# Sizing of Energy System of a Hybrid Lithium Battery RTG Crane

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***Abstract*—Rubber tyred gantry (RTG) cranes are an important piece of transport equipment in ship and rail container terminals. They have a diversified power demand, for example, peak powers of 292-kW driving, 178 kW regenerating, and 7-kW idle power. The high peak power demand determines the system prime mover (internal combustion engine) rating, which is highly over-rated for the crane average energy requirements. Such a variation in peak to idle power demand favors a hybrid power solution which, given appropriate design, can yield significant gains in fuel or energy usage and, importantly, reductions in local emissions, thus improving air-quality. In this study, a hybrid energy source for an RTG crane is presented. The hybrid energy source comprises of a lithium battery and a down-sized diesel-generator connected to the dc link through an active front end unit. While other systems have been previously proposed, the system presented here utilizes a smaller diesel-generator, thus reducing plant and fuel consumption. In addition, the battery connects directly to the dc link reducing system power electronics while improving battery response and efficiency. Experimental results from a full-size evaluation system are presented showing a 57% reduction of fuel consumption compared to a conventional RTG crane system.**

***Index Terms*—Diesel-generator, hybrid energy source, lithium battery, rubber tyred gantry (RTG) crane.**

## I. Introduction

HYBRID energy sources will lead to significant fuel reduction of vehicles having diversified power duty cycles, such as automobiles [1]–[6], aircrafts [7], and ships [8], [9]; and especially vehicles with regenerated power [10], [11], such as mining equipment [12]–[14], elevators [15], and cranes [16], [17].

Rubber tyred gantry (RTG) cranes are important horizontal transport equipment in ship and rail container terminals [18]–[20]. Compared to rail mounted gantry cranes which can move only on rail tracks, RTG cranes can move to other yard areas easily, a feature that is favored by container terminals having a shortage of grid and space, such as Yangshan Port, Shanghai, China.

RTG cranes have diversified load cycles [16]. For example, for a typical RTG crane system, the peak driving power is 292 kW when a heavy 40-T container goes up and the peak regenerated power is 178kW when a 40-T container goes down. In contrast, RTG cranes have a steady average power demand of only 7 kW for lighting and air conditioning and other ancillaries when the hoists are in an idle state.

A conventional RTG crane adopts a single diesel-generator as the unique power/energy source. For example, the diesel-generator has an output power of 410 kW to deal with the 40-T heavy container peak power demand. Note, the higher power rating is required to maintain engine stability during the hoist power transients. Braking resistances are used to consume the regenerated power when the container goes down. This is the worst case load scenario. In practice, the typical container mass is about 10 T; hence, the corresponding power demand is much lower than the engine 410-kW rated peak power. Consequently, the diesel engine runs usually in a low-efficiency area of its performance characteristic, consuming more fuel and emitting high $CO_2$ and other undesirable particulates than when at optimum power and speed.

Consequently, the RTG crane system is a candidate for hybridization of onboard energy sources and this paper will demonstrate the technical feasibility of a representative hybrid RTG crane system.

An important contribution in the field is the work of USA researchers who adopt a hybrid energy source comprising of a 455-kW diesel-generator and a 2.12-MJ flywheel to power a RTG crane [21]. The idea is to use the flywheel to recover potential energy when a container goes down and then to reuse the stored flywheel energy when a container goes up. Experimentally, a 20.9% reduction in fuel consumption was achieved. More recently, UK researchers used simulations to show a 38% reduction in fuel consumption may be achieved with a 200-kW prime source and a 3.34-MJ flywheel [22]. However, the simulations were not experimentally validated.

Another important work is the contribution of Korean researchers who adopt a hybrid energy source comprising of a diesel-generator and a supercapacitor to supply a RTG crane [16]. The idea is that the 120-kW diesel-generator acts as an average power provider (energy), while a 4.19-MJ supercapacitor

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acts as the system peak power source. A 250-kW bidirectional dc–dc (BDC) converter is placed between supercapacitor and dc link to control the supercapacitor current. The small 120-kW diesel-generator results in reduced idle fuel consumption and when coordinated with the supercapacitor, the diesel-generator runs largely in a high efficiency area. Additionally, the regenerated power during hoist down is absorbed by the supercapacitor. Consequently, a 35% reduction in fuel consumption is achieved.

Another important work is the contribution of Japanese researchers who adopt a hybrid energy source comprising of a diesel-generator and a small capacity lithium battery to power a RTG crane (Sybrid System) [23]. The diesel-generator has a power rating of 130 kW comprising of 100 kW for hoisting and 30 kW for auxiliary devices. A 14.4-kWh lithium battery is chosen to supply the peak hoisting power and absorb the regenerated power. The battery works at a 20C charge and discharge current, hence the battery can be considered as a 288-kW power source. A 288-kW BDC converter is placed between the battery and dc link, and a 100-kW dc–dc converter is placed between the diesel-generator and the dc link. With this solution, an average 50–60% fuel reduction is achieved.

A conceptional battery-supercapacitor hybrid energy source for RTG cranes is suggested in [17], where sizing of the battery and the supercapacitor are described in detail over a 4-h short period crane operation and a 16-h long period crane operation.

In this study, a diesel-generator and lithium battery hybrid energy source for RTG cranes is implemented, as shown in Fig. 1. A 128-kWh lithium battery is used to provide the peak power when the hoist goes up and also to absorb the regenerated power when the hoist goes down. In the idle states, the battery can power the long term operations of low-power auxiliary devices, such as lighting and air conditioning. When the battery state-of-charge (SOC) is smaller than 0.5, a 50-kW diesel-generator is turned on to charge the battery. A 60-kW active front end (AFE) unit is used to control the output power of the diesel-generator.

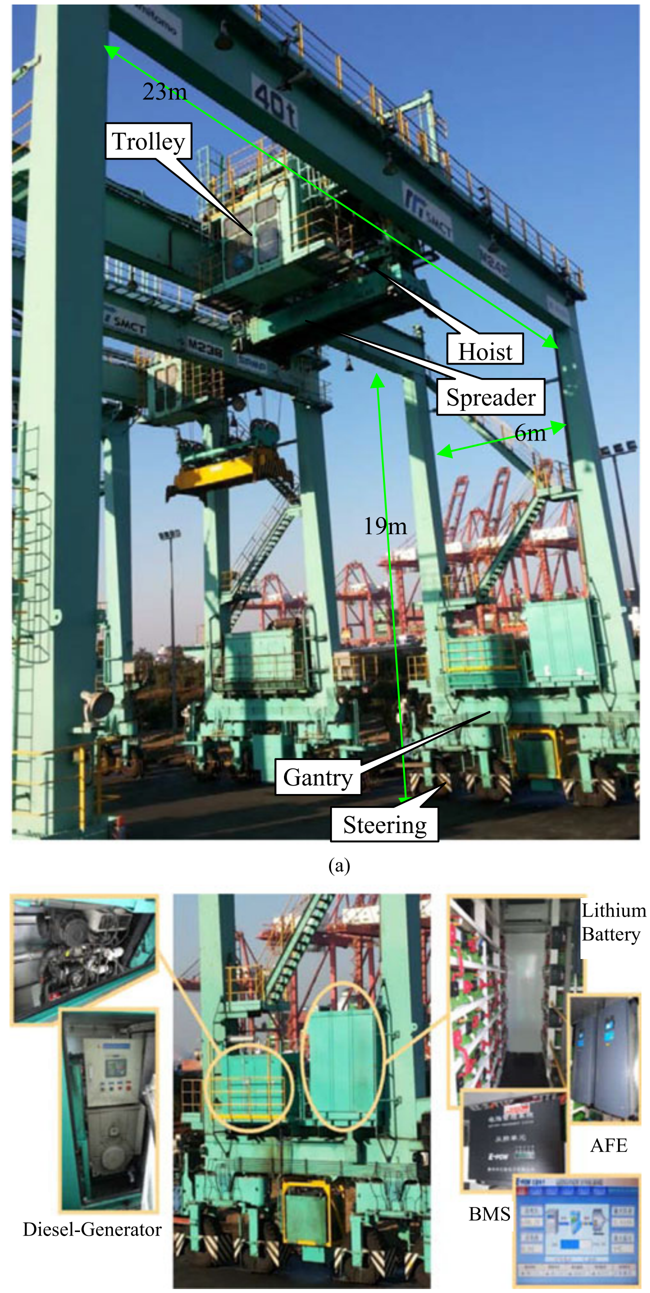
Compared to the Korean solution [16], a smaller diesel-generator is adopted, resulting in lower idle fuel consumption. In addition, the lithium battery connects directly to the dc link and the 250-kW BDC converter is omitted. Thus, the battery has a quicker response and a better efficiency. Consequently, compared to a conventional RTG crane, a 57% reduction of fuel consumption is achieved. When compared to the Japanese solution [23], a smaller diesel-generator is adopted, thus lowering idle fuel consumption. In addition, the lithium battery connects directly to the dc link; hence, the 288-kW BDC converter is omitted and the battery has a quicker response and a better efficiency. The 100-kW dc–dc converter placing between the diesel-generator and the dc link is also removed resulting in a simpler topology for the system discussed in this study.

An important contribution of the paper is the realization of a full-scale demonstrator system to experimentally validate system design studies and simulations.

## II. Architecture of the Hybrid RTG Crane

### A. Architecture of RTG Cranes

An RTG crane presents a bridge structure, as shown in Fig. 1(a). At the top of the crane, there are girders that allow trolley lateral movement. A hoist under the trolley picks up containers through a spreader. The RTG crane can move around a container yard by its gantry mechanism. The hybrid RTG crane is shown in the front of Fig. 1(a), which has a small chimney and a cyan spreader, and a conventional RTG crane is shown behind the hybrid one, which has a big chimney and a yellow spreader.




(a) (b)

Fig. 1. Hybrid RTG crane (a) and its energy system (b).

The energy system of the hybrid RTG crane is detailed in Fig. 1(b). The lithium battery system is in the right tall box which holds the battery, an AFE unit, and the battery management system (BMS). The diesel-generator is placed in the left short box.

The schematic of the hybrid RTG crane is shown in Fig. 2. The crane shows a micro-dc-grid structure. The lithium

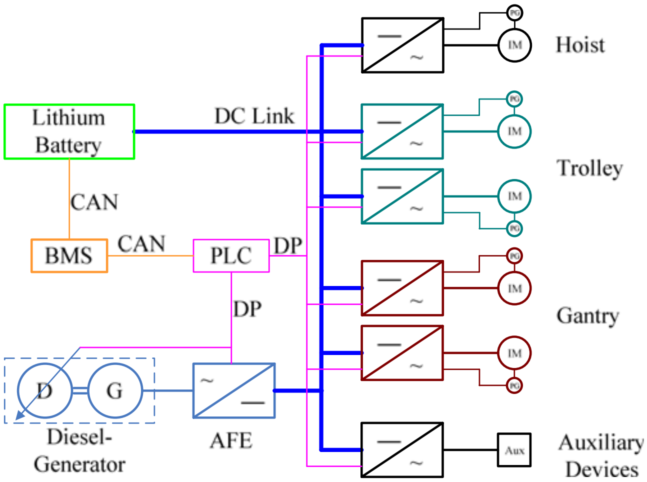



Fig. 2. System schematic of the hybrid RTG crane.

TABLE I
KEY CHARACTERISTIC PARAMETERS OF RTG CRANES

| Parameters | Value | Unit |
|---|---|---|
| Rated load | 40 | Tonne |
| Spreader mass | 11 | Tonne |
| Trolley mass | 25 | Tonne |
| Hoist speed (Full load) | 26 | m/min |
| Hoist speed (No load) | 52 | m/min |
| Gantry speed | 90 | m/min |
| Trolley speed | 70 | m/min |
| Hoist height | 18.1 | m |
| Hoist motor power | 170 | kW |
| Gantry motor power | 2 × 50 | kW |
| Trolley motor power | 2 × 15 | kW |

battery is directly connected to the dc link, and the output of the diesel-generator is feed to an AFE unit, which connects to the dc link. The hoist motor, trolley motors, gantry motors, and the auxiliary devices get their energy from the dc link through converters.

PLC is the control center, and it controls the diesel-generator and all converters through Profibus DP bus. PLC communicates with the lithium battery through the BMS by a Profibus DP to CAN converter. BMS adopts CAN bus to monitor the lithium battery state and report the battery state to PLC. BMS measures the battery electrical parameters, such as voltage, current, and temperature, and uses these measurements to estimate the SOC and to complete battery voltage balancing.

## B. *Characteristic Parameters of a RTG Crane*

Key characteristic parameters of RTG cranes are shown in Table I. These parameters are used both to conventional RTG cranes and hybrid RTG cranes.

# III. Sizing of the Lithium Battery

## A. *Typical Load Cycle of a RTG Crane*

The typical load cycle of a RTG crane is shown in Fig. 3. For ①→ ③, the crane has a container and for ④→ ⑥, the crane has no container.

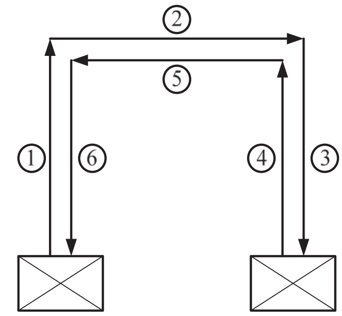



Fig. 3. Benchmark load cycles of a RTG crane. ① hoist up, ② trolley right, ③ hoist down, ④ hoist up, ⑤ trolley left, ⑥ hoist down; ①→ ③ with container, ④→ ⑥ without container.

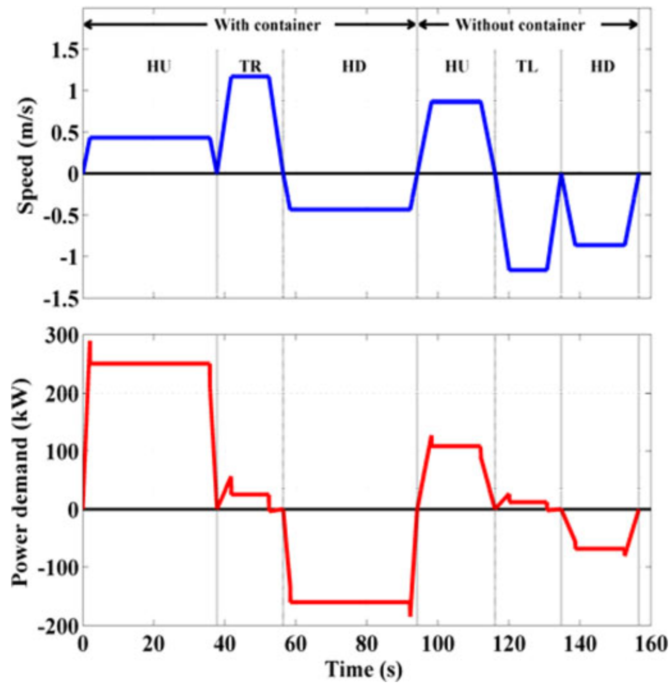



Fig. 4. Power demand of RTG cranes at a heavy 40-T container. HU: hoist up, TR: trolley right, HD: hoist down, and TL: trolley left.

## B. *Power Demand of RTG Cranes*

The speed and power demand of a RTG crane operating a heavy 40-T rated container is shown in Fig. 4 [16], [17], [24]. During the first half cycle, the crane is carrying a 40-T container, and during the second half cycle the crane does not carry a container. The total time span is 156 s: the first half cycle takes 94 s and the second half cycle takes 62 s. The peak driving power is 292 kW when the container is hoisted up, and the peak regenerated power is 178 kW when the container is hoisted down. For the load cycle in Fig. 4, the average power demand is 42.8 kW; hence, the peak-to-average power ratio of 6.8 makes the system highly suitable for energy source hybridization.

The characteristics in Fig. 4 are calculated from parameters given in Tables I and II, where $\eta_{\text{inv}}$, $\eta_M$, and $\eta_J$ are the transfer efficiencies of the inverters, machines, and gearboxes, respectively, as illustrated schematically in Fig. 5.

TABLE II
TRANSFER EFFICIENCIES OF DEVICES OF RTG CRANES

| Parameters | Driving | Regenerating |
|---|---|---|
| $\eta_{\rm inv}$ | 0.98 | 0.98 |
| $\eta_M$ | 0.96 | 0.82 |
| $\eta_j$ | 0.92 | 0.92 |

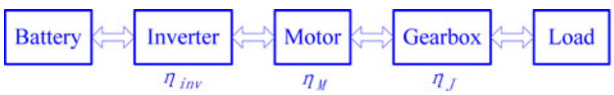



Fig. 5. Transfer efficiencies of devices of RTG cranes.

The performance of a RTG crane is 20 moves/h [18], or 40 to 45 TEU (Twenty-foot Equivalent Unit) /h, an industry standard definition for the system. The typical operation of an RTG crane in 1 h is eight moves of 30-T containers, 12 moves of 15-T containers. The RTG crane goes idle after it has completed 20 moves; hence, the average power demand of a RTG crane is 24.8 kW.

### C. Sizing of the Lithium Battery

To omit the BDC converter, the lithium battery is directly connected to the system dc link, which usually has a voltage of 500–700 V. To better absorb the regenerated energy when the hoist goes down, the battery rated voltage should be lower than 700 V, and hence the lithium battery rated voltage was chosen as 640 V.

The typical average power of a RTG crane is 24.8 kW. The lithium battery is expected to supply a 1.5–2-h RTG operation, and thus it has a capacity of 37.2–49.6 kWh. To expand the battery life, a SOC usage is chosen as 0.3, yielding a lithium battery capacity of 124–165.3 kWh. For economy, the lithium battery capacity is chosen as 128 kWh, for which the rated current of 200 A is quoted.

The peak discharging current of the lithium battery is checked to ensure that it stays within the quoted limit by considering the hoist power when a 40-T container is hoisting up at constant speed:

$$P_{\rm hoist\_const} = Fv = mgv = 216.6\,{\rm kW}. \quad (1)$$

The hoist accelerating acceleration time when a 40-T container is hoisting up is 4 s, and thus the hoist accelerating power is

$$P_{\rm hoist\_acc} = Fv = m\frac{dv}{dt}v = 4.8\,{\rm kW}. \quad (2)$$

A typical hoist motor, such as a Siemens 1PH8 servo motor at 182 kW, has an inertia of 5.2 kg·m$^2$ and a speed of 1000 r/min [25]. Thus, at full speed, its energy is

$$W_{\rm hoist\_motor} = 0.5 J_{\rm motor}\omega^2 = 28.5\,{\rm kJ} \quad (3)$$

and the corresponding peak motor accelerating power is

$$P_{\rm hoist\_motor\_acc} = 28.5\,{\rm kW}. \quad (4)$$

The auxiliary power for lighting and air conditioning is

$$P_{\rm aux} = 7\,{\rm kW}. \quad (5)$$

The peak lithium battery power is then

$$P_{\rm bat\_peak} = \frac{P_{\rm hoist\_motor\_acc} + \frac{P_{\rm hoist\_const} + P_{\rm hoist\_acc}}{\eta_M \eta_J}}{\eta_{\rm inv}} + P_{\rm aux} = 292\,{\rm kW}. \quad (6)$$

Thus, the peak battery discharging current is then

$$I_{\rm bat\_peak} = P_{\rm bat\_peak}/V_{\rm dc} = 456\,{\rm A} \quad (7)$$

which is 2.28 times the rated lithium battery current; hence, a specific supercapacitor type lithium battery having a high peak power capability is chosen to provide this 2.28 C discharge current, see Section VI-A for details.

## IV. SIZING OF THE DIESEL-GENERATOR

In terms of energy management philosophy, the primary purpose of the diesel-generator is to recharge the lithium battery, which is essentially providing the average power (i.e., energy) to the system.

The typical average power demand of a RTG crane is 24.8 kW. The average power demand of a RTG crane under 40-T heavy rated container is 42.8 kW (see Fig. 4). The SOC usage of the lithium battery is 0.3, and the lithium battery capacity is 128 kWh, and the recharged battery energy is 38.4 kWh.

The output power of the diesel-generator should be greater than 42.8 kW, so that the battery SOC usage will not exceed 0.3 during a 40-T heavy rated container operation. Moreover, the larger the power of the diesel-generator, the shorter the charging time of the lithium battery, and the larger charge current to the lithium battery when the hoist goes down, and the larger the idle fuel consumption. As a tradeoff, the output power of the diesel-generator is chosen as 50 kW; hence, it takes approximately 1.5 h to fully recharge the lithium battery.

## V. ENERGY CONTROL STRATEGY OF THE HYBRID RTG CRANE

Operational modes of the hybrid RTG crane are shown schematically in Fig. 6. Pure battery modes are shown in Fig. 6(a) and (b). Hybrid power sources modes are shown in Fig. 6(c)–(e). A thermostat control strategy is used to switch the two modes [26]. When the lithium battery SOC is less than 0.5 the controlling PLC receives the SOC information from the BMS and then notifies the diesel-generator to turn ON to charge the battery. The RTG crane is then in hybrid power source mode. When the battery SOC is greater than 0.8, the diesel-generator will be turned OFF by the PLC and the hybrid RTG crane will operate in pure battery mode. As previously discussed, the minimum lithium battery SOC usage is chosen as 0.3 to expand operating life.

## VI. EXPERIMENTAL RESULTS

A prototype hybrid RTG crane and the terminal applications results are reported here.

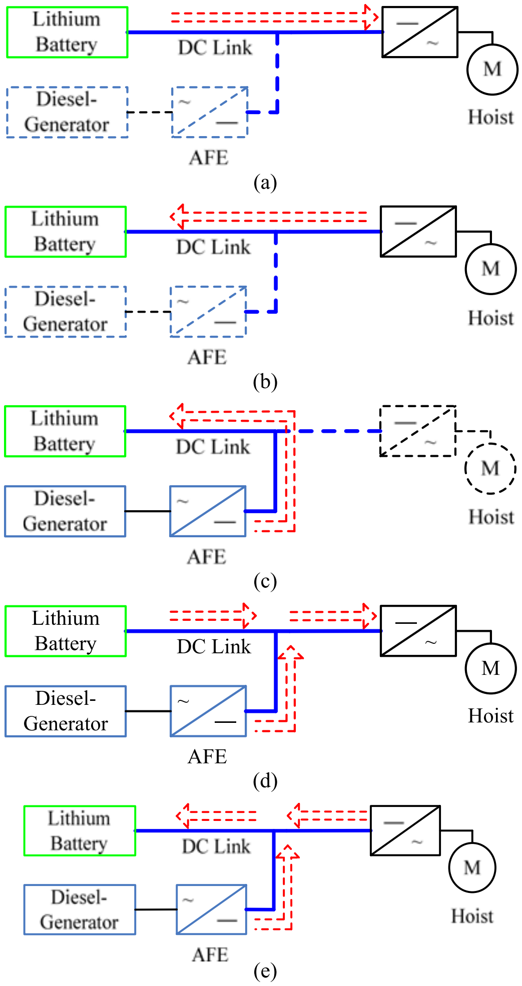



Fig. 6. Operational modes of the hybrid RTG crane. (a) Battery driving. (b) Battery charging. (c) Diesel-Generator charging. (d) Hybrid driving. (e) Hybrid charging.

## A. Lithium Battery Structure

Lithium iron phosphate batteries are chosen to power the hybrid RTG crane. These batteries are supercapacitor type lithium batteries, i.e., they sacrifice some energy density in place of power density. Hence, the battery can support a 10C continuous discharge current and a 2C fast charge current while maintaining a 5000 cycle life (quoted at 80% depth of discharge) [27]. These lithium batteries can provide the 2.28 C peak discharge current when a 40-T container is hoisting up and absorb fast the regenerated power when a 40-T container goes down. The SOC usage is 0.3, i.e., from 0.8 to 0.5. A single battery cell has a capacity of 3.2 V and 50 Ah. Sixteen cells form a battery module which has four parallel paths, and each path has four cells in series. The battery module has a capacity of 12.8 V and 200 Ah. Fifty battery modules are in series to form the RTG crane battery of 640 V and 200 Ah (see Fig. 7).

## B. Hoist Converter Power Under a 40-T Container

Experimental hoist converter power of the hybrid RTG crane under a 40-T container is shown in Fig. 8. The crane has a peak driving power of 281 kW when a 40-T container goes up and a peak regenerating power of 202 kW when the 40-T container goes down. The experimental data agree qualitatively with the theoretical power demand shown in Fig. 4 and agree with the theoretical peak lithium battery power calculated from (6).

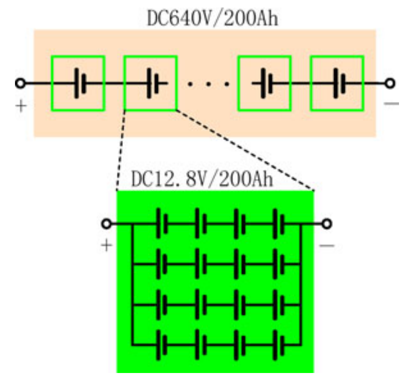



Fig. 7. Lithium battery structure of the hybrid RTG crane.

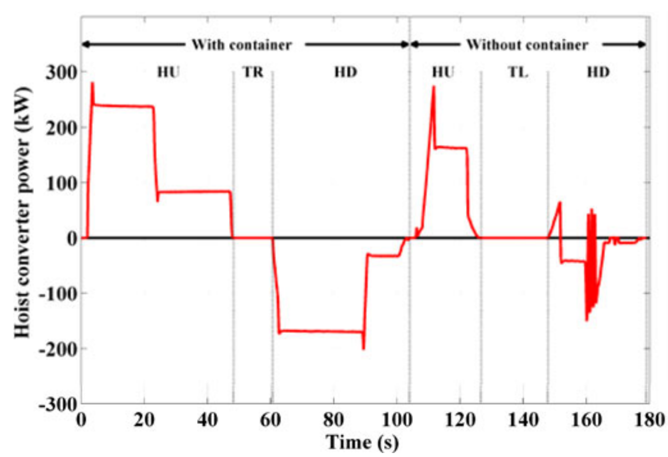



Fig. 8. Experimental hoist converter power of the hybrid RTG crane under a 40-T container. Other conventions are the same as in Fig. 4.

## C. Benchmark Load Cycles

To test the energy consumption of the experimental hybrid RTG crane, a benchmark load cycle is defined (see Fig. 3).

The benchmark test lasts for approximately 2 h and consists of four typical load operations: 1) the idle operation; 2) 0-T operation; 3) 15-T operation; and (iv) 30-T operation. The idle operation lasts 30 min and each of the other three operations takes approximately 30 min to complete ten load cycles.

## D. Two Cranes Under Benchmark Test

In addition to the parameters shown in Table I, the conventional RTG crane has a diesel engine of 410 kW and a generator of 322 kW. The hybrid RTG crane has a lithium battery of 128 kWh and a diesel-generator of 50 kW.

TABLE III
DIESEL CONSUMPTION COMPARISON

| Operation | Load cycles | Time (Minutes) | Conventional | Hybrid | | Percent reduction (%) |
|---|---|---|---|---|---|---|
| | | | Diesel consumption (L) | Energy consumption (kWh) | Equal diesel consumption (L) | |
| Idle | 0 | 30 | 5.20 | 3.62 | 1.04 | 79.9 |
| 0 T | 10 | 28 | 9.47* | 9.20 | 2.65 | 72.0 |
| 15 T | 10 | 33 | 13.85 | 15.71 | 4.53 | 67.3 |
| 30 T | 10 | 36 | 18.5 | 19.45 | 5.61 | 69.7 |

*The conventional RTG crane takes 25 min to complete ten load cycles and 3-min idle diesel consumption is added to compare with the hybrid one.

### E. Results of Benchmark Test

The performance of the conventional and the hybrid RTG cranes are compared by the benchmark test.

To test the hybrid RTG crane, the lithium battery is charged fully by the diesel-generator and then the diesel-generator is turned OFF. During the benchmark operations, the lithium battery is the only energy source and a dc electricity meter (Suzhou Lanlex: LSM-50DEE) is used to accurately measure the battery energy consumed.

For this specific hybrid RTG crane operated in diesel-generator mode, Fig. 6(c), 9.7 L of diesel are consumed to charge the battery resulting in a 33.6-kWh battery energy increment. Hence, the hybrid RTG crane has a diesel to electrical energy converting efficiency of 3.47 kWh/L.

By way of comparison, the energy consumptions of the conventional and the hybrid RTG cranes are shown in Table III. The typical load distribution of a RTG crane is an idle state of 10%, a 15-T load of 54%, and a 30-T load of 36%. So the diesel reduction rate of the hybrid RTG crane is 69.4%.

### F. Terminal Applications

The hybrid RTG crane is put into operation in Waigaoqiao Port Phase V Terminals, Shanghai, China, Fig. 1. During one-year operation, it handled 127654TEU containers with a total diesel consumption of 51 750 L. The average diesel consumption was 0.405 L/TEU. The conventional RTG crane has currently a diesel consumption of 0.95 L/TEU; and thus, the diesel reduction rate of the hybrid RTG crane is 57.37%.

## VII. ECONOMICS ANALYSIS

The initial investment of the energy system of a hybrid RTG crane is 1.2 million RMB. The battery cost is 0.75 million RMB with a battery life span of five years. Suppose that 0.12 million containers are handled every year by a RTG crane, with a diesel consumption of 0.95 L/TEU by a conventional RTG crane and a diesel price of 6 RMB/L. The hybrid RTG crane has a diesel reduction rate of 57.37% and every year the diesel reduction is 65 402 L. Thus, the diesel cost is 0.39 million RMB. Consequently, three years and 21 days are needed to equalize the initial investment of the hybrid RTG crane.

For the emission issue, every year, 65 402-L diesel is reduced by a hybrid crane that equals a reduction of 81 448-kg standard coal and a reduction of 178 570-kg $CO_2$. Notwithstanding the aforesaid analysis, no estimate is included for the environmental or public health cost savings augmented by the hybrid RTG.

## VIII. CONCLUSION

The diesel-generators in published work to date [16], [21], [23] all share the peak hoisting power. RTG cranes have variable load cycles and, thus, the diesel-generators are not always working at the high-efficiency area of their characteristics. In this study, the diesel-generator does not share the peak hoisting power and purely acts as an average energy source with the main aim to charge the battery within a predefined SOC regime. This is a unique feature of this study. With the assistance of AFE, the diesel-generator has a constant output of 50 kW for any system load, thus it always works at high efficiency and has minimum fuel consumption.

The proposed hybrid RTG crane has a simple and concise micro-dc-grid topology with the battery connected directly to the dc link and the diesel-generator feeding to the dc link through an AFE unit. The battery and the diesel-generator are sized based on typical load cycles. The 128-kWh lithium battery is the main energy source and the 50-kW diesel-generator is the assistant energy source. An easily implemented thermostat control strategy is used to switch the diesel-generator. While other systems have been previously proposed [16], [21], [23], the system presented here utilizes a smaller diesel-generator, thus saving installed plant and lowering fuel consumption. In addition, the lithium battery connects directly to the dc link reducing system power electronics while improving battery response and efficiency. Experimental results show that a 57% reduction of fuel consumption is achieved compared to a conventional RTG crane. Through fuel reduction, three years and 21 days are needed to equalize initial investment of the hybrid RTG crane. The disadvantage of this hybrid solution is the high initial investment of the 128-kWh lithium battery, and a smaller battery and a larger diesel-generator might be chosen to lower the initial investment. This topology is simple and flexible and low emission energy sources might be adopted to replace the diesel-generator conveniently, such as a fuel cell or a liquid natural gas generator.

## ACKNOWLEDGMENT

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