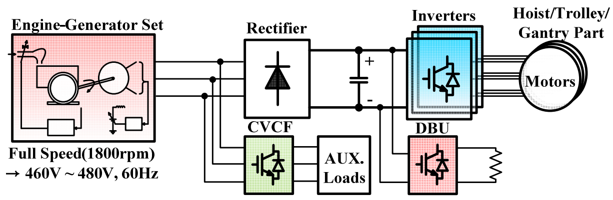
$$Q_h = 60 \times \omega_{rpm} \times S_t \quad [l/h] \tag{1}$$

$$S_t = P / P_{rated} \times S_{rated} \quad [l/rev] \tag{2}$$

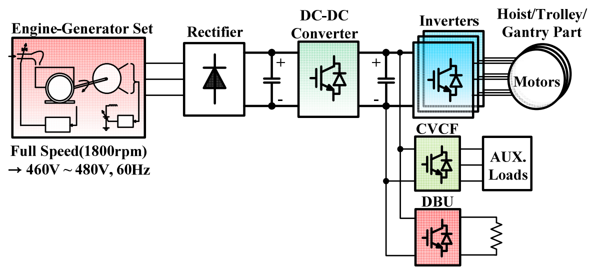
where the speed of engine is ω_{rpm} $[rev/\min]$, and at rated power P_{rated} the fuel consumption per one revolution is S_{rated} $[l/rev]$ for any operation power P at RTGC system.

Table 1. RTGC System Specifications

Parameters			Value, Unit	
Lifting Capacity / Height			40.0 MT / 18.1m	
Span Width / Trolley Travel Length			23.7m / 18.3m	
Spreader Approach			2.7/2.7m	
Gantry Wheel Base			11.0/3.0m	
Trolley Rail Gauge			7.1m	
Diesel engine specification			580HP(432kW)	
Engine Speed			1800RPM (rated)	
Fuel consumption (full load)			120.4 l/h	
Power Supply			Generator AC460V60Hz	
Motion	SPEED(M/MIN)		Motors	
			Output [kW]	Speed [rpm]
Hoisting	At no load	40	AC 210	850/1360
	At rated load	25		
Trolley	At rated load	70	AC 37	1750
Gantry	At no load	134	AC 37	1800
	At 25ton load	67		
Other (Skew, anti-sway, wheel turning, spreader)			AC 1.8, 15, 7.5, 7.5	1800



(a) Conventional system



(b) Proposed system

Fig. 1. The configuration of RTGC system

Fig. 2 shows the typical operation cycle of RTGC, which has the 9 operation modes while the container moves from the position A to the position B. The following assumptions are considered to analyze fuel consumption at each operation mode:

1. each system of power electronics equipment and GENSET has constant efficiency (the former is 0.9 and the latter 0.8).
2. even if the RTGC system is being operated, the instantaneous power is unchanged as an average value at every mode.
3. every operating modes of one cycle are performed during 360 seconds (Table 2).

Table 2. Estimated Fuel Consumption of RTGC per one cycle operation

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	1 cycle
	Trolley	Lowering	Hoisting	Trolley	Lowering	Hoisting	Gantry	Gantry	Waiting	-
Moving length [m]	18.3	15	15	18.3	15	15	50	50	-	-
Moving time [sec]	15.7	22.5	36	15.7	36	22.5	44.7	22.4	144.5	360
	Conventional RTGC									
Power Demand [kW]	51.25	27.5	287.5	51.25	27.5	90	51.25	51.25	27.5	63.9
Engine speed [rpm]	1800									-
Fuel consumption [ml]	62.29	47.90	801.27	62.29	76.64	156.77	177.35	88.88	307.64	1781
	Improved RTGC									
Power Demand [kW]	51.25	5.5	287.5	51.25	5.5	90	51.25	51.25	27.5	60.3
Engine speed [rpm]	800		1800	800		1800	800			-
Fuel consumption[ml]	27.69	4.26	801.27	27.69	6.81	156.77	78.82	39.50	136.73	1279
Fuel saving [%]	55.54	91.1	-	55.54	91.1	-	55.54	55.54	55.54	28.15

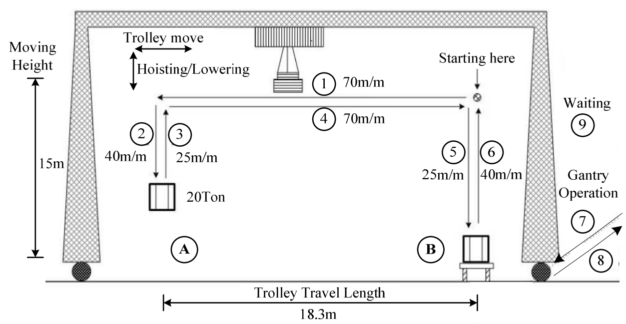


Fig. 2. The configuration of RTGC system

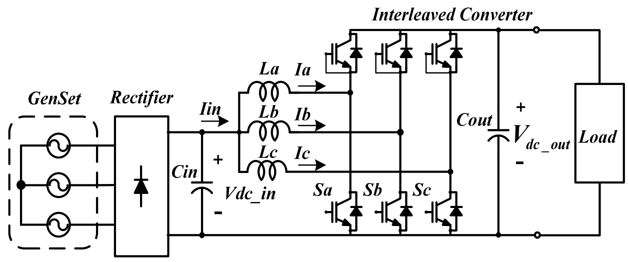
Under the above assumptions both conventional and improved RTGC systems are analyzed and compared in this paper.

2.2 Voltage compensating converter

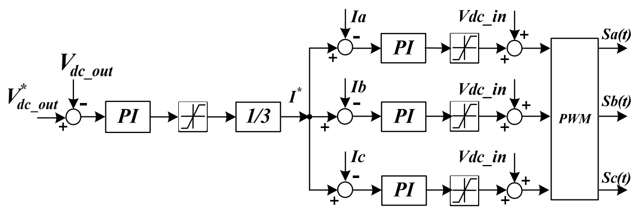
The DC-DC converter of Fig. 1(b) is shown in Fig. 3(a) of 3-phase IBC configuration, which is composed of the inductors, one 6-IGBT package and a single capacitor bank, and has the control block diagram in Fig. 3(b). This DC-DC converter has the step-up function because all loads can be operated over wide range even if the GENSET is rotated at the very low speed (the idling mode). This IBC plays a role to maintain dc bus voltage to a certain level during all operations of RTGC.

At all phase switching frequency is identical and each switch has the $120\,^{\circ}C$ phase shift. The rising and falling slope of the inductor current in the IBC are expressed by (3) and (4). The slope of the input current ripple of 3-phase IBC consists of three parts according to the duty ratio. The input current ripple is described by submission of each phase current slope and rising or falling time as Eq. (5). Output voltage ripple characteristics is analyzed same method like current ripple and result is expressed in Eq. (6). DC reactor and filter capacitor is designed to acceptable current ripple range, such as 20% in rated load.

Direct digital control method for designing a DSP based



(a) Configuration of IBC



(b) Control block diagram of IBC

Fig. 3. Control block diagram of interleaved converter

double loop voltage and current control is achieved for IBC.

An output voltage and input current PI controller scheme is described in Fig. 3(b). Voltage controller play role to compensate dc-bus voltage constantly, also output is become current reference of input site. Current controller is composed of 3 part independently one another and regulate current of dc reactor by its reference. The transfer function of each controller is presented in Eqs. (7) and (9). PI gains of each controller are expressed in Eqs. (8, 10). The result of converter design is presented in Table 3.

$$\frac{di_L}{dt} = \frac{V_{IN}}{L} \tag{3}$$

$$\frac{di_L}{dt} = \frac{V_{IN}\text{-}V_{OUT}}{L} \tag{4}$$

$$\Delta i_{IN} = \frac{V_{OUT} T_S}{L}\left(N_{ON} - 3D\right)\left(D - \frac{N_{ON} - 1}{D}\right) \tag{5}$$

Table 3. Converter specification

	Parameters	*Value*	*Unit*
Input	Input Maximum Current	800	A
	Boost Inductance	1	mH
	Capacitor Bank	10000	uF
	Switching Frequency	5.0	kHz
Output	Rated Power	400	kW
	Rated Voltage	660	V
	Capacitor Bank	10000	uF
Control	F_{NC}	500	Hz
	F_{NV}	50	Hz

$$\Delta V_{OUT} = \frac{V_{OUT} T_S}{RC}\left(\frac{(4-N_{ON})(N_{ON}-3D)}{9(1-D)}\right) \tag{6}$$

$$\begin{cases} 0 \le D \le 1/3 & N_{ON}=1 \\ 1/3 \le D \le 2/3 & N_{ON}=2 \\ (2/3 \le D \le 1 & N_{ON}=3 \end{cases}$$

where T_S and D are the sampling time and duty ratio, N_{ON} is the number of instant on state switch, R is load resistor, C is the dc link capacitor.

$$\frac{I_{IN}(s)}{I_{IN}^{*}(s)} = \frac{\frac{K_{PC}}{L_{dc}}s + \frac{K_{IC}}{L_{dc}}}{s^2 + \frac{K_{PC}}{L_{dc}}s + \frac{K_{IC}}{L_{dc}}} \tag{7}$$

$$K_{PC} = 2\zeta\omega_{NC}L_{dc}., K_{IC} = \omega_{NC}^2 L_{dc} \tag{8}$$

$$\frac{V_{OUT}(s)}{V_{OUT}^{*}(s)} = \frac{\frac{K_{PV}}{C_{OUT}}s + \frac{K_{IV}}{C_{OUT}}}{s^2 + \frac{K_{PV}}{C_{OUT}}s + \frac{K_{IV}}{C_{OUT}}} \tag{9}$$

$$K_{PV} = 2\zeta\omega_{NV}C_{OUT}., K_{IV} = \omega_{NV}^2 C_{OUT} \tag{10}$$

where ω_{NC} and ω_{NV} are the control speed of each controller. ζ is damping ratio of controller (0.707). The relationship between current and voltage control is described as $\omega_{NC} = 10\omega_{NV}$.

3. Simulation and Experiment

Simulation and experimental studies are performed and compared in order to verify the feasibility for the proposed VSG system and developed IBC.

3.1 Feasibility study

The calculated results of the fuel consumption of conventional and improved RTGC are presented in Table 2. It is obvious from the comparison of specific fuel consumption determined by calculation between conventional and improved RTGC. For one cycle the calculated fuel consumption can be totally reduced by 28% at the improved system. Particularly the fuel consumption at lowering mode is reduced largely up to 91% because AUX loads are supplied by regenerating energy, and not from GENSET.

The simulation parameters are given as in Table 3. Fig. 4 shows simulation result of several operation modes desired on Fig. 2. During the RTGC driving range as shown Fig. 4(b), operator drives a RTGC, and the converter, regardless of engine speed and the dc-bus voltage is controlled as 660V. GENSET operates 2 step speed operations such as low speed is 800RPM and full speed is 1800RPM.

The each operation mode is defined as follows:

- Initialization: GENSET speed increases from 0 to 800RPM, dc-bus and input side capacitor charged by charging circuits to avoid inrush current.
- Mode IX: Idle operation, after the initial charge, the IBC controller operated to smoothly build up the dc-

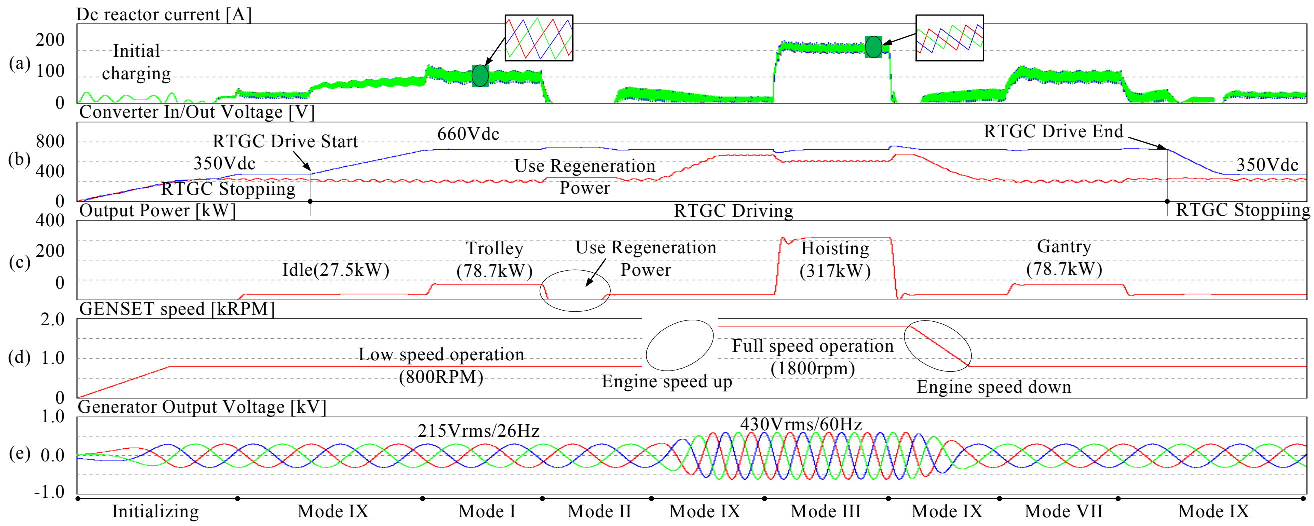


Fig. 4. Simulation results of IBC converter under several operation modes

bus voltage until 350Vdc, such as acceptable operation range for 220Vrms CVCF supplier, AUX load is about 27.5kW. When operator start drives RTGC, IBC controls dc-bus voltage until 660Vdc, smoothly.

- Mode I: Trolley operates, GENSET Low speed operation, load reaches 78.7 kW because include trolley and AUX loads.
- Mode II: Lowering operation, no power demand from GENSET like as Figs. 8(a), (c) because AUX loads use regenerating power from hoisting motor.
- Mode III: Hoisting operation, GENSET operates full speed, load reaches 317kW.
- Mode VII: Gantry operation, Gantry motor operates with container load, power demand reaches 78.7kW. The dc-bus voltage is regulated nearly constant 660Vdc by IBC, but in case of conventional system the voltage is varied largely like input voltage of converter.

The outlook of developed IBC for voltage compensation and laboratory experimentation settings are shown in Fig. 5. In order to verify the operation and performance of converter, 50kW motor load test processed in laboratory result is shown in Fig. 8. Efficiency of converter is measured by LeCroy Wave Runner oscilloscope, of which the measured results are obtained as in Fig. 8 over 98% at higher than the 10% load.

3.2 Field tests with real RTGC

IBC is installed in RTGC and operation of improved system is verified by rated and maximum load as 40 ton load test. Fig .7 is showing in out voltage and input current waveforms when hoisting 40ton container.

In addition, fuel consumption is compared with conventional system, to verify fuel savings of improved system, through three operating modes, an each one is continued during one hour with 26ton container. In the idle operation only auxiliary load is works and engine is still running with 800rpm. In another case when hoisting, engine is running with 1800rpm, outside those times running with 800rpm. The one cycle of other two modes take 6 minutes and it consists as follows:

- Bidirectional: each operation as hoisting, lowering and trolley moving are repeats two times with container load.
- Unidirectional: each operation repeats two times but only one is with container load.

Result of fuel consumption test is shown in Table 4. In idle operation mode fuel consumption is reduced by 35.7%, and in unidirectional and bidirectional load mode reduced by 14.4 and 21.3%, respectively.

If it is assumed that RTGC with energy saving VSG system is operated during 20 hours a day by unidirectional

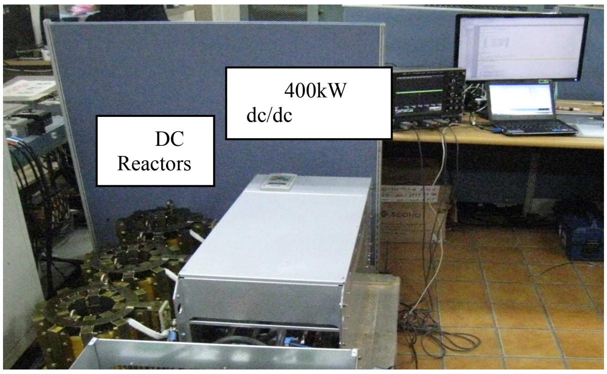


Fig. 5. Experimental settings for compensation converter

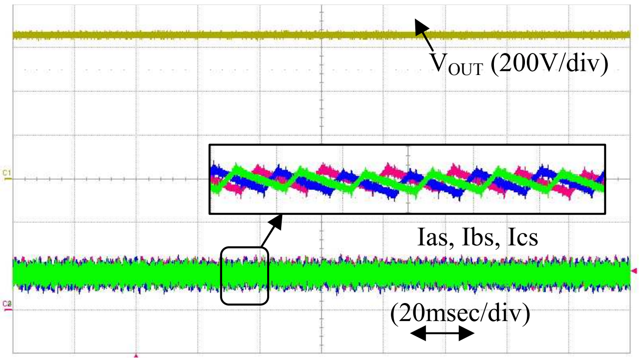


Fig. 6. Output voltage & current waveform in 50kW Motor load

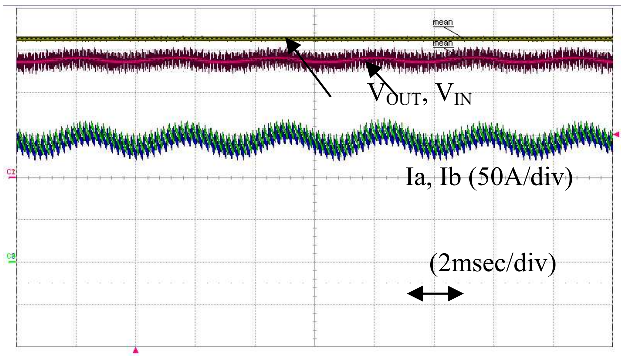


Fig. 7. In/Out voltage & current waveform in hoisting mode of RTGC

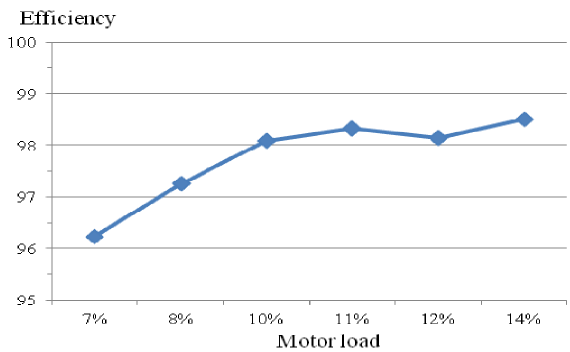


Fig. 8. Converter efficiency with motor load test

Table 4. Fuel Consumption effect under operation mode

Operation mode	Used fuel [l/h]		Fuel saving
	Conventional	Improved	
Idle Operation mode	7.0	4.5	35.7%
Bidirectional load operation	20.8	17.8	14.4%
Unidirectional load operation	18.3	14.4	21.3%

load mode, fuel saving is expected to more than 2300 liters (roughly 21.3% of total fuel consumption in conventional system) in a month.

4. Conclusion

In this paper the VSG system with energy saving function is proposed to reduce fuel consumption of RTGC.

The proposed system can be configured simply by addition only one converter to conventional RTGC. And the fuel consumption prediction of the GENSET was performed during 1 cycle operation. The improved system has the 28.15% energy saving effect comparison to conventional system. The interleaved dc/dc converter of 400kW class is developed for this system and a performance of this converter is evaluated through simulation and experimentation. And the theoretical analysis of voltage and current ripple was performed. The base on the theoretical analysis, the hardware of system design to enough ripple factor. The experiment of this system is evaluated to verify performance and reliability under 55kW motor load. The efficiency of IBC was measured as higher than 98% at over the 10% load.

Improved system was performed in real RTGC, and the fuel consumption is compared with conventional system under field test with RTGC. The improved system can cut down fuel consumption by 35.7% and 21.3% at idle and unidirectional load operation mode, respectively. All of test results verify the system was operate a robustly and economically.

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