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Sizing an Energy System for Hybrid Li-Ion Battery-Supercapacitor RTG Cranes Based on State Machine Energy Controller

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ABSTRACT Ports and container terminals play an important role in the global logistics system. Handling containers inside container terminals and rail terminals are mostly carried out by rubber tire gantry (RTG) cranes. These cranes have quite different power profile compared to hybrid vehicles. They have a broad power demand, varying from 10kW to 350kW, 170kW regenerating power, and a maximum of 30kW auxiliary power. The high peak demand due to the acceleration of hoist drivetrain determines the prime mover (diesel generator) capacity. This capacity is highly over-rated when comparing with crane's average power demand. Such power profiles having high peak power to average power ratio can be supplied through hybrid systems which can downsize the diesel generator, improve fuel efficiency, reduce CO_2 emissions, and reduce maintenance cost. In this study, a hybrid energy source is presented for an RTG crane. The hybrid energy source comprises a Lithium-ion battery bank, supercapacitor (SC) bank connected to the DC-link through bi-directional DC/DC converters, and a downsized variable speed diesel generator (VSDG) connected to the DC-link through an active rectifier. The narrowband operation of the battery bank helps to increase the healthy life of the battery system reducing risk due to unhealthy conditions during faults and abnormal situations. In this paper, the sizing of a hybrid energy system controlled by a state machine controller is presented. Unlike traditional optimization-based sizing techniques, unique features of demand profile, operating environment, system redundancy, backup operation, readily available components, and specific features of state machine controller were highly considered which differentiate the method of sizing from others.

INDEX TERMS Hybrid energy source, Lithium-ion battery, rubber tire gantry (RTG) crane, supercapacitor (SC) bank, variable speed diesel generator (VSDG).

I. INTRODUCTION

Hybrid energy sources are popular among microgrids as a primary storage device and for peak shaving. They are well reputed for their transient characteristics compared to conventional battery storage systems. These hybrid energy storages can be used to power equipment and systems having diversified power duty cycles such as mining equipment, locomotives, cranes, elevators and dump trucks [1]–[7]. When it comes to container terminal handling cranes, energy usage and peak power requirement can be reduced in two ways. The popular method is to integrate energy storage systems where net energy requirement is considerably low [8]. Integrating a group of cranes to a single voltage bus (AC or DC) such as, a group of grid connected ship to shore (STS) cranes or a group of electrified rubber tire gantry (ERTG) cranes can be operated with simultaneous coordinated activities using algorithms to minimize peak load requirements [9] and utilize regenerative energy in more convenient way.

Rubber tire gantry (RTG) cranes are used to stack containers inside container storage yards in ship and rail container terminals. RTG cranes have competitive advantages against rail mounted gantry (RMG) cranes which can move only on rail tracks, where RTG cranes can move to other storage yard blocks easily. This feature is highly essential to container terminals having a shortage in grid power and space.

RTG cranes have diversified load profile [10]. A typical RTG crane demands approximately 300kW when accelerating 40t container from 0 to rated speed (0.433m/s) within 2s

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and returns peak regenerated power of 250kW during lowering deceleration. These cranes have average power demand of 10kW to 30kW for auxiliary systems such as lighting, air-conditioning, control power and hydraulic systems.

A conventional RTG crane consists of a single diesel generator as the main energy source. In practice this generator is rated above 400kW to deal with a 40t heavy container at rated acceleration (2s). This onboard diesel generator (DG) operates as an iso-synchronous generator. Therefore, engines with higher power ratings are selected to maintain engine stability against high power slew rate during hoist acceleration. Dynamic braking resistors are used to dissipate energy during lowering. In practice a typical container weights 10 to 20t, hence corresponding power demand is comparatively low when comparing with DG capacity. This leads diesel generator to run into a low efficiency area of its performance characteristics resulting high fuel consumption and high CO_2 emissions than operating at optimum speed and torque.

As a result, RTG crane system is a better applicant for hybridization with onboard power system and this paper will reveal the technical feasibility of a hybrid RTG crane with hybrid energy storage system.

Increasing fuel prices had been an encouragement for hybridization since early 2000 [11]. A system equipped with 2.12MJ (usable energy) fly wheel and a 455kW diesel generator had been tested by USA researches. They had used a fly wheel based on high speed permanent magnet synchronous machine which stores 0.59 kWh at 20000 rpm. A 20.9% reduction in fuel consumption had been achieved during testing [12]. Further tests had been carried out in Yantian International Container Terminals where RTG cranes are equipped with 410kW diesel generators. A flywheel with 2.1MJ usable energy at 18000 rpm had been used to demonstrate two test cases. A test case with standard RTG (equipped with 410kW genset) had achieved a 15.25% fuel saving. The second test had been conducted with a new genset (equipped with 322kW genset) where fuel saving was recorded as 37.68% [13]. A supercapacitor-based hybrid system tested by Korean researches is described in [10]. They had adopted a 4.19 MJ supercapacitor bank and a 120kW downsized diesel generator (DG) operates efficiently due to high loading over capacity ratio compared to typical DGs which are used in conventional RTG cranes. A 35% reduction in fuel consumption had been achieved by the experimental validation.

Another commercial hybrid system developed by Sumithomo Material Handling Systems comprised of a Li-ion battery bank and a downsized constant speed diesel generator [14]. The DG has a rating of 130kW where auxiliary systems are directly fed by the DG. A series connection of twenty GS YUASA LIM30H Li-ion battery modules are used to build the battery bank. These batteries are specially designed for hybrid and electric industrial applications where they can be charged and discharged at 20C (600A). A bi-directional DC/DC converter is used to interface battery with the DC link to control the power flow of the battery bank. An average of 50-60% reduction in fuel consumption has been achieved from the system.

Another system developed by EcoPower Hybrid Systems, Inc has adopted a lead acid battery system with a 80kW (continuous power) downsized diesel generator. The battery bank is developed with 108 Exide 6V, 180Ah battery modules. The direct connection of battery bank to the DC-link has allowed the battery bank to act as a low pass filter. The developers had achieved 35-40% reduction in fuel consumption according to [15].

A system developed by Norwegian researches has adopted a 50kW diesel generator with a 91kWh Li-ion battery bank [16]. The system is more likely to be an electric crane where DGs prime task is to charge the battery bank. Therefore, generator is forced to shut down during most of the idling period and during charging mode generator operates on its full power under its maximum fuel efficiency. During test operations the system has proven 65-75% reduction in fuel consumption.

A research conducted to develop an energy management system (EMS) for Siemens Eco RTG crane had used equivalent consumption minimization strategy (ECMS) to improve the fuel efficiency of the system. The hybrid energy source comprises of a variable speed diesel generator (VSDG) and a 1.38kWh supercapacitor bank discussed in [17], [18]. The smart controller of the VSDG system adjust the speed of the DG according to the real-time demand. Constant speed diesel generators are extremely fuel inefficient under light load and no-load conditions. Therefore, use of VSDG has a considerable impact for highly varying demands in a wide band such as RTG cranes where VSDG adjusts the engine speed according to brake specific fuel consumption (BSFC) curve under defined load. The proposed system calculates the power share from VSDG using ECMS. The engine start-stop technique had also been adopted where crane operate as a full electric system using supercapacitor (SC) bank. During trials a 52.2% fuel reduction had been achieved.

A commercial hybrid system developed by Chinese engineers comprised of a hybrid energy source equipped with 200kW VSDG and a 30Ah Lithium Titanate battery bank where 192 cells are serially connected [19]. A 200kW bi-directional DC/DC converter has been used to integrate battery bank to DC-link which operates under constant voltage mode to regulate DC bus voltage. The system has recorded 1.175 L/move where a 41.25% fuel reduction can be seen compared to conventional system having a consumption of 2 L/move.

In this paper, a variable speed generator, Lithium ion battery bank and a supercapacitor bank-based hybrid energy source for RTG cranes is implemented. A 14kWh Lithium ion battery combined with 48.4F supercapacitor bank and a 200kW VSDG combinedly provide peak power when the hoist goes up while battery bank and SC bank combinedly absorb the regenerated power when the hoist goes down. In idle condition, battery can power long durations until it reaches its bottom margin (40% SOC). The DC bus voltage is maintained by SC bank while VSDG and battery support the system through controlled current mode. When battery state of charge is less than 40%, VSDG is used to charge the battery for a level of 60%. A 250kW active front end (AFE) converter is used to control output power of VSDG.

All existing systems are equipped with considerably large storage systems either with Li-ion battery, lead acid or supercapacitor storage systems allowing low charge and discharge rate for each individual cell. Although the datasheets of battery systems reveal that they can stand discharging and charging rates varying from 15C to 20C under test conditions, most of these battery cells have higher failure rates after two to three years under 15C to 20C charging and discharging cycles. Changes in operating conditions such as ambient temperature, vibrations and high current discharging and charging could be the main reasons for the failures. Although high battery capacities reduce the stress on individual battery cells due to high power demands, their cost of investment may be too high. Considering the above facts this paper suggests a storage system combined with Li-ion battery bank and a SC bank. A sizing technique that uses considerably large storage system is discussed in [20]. During above sizing technique, fuel savings are given priority where long-term operational costs and reliability related issues are not considered.

The focus of this paper is to present sizing of hybrid energy storage system. Most of the existing sizing methods based on optimization techniques. These techniques narrow down the capacities of internal combustion (IC) engine and energy storage components to minimize the fuel consumption. But in practice, fuel consumption does not always provide the most economical solution in long run. Maintenance cost plays a considerable role in long run where spare parts availability and their cost plays a vital role. Therefore, in proposed system unique features of demand profile, operating environment, system redundancy, backup operation, readily available spare parts and specific features of state machine controller are considered for the sizing of the IC engine and energy storage components which makes the proposed system distinguishable from other systems.

II. DESIGN OF THE HYBRID RTG CRANE

RTG crane is a bridge type moving structure as shown in Fig. 1. As the name suggests these cranes consist of rubber tire-based travel mechanism. At the top of the crane, there are two main girders that allow a trolley to move horizontally. A hoist system consists of hoist motor, hoist gear box, hoist service brake system, pulleys, steel ropes, head block and spreader. Spreader is an equipment used to attach container to the hoist system. The operator cabin is mounted underneath the trolley where spreader view is clearly visible for the operator. The rubber tire gantry system allows the crane to move around a container yard without much restrictions. A conventional crane is shown in Fig. 1 where basic cranes movements are shown from arrows indicated as 1,2 and 3.

FIGURE 1. Directions of motions of RTG crane (1-Trolley, 2-Hoist, 3-Gantry).

Conventional RTG cranes are powered by onboard diesel generators. Typically, almost all manufactures mount electrical cabinet and onboard DG on two sill beams of the crane. In hybrid RTGs, one extra unit is added on one of the sill beams to employ the energy storage system.

The single line diagram of the proposed hybrid RTG crane is shown in Fig. 2. The crane system is highly identical to DC microgrid structure. The Li-ion battery bank and SC bank are connected to DC link through DC/DC converters and the output of the diesel generator is fed to an AFE unit, which connects to the DC-link. Three leg interleaved DC/DC converters [21], [22] are used to interface SC bank and Li-ion battery bank to DC bus. These converters exhibit several advantages against conventional bi-directional DC/DC converters such as low current ripple, wide input/output voltage range, high power density, modular architecture and high efficiency. At present Siemens [23], Danfoss [24] and Liebherr [25] are some manufacturers who provide industry standard DC/DC interleaved converters for hybrid applications and storage system integration. The hoist motor, trolley motor, gantry motors and the auxiliary system get their energy from the DC link through variable frequency drives and constant voltage constant frequency converter respectively. Programmable logic controller (PLC) is the brain of the RTG crane. It controls the VSDG, AFE, DC/DC converters and all motor inverters communicating through profibus or Modbus.

Typically, battery management system (BMS) and supercapacitor management system (SCMS) communicates using control area network (CAN) protocol. Therefore, PLC communicates to BMS and SCMS through communication protocol converters. BMS measures battery terminal voltage, cell voltages, current and temperature. These measurements are used to estimate SOC. SCMS also measures the terminal

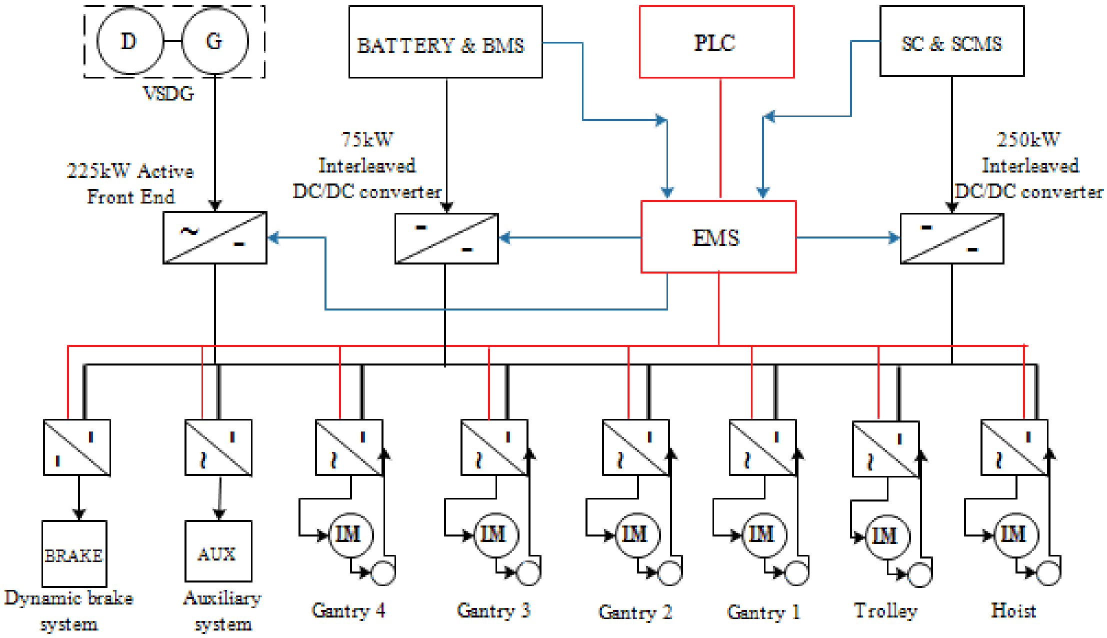

FIGURE 2. System configuration of proposed hybrid RTG crane.

TABLE 1. Crane specifications.

Parameters	Value	Unit
Gantry span	6 wide+lane	-
Lifting height	1 over 6	-
Lifting capacity	40.5	t
Spreader mass	11	t
Hoist motor power	180	kW
Trolley motor power	30	kW
Gantry motor power	25×4	kW
Hoist speed (Full load)	0.433	m/s
Hoist speed (No load)	0.866	m/s
Hoist acceleration and deceleration (Full load)	2	s
Hoist acceleration and deceleration (No load)	4.5	s
Trolley speed	1.166	m/s
Trolley acceleration and deceleration	4	s
Gantry speed (no load)	1.5	m/s
Gantry acceleration (no load)	8	s

voltage, cell voltages, temperature and estimates SOC simultaneously completing cell voltage balancing.

Key specifications of a 1 over 6 (moving one container over height of 6 standard containers) standard RTG crane is shown in Table 1 [26], [27]. To simulate a load cycle of a RTG drive train, a crane equipped with a single hoist motor, a trolley motor and four gantry motors is used. These parameters are valid for both conventional and hybrid RTG cranes.

III. SIZING HYBRID ENERGY SYSTEM

A. DEMAND CYCLE (LOAD CYCLE) OF A RTG CRANE

The most energy consuming load cycle is shown in Fig. 3 where a 41t container is raised over 6 standard containers, trolleyed to far end (across width of 5 containers) and lowered to ground. This load cycle includes highest power peaks due to acceleration and deceleration which is corelated with the minimum capacity of the SC bank required.

B. POWER DEMAND OF RTG CRANES

The power demand of a RTG crane operating a heavy 41t container is shown in Fig. 4 where the container path is shown in Fig. 3. During the moves 1,2,6 the crane does not carry a container. The peak driving power is 292kW during the hoist system acceleration while steady state demand reaches 225kW to maintain a constant speed of 0.433m/s and the peak regenerated power is 170kW during deceleration of the hoist system. For the above shown load cycle, average power demand is 61.6kW where auxiliary power demand is considered separately during simulations. The peak to average power ratio of 4.7 makes the RTG cranes highly acceptable for hybrid applications. The typical operation of an RTG crane in 1 hour is 8 moves of 30t containers or 12 moves of 15t containers. The idling period typically depends on the site conditions where a busy condition can be expected on arrival of a main line ship whereas quiet operation can be expected during unloading and loading of feeder vessels.

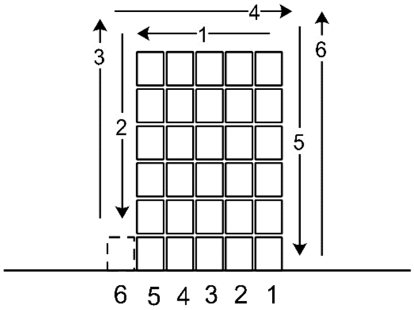

FIGURE 3. Highest energy consuming load cycle of a RTG crane. 1- Trolley left, 2-Hoist down, 3-Hoist up with container, 4-Trolley right, 5-Hoist down with container, 6-hoist up with empty spreader.

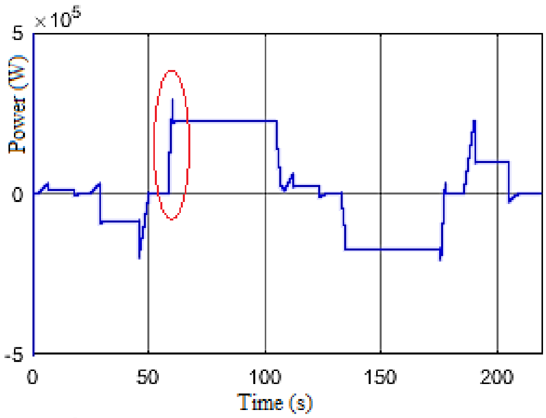

FIGURE 4. Power profile of most energy consuming load cycle.

C. SIZING OF THE VARIZBLE SPEED DIESEL GENERATOR AND ITS CONTROL

Container ships operate under tight schedules due to their high operating costs. Therefore, delays due to operations can cost a lot while increasing berthing traffic inside container terminals. Besides that, terminal operating business is considered as highly profitable where highest priority is given to equipment availability and reliability when selecting handling equipment. Due to above facts, still most terminal operators choose conventional crane systems and full electric systems instead of hybrid systems. The reason for that is the failures in battery systems and SC systems can totally immobilize the crane blocking other RTG cranes moving across the block.

Therefore, to overcome the above issue, the crane should be able to function temporarily with de-rated ratings under generator power in case of failure either in battery bank or SC bank or both. During such situations, the VSDG should be able to function as a constant speed generator where response is much faster than a VSDG. De-rating performance parameters (hoist full load speed, hoist no load speed, hoist acceleration under full load and hoist acceleration under no load) by 50% will result in reduction of power demand by half ranging 180kW to 220kW.

When selecting generator capacity following guidelines were considered.

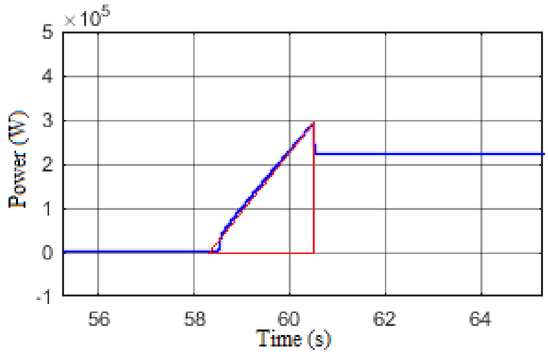

FIGURE 5. Power ripple during acceleration of hoist system with rated load (41t).

1. The DG must be rated above 180kW to operate as a backup during critical failures of battery system or SC system.

2. The addition of maximum generator continuous power ($P_{gen-\max-con}$) and maximum operating continuous battery power ($P_{bat-\max-con}$) should be greater than maximum steady state demand.

$$(225 + 30)kW < (P_{\max-gen-con} + P_{bat-\max-con}) \quad (1)$$

where 225kW and 30kW present the maximum steady state demand (see Fig. 5) and maximum auxiliary demand respectively.

3. Most generator manufacturers do not recommend running generator set less than 25% or 30% of its rated load depending on manufacturer [28]–[31]. This loading level is mainly defined for high speed diesel generators (>1200 rpm) which operates at 1500rpm in 50Hz and at 1800rpm in 60Hz systems. During such high speeds, low loadings result low mean cylinder pressure and low combustion temperatures which allows a fixed oil flow to enter combustion area weakening piston seals. This is commonly referred as slobbering. Typically, VSDGs supply low power demands at low rpms which result in high mean pressure compared to constant speed generators. Therefore, low rpms can produce high mean exhaust pressures keeping piston seals tight. Considering above facts, the minimum loading level is selected as 25% for VSDG sizing.

$$0.25 \times P_{gen-\max-con} \leq P_{bat-\max-con} \quad (2)$$

Following equations 1 and 2, 200kW diesel engine coupled to a 250kVA alternator is selected with prime power rating where 10% overload capability is available for a 1-hour period within 12-hour cycle of operation.

Secondly, 200kW diesel engine is mid-range engine which has a large market in commercial trucks, excavators, buses and marine applications which reduce investment cost due to huge market share and reduced operational costs due to well established supply chain in spare-parts.

A VSDG is a fuel-efficient solution compared to constant speed diesel generator due to the characteristics of the demand profile (generator is partially loaded, or light loaded during most of the operating period). The common DC bus allows to interface a variable speed diesel generator (VSDG) without much modifications for the system. The variable frequency and variable voltage of the generator is rectified using an active front end converter which is controlled in controlled current mode or constant voltage mode. The system adjusts the engine speed to maximize fuel economy according to real time demand.

D. SIZING OF THE Li-ION BATTERY AND ITS CONTROL

Usually, batteries are popular for high energy density relative to its power density. The expected lifespan of a battery inside a hybrid system is very essential for the expected return on investment. Nowadays, Li-ion batteries are popular for hybrid applications due to their high energy density and power density compared to other chemical battery technologies. There are several key factors that are directly related to the life span of battery cells such as ambient temperature, peak discharging currents, depth of discharge, type of DC/DC converters used to interface battery to DC-link (whether converter is a single leg drive or with interleaved legs), cooling system, SOC operating range and active cell balancing system.

Due to the failures on system components and violation of above mentioned limits, the effects of capacity fade can be visualized before the expected lifetime of the battery cells. During sizing of the Lithium battery system, precautions are taken to minimize the effects from above factors.

The maximum average power of an operation cycle is 61.6kW (calculated from Fig. 4). Typically, this value is 24.8kW [20] due to idle time between loading and unloading cycles and due to variation of container loads. The main objective of the battery bank is to supply total crane power during idling period, absorb a portion of regenerative energy and supply 50kW continuous power (25% of VSDG capacity) to minimize the operation time of the VSDG below 50kW. GS YUASA's LIM40-7D 26.6V, 40Ah [32] battery module is considered for the battery bank. Each battery module includes seven cells with a rating of 3.8V, 40Ah. These cells are made from $LiMn_2O_4$ as the positive active material and hard carbon as negative active material [32]. These battery cells can provide 5C peak discharge current and 3C charge current at desired operating conditions. The closest battery bank voltage can be calculated by using equation

$$P_{bat} = V_{bat}.I_{bat} \tag{3}$$

where P_{bat} is the rated power of battery bank, V_{bat} is the rated battery bank terminal voltage and I_{bat} is the maximum allowable discharge current. If selected power capacity is 55kW, maximum charge and discharge current is restricted to 3.75C, under rated terminal voltage 366V. A set of 14 battery modules are connected serially to construct the battery system. The constructed battery bank has a rated voltage of 372V which is closer to calculated value 366V. This battery module is connected to DC-link through 75kW bi-directional interleaved DC/DC converter restricting converter current to ±75A on DC-link side. The battery converter operates on controlled current mode to eliminate the battery system from high discharge and charge currents.

The energy management system controls the battery SOC level in a narrow band (40%-60%). The bottom margin of the band is kept as high as 40% to avoid 100% depth of discharge during failures. In an event of capacity fade, error tolerance of SOC estimation may be quite high which results in the battery system to be deeply discharged. Hence the situation is avoided using 40% SOC margin for bottom end. When the battery reaches 40% SOC, the battery is charged to the top margin using VSDG. During charging mode battery may experience 3.75C continuous current which will increase the internal temperature of the battery system. On the other hand, battery stores a part of electrical energy that is produced by the VSDG during operation. The round-trip efficiency of a battery converter system is close to 85% where 15% of energy is lost during bi-directional transformation. The 20% SOC of battery bank represents approximately 2.9kWh which is higher than 20% of positive energy (3.67kWh) that is demanded by the highest energy consuming operating cycle. Therefore, charging battery from VSDG to unnecessary levels may tend to increase system inefficiency. But this can be avoided by controlling battery SOC between 40% and 60%.

E. SIZING OF SUPERCAPACITOR BANK AND ITS CONTROL

Unlike batteries, supercapacitors do not use chemical reactions to store energy. These supercapacitors are a type of capacitors with very high energy density compared to conventional electrolyte capacitors due to its porous carbon electrodes and special double-layer dielectric materials. Current supercapacitors can have capacitance values that are thousands of times higher than conventional electrolyte capacitors. Supercapacitors can handle high peaks in power compared to batteries which makes them most suitable source to supply transient demands. Supercapacitor systems have very low energy density compared to chemical battery systems. This make supercapacitor banks extremely expensive to equivalent battery capacities. In proposed hybrid RTG crane, SC bank is used to supply transient power demand which is above the battery and VSDG maximum output current. During operations high peak currents are visible for a maximum period of 4.5s due to hoist acceleration and deceleration. There are two possible methods to respond transient demand as quick as possible. One, is to match the supercapacitor bank voltage and directly connect the SC bank to DC-link where SC bank acts as a low pass filter. Second method is to use a constant voltage-controlled DC/DC converter to interface the SC bank to DC-link where DC-link voltage is maintained by SC converter. Typically, supercapacitor cell has a rated voltage between 2.7V to 3.0V and 3000F nominal capacity. When selecting SC capacity, 5 key factors are considered.

1) THE ENERGY CONTENT DURING PEAK TRANSIENT PERIOD (E_{peak})

The energy required during acceleration from 0 to rated speed with rated load. (the area covered from the red triangle in Fig. 5)

2) ENERGY BUFFER (Z)

The energy content during peak transient period (E_{peak}) is multiplied by a factor (Z) to compensate unpredictable disturbances.

3) MAXIMUM ENERGY CONTENT AFFECTED BY THE STATE TRANSITION DELAY ($E_{t-delay}$)

State control machines introduce time delays between two state transitions to avoid toggling between states. During some state transition delays (t_{delay}), SC bank must supply the demand to avoid power swing on demand. The maximum permissible energy during time delay can be calculated as follows,

$$E_{t-delay} = P_{\max} \times t_{delay} \tag{4}$$

where $P_{\max}$ is the maximum peak demand of RTG crane hoist system.

4) SC STATE OF CHARGE (SOC) BOTTOM MARGIN ($SOC_{bottom-margin}$)

SC SOC is tightly coupled with terminal voltage. In proposed system, SC system is used to regulate DC bus voltage. DC/DC converters are most likely to drive unstable when SC terminal voltage reach bottom operating voltage margin of the DC/DC converter. Therefore, SC SOC bottom margin is selected as 30% to calculate the SC bank capacity.

5) SC SOC OPERATING POINT ($SOC_{operating-point}$)

SC bank primary function is to maintain DC link voltage while providing transient demand. The system is also supposed to absorb regenerative transient peaks during operation. In such cases SC bank can be overcharge due to insufficient reserved capacity. Considering above requirements, the energy management strategy controls the SC SOC at 70% using a close loop controller where 30% (from 70% to 100%) of SC capacity is reserved to absorb regenerative energy peaks during lowering and deceleration.

Considering above guidelines, the minimum energy capacity for the SC bank ($SC_{capacity}$) can be calculated as follows.

$$SC_{capacity} = \left[\frac{\left(Z \times E_{peak}\right) + E_{t-delay}}{SOC_{eff-range}} \right] \tag{5}$$

where $SOC_{eff-range}$ is the effective range of state of charge defined as,

$$SOC_{eff-range} = SOC_{operating-point} - SOC_{bottom-m\arg in} \tag{6}$$

Thus E_{peak} can be roughly calculated as 0.0854kWh from the enclosed area by red lines in Fig. 5. $E_{t-delay}$ can be calculated using Eqn. 4 taking $P_{\max}$ as 300kW (from Fig. 5). The effective SOC range of SC bank ranges from bottom margin (30%) to its steady state operating point (70%). Considering energy buffer as 100%, the minimum capacity of SC bank is calculated as below.

$$SC_{capacity} = \left[\frac{\left(2 \times E_{peak}\right) + E_{t-delay}}{SOC_{eff-range}} \right] = 0.468kWh \tag{7}$$

SC capacitor banks are developed using supercapacitor cells. A commercial supercapacitor cell developed by Maxwell is selected for the design. The cells have ratings of 3000F and 2.85V where maximum permissible voltage is 3.0V [33].

Assuming 50% energy stored inside SC cell is effective due to losses in DC/DC converter and SC cell itself due to high discharge currents (close to 500A), the number of SC cells can be calculated as follows. Considering a serially connected SC string with N cells,

$$SC_{capacity} = \frac{1}{2} \times \left(\frac{C_{rated}}{N}\right) \times \left(NV_{effective}\right)^2 \tag{8}$$

where C_{rated} is the used standard SC cell capacitance in Farads and $V_{effective}$ is cell voltage where 50% of stored energy retains inside the cell.

According to Eqn. 8, 248 cells are required to meet the capacity. Typically, DC bus voltage of RTG cranes vary from one manufacturer to another ranging from 600VDC to 750VDC. The connection of SC cells depends on the three factors, maximum super capacitor cell voltage, number of supercapacitor cells and DC bus voltage. Considering above facts, two parallelly connected SC cells are organized to a single module and then 124 modules are serially connected to form the SC bank. Due to above configuration, maximum SC bank voltage restricted to 372V and 250kW bi-directional 3 leg DC/DC converter is used to interface the SC bank to DC-link.

F. SIZING OF BRAKING UNIT

Braking units are used to control the voltage of intermediate DC bus between rectifier and motor drives (DC motor drives and variable frequency drives) when load feeds regenerative energy. Braking unit diverts excess energy to a braking resistor where excess energy is converted to heat. Most of these braking units are activated when the intermediate DC bus voltage exceeds a specified DC bus voltage level.

To size the resistance of the braking system, the maximum steady state regenerative power level (143kW) is selected instead of peak regenerative power level (170kW) considering 18% short time (4s) overload which can be tolerated by the braking units.

As auxiliary power consumption and power absorption by Li-ion battery bank amounts to 50kW+ continuous power, the net power rating of the braking system is reduced. But this can restrict the performance when the crane is subjected to hybrid system failures as discussed in Part c of Section III. Despite the fact that hoist full load speed, hoist no-load

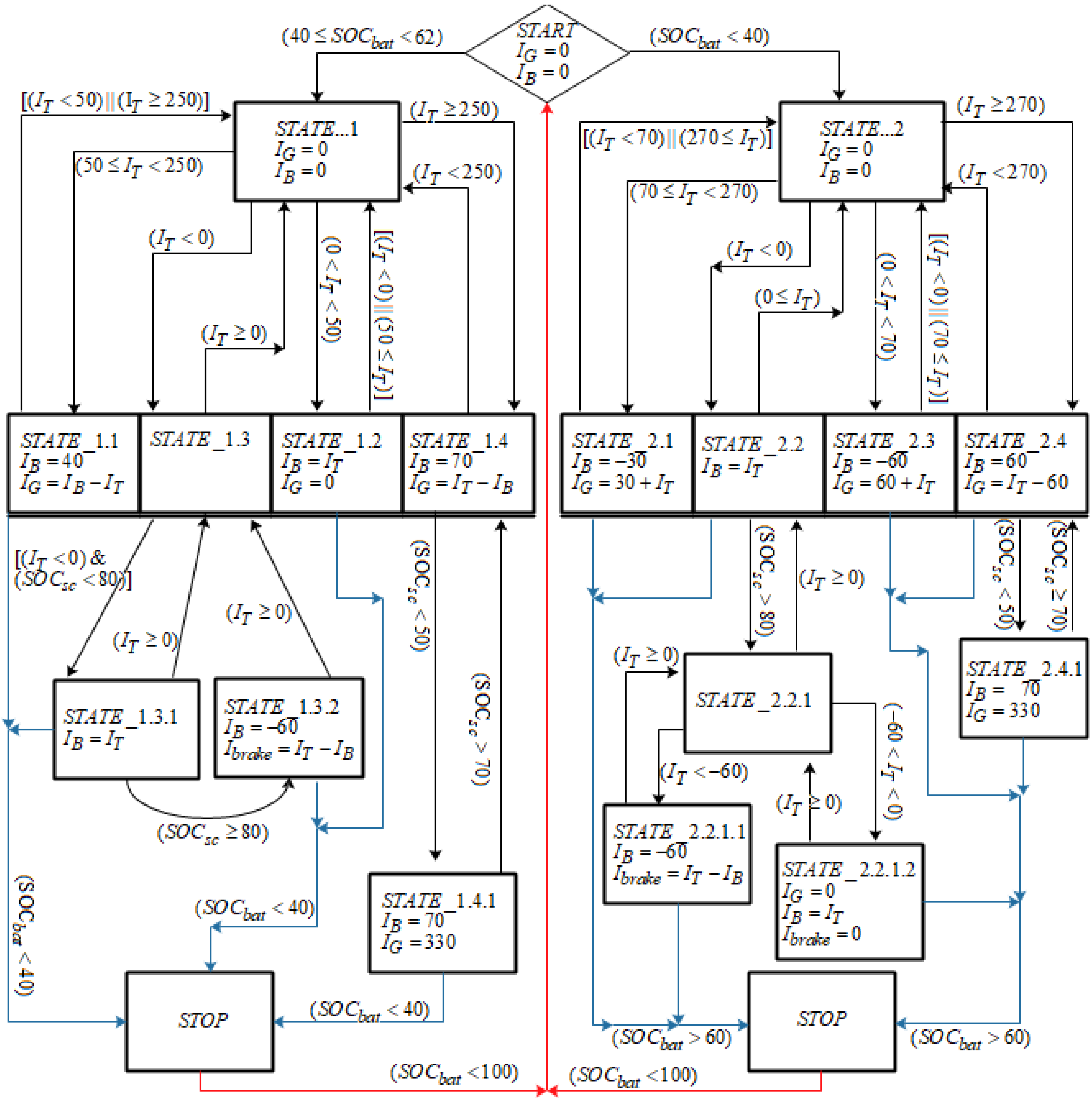

FIGURE 6. State Machine Controller [35].

speed, hoist acceleration under full load and hoist acceleration under no-load are temporarily de-rated during hybrid system failures, deceleration and lowering speed can be maintained at same levels if power rating of braking chopper and resistors is adequate.

Considering above facts 150kW braking system is used in simulations with 1.06Ω resistor and chopper with 375A rated current. In actual system this can be replaced with commercially available ratings, such as three 50kW chopper units where each unit is equipped with 3.2Ω, 125 A resistor [34]. Unlike conventional braking choppers, the system uses a closed-loop current operated controller where current reference is produced by the energy management system.

IV. ENERGY MANAGEMENT STRATEGY

As discussed in Section III, battery, SC and VSDG are connected to DC-link. The battery lifetime and efficiency can be improved if the peak transient charging and discharging current is mitigated by SCs. In addition, since the battery bank, SC bank and VSDG are characterized by different operating voltages, the DC/DC converters are used to match

TABLE 2. Hybrid system specifications.

Parameters	VSDG	SC	Battery
Rated current (A)	300	-	40
Max current (A)	400	500A	150
Current slew rate (A/s)	50	-	100
SOC (min)	-	70%	40%
SOC (max)	-	80%	60%
Control mode (CC, CV)	CCM	CVM	CCM
Capacity	250kVA	48.38F	40Ah
Rated DC bus voltage (V)	680		

the output voltages of battery bank, SC bank and VSDG and thus manage the power flow.

Prior to evaluate the operation of the total system, energy storage systems, power electronic converters and demand profiles must be accurately modeled. Modeling of such components and energy management strategy have been discussed in detail in [35] and [36] and not duplicated here. The goal for the energy management strategy is to minimize the fuel consumption of the crane while operating battery within its charging and discharging limits to ensure safe operation. Besides the controller should not only minimize the fuel consumption for a single time instant, but it should continue for a longer period. This power flow management is done by a state machine controller which determines the operating point of dedicated converters. The hybrid energy storage system leads to come up with following specifications shown in Table 2. The state control algorithm is shown in Fig. 6 which schematically visualizes the operational modes of the hybrid RTG crane which is deeply discussed in [35] where I_T is the total demand current, I_G is the VSDG output current, I_B refers to battery current (+ for discharging and – for charging) and I_{brake} is the braking chopper current (all currents are measured at DC bus level). The SOC_{bat} and SOC_{sc} refer to state of charge of Li-ion battery and SC respectively. The supercapacitor bank DC/DC converter regulates the DC bus voltage while other converters operate in controlled current mode. A supercapacitor charge controller is used to maintain SOC_{sc}, which partially contributes to generate I_{bat} depending on demand [35]. There are pure battery modes (when demand is less than 34kW and battery SOC is between 40% and 60%) and hybrid power source modes.

The controller makes decisions considering two main factors.

1) Battery SOC level
2) Demand current

When lithium battery SOC is between 40% and 60%, the controller receives the SOC information from the battery management system and then decides to supply demand combinedly from VSDG, SC and battery. During above operating

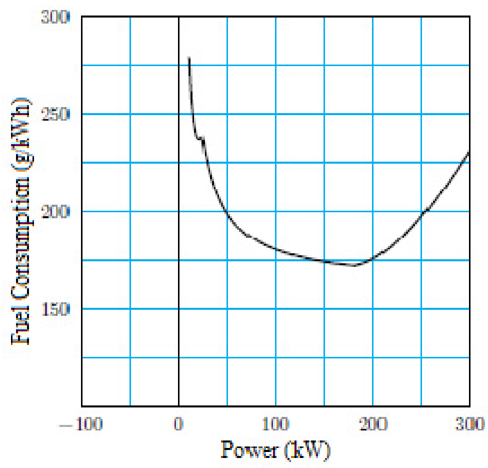

FIGURE 7. Brake specific fuel consumption of VSDG used for simulation [18].

mode, battery only gets recharged from regenerative energy. As the battery SOC drains below 40%, the controller decides to supply demand from VSDG and SC while charging battery from VSDG until battery SOC reaches 60%. If the demand is exclusively high in this occasion, battery support is sought to balance the demand for shorter durations by interrupting the charging process as shown in State_2.2 and State_2.4 in Fig. 6. During the regenerating mode, SC bank absorb a portion of energy (restricted to maximum of 80% SOC to avoid voltage instabilities) along with Li-ion battery bank. If the regenerating current exceeds the safe operating current limit of battery bank, then excess current is passed to braking chopper to dissipate excess regenerative energy as heat.

V. SIMULATION RESULTS AND DISCUSSION

For system performance analysis, a complete RTG crane model is established on MATLAB/Simulink environment. Both the battery, SC and VSDG models are developed based on experimental data presented on datasheets. The system has been simulated for 4800s following the demand profiles presented in [36]. During that period 18 container moves were simulated with 30kW continuous auxiliary power.

The fuel consumption of the simulation was evaluated referring to the VSDG test data presented in [18]. The Fig. 7 presents the variation of brake specific fuel consumption of the VSDG.

As shown in Fig. 8 (a 1200s of time window is presented), the proposed hybrid system has supplied the demand without violating the current limits proposed on Table 2. The simultaneous operation of VSDG, SCs and battery combinedly supply the peak demands exceeding 500A peak currents. In Fig. 8 all currents are measured form DC bus side which maintains 680VDC. Therefore, the powers representing currents can simply be calculated by multiplying by DC bus voltage.

The Fig. 9 presents the SOC variations of SC and Li-ion battery in blue and red respectively in the first plot, DC bus voltage in the second plot and cumulative fuel consumption

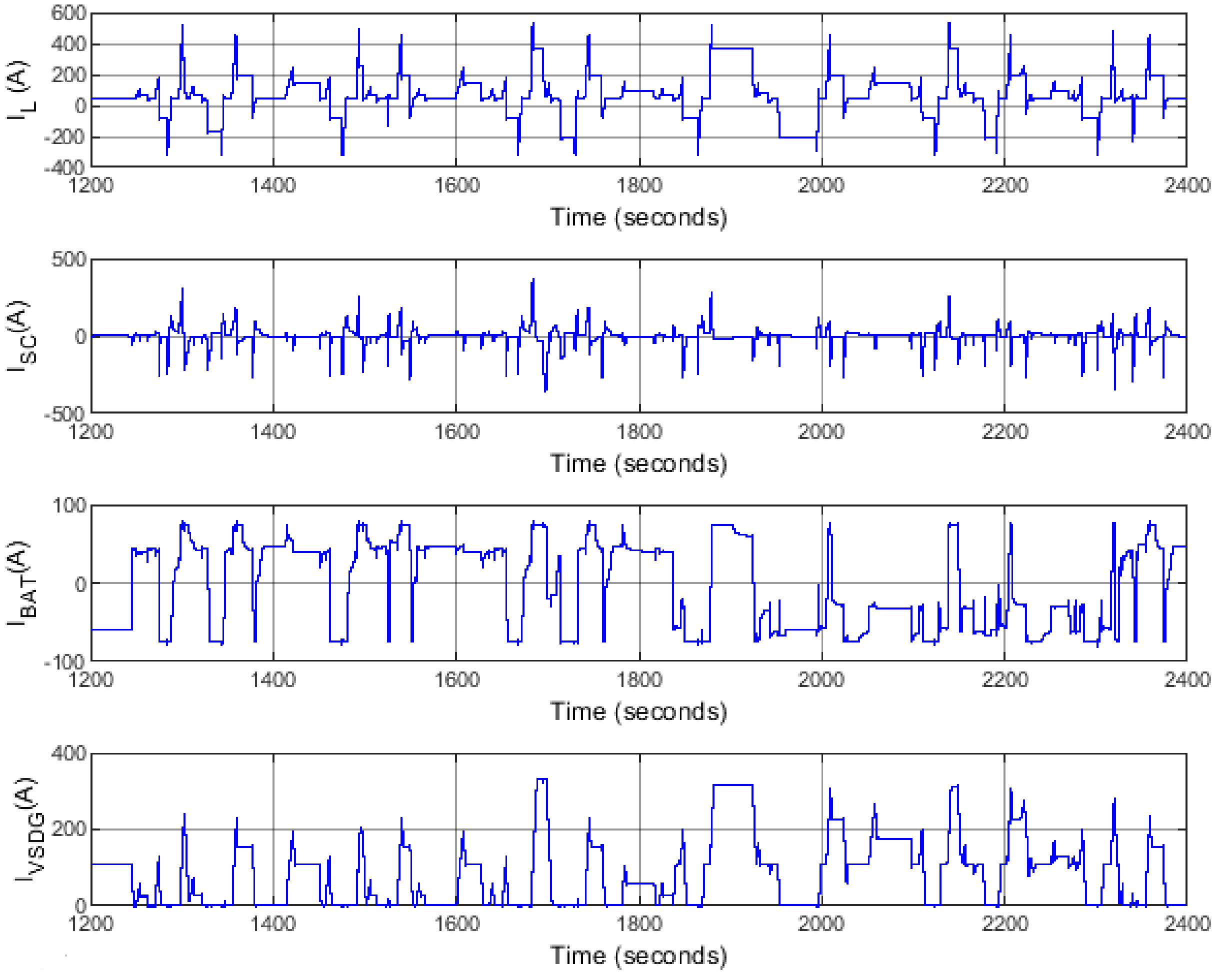

FIGURE 8. Current variations during simulations.

in the final plot. The SOC transition cycles represent the complete transitions that Lithium battery had undergone either charging from 40% to 60% or discharging 60% to 40%. Due to the narrow band SOC variation (between 40% and 60%) of Li-ion battery bank, 11 SOC changeovers can be seen, which reduce the VSDG light loading condition. The SOC variations of SC bank indicate how transient demands have been filtered from battery bank. Typically, 50A/s slew rate takes 6s to reach maximum loading level of VSDG where SC bank fulfils energy requirements while maintaining the DC bus voltage within the limits. Such situations create large SC state of charge drops (below 50% SOC) which can lead to instability of bus voltage condition on system. Even under such disturbances, the DC bus voltage can be maintained safely as shown by plot 2 in Fig.9 where DC bus voltage maintained between 680 $\pm$ 10V. A volume of 15.4 liters of diesel consumption was recorded as shown in the third plot. This figure is used to calculate fuel consumption per move. During simulation, VSDG loading and fuel consumption per move are presented in Table 3.

The event presents a total of 18 moves within 80-minute period and total consumption was reported as 15.4L and fuel consumption per move found to be 0.85L/move. This fuel consumption per move can be compared with actual statistical values for 36 hybrid RTG cranes which operated inside Port of Colombo.

TABLE 3. Diesel consumption and generator loading.

Fuel Consumption (l)	15.4
Fuel consumption per move (liters/move)	0.85
Battery SOC transition cycles	11
VSDG loaded period from 4800s	2922
VSDG loading more than 50kW (s)	2466
VSDG loading more than 100kW (s)	728
VSDG loading more than 150kW (s)	323

The hybrid RTG cranes operated in Port of Colombo were equipped with 13.8kWh Li-ion battery bank with 200kW VSDG and recorded 2,218,729 moves resulting 1.175L/move fuel consumption per move in 2016. The simulated results obtained for fuel consumption per move as shown in Table 3 (0.85L/move) has reported 27% reduction in fuel consumption when comparing with statistical data (1.175L/move) predicting the proposed system could be more efficient than the

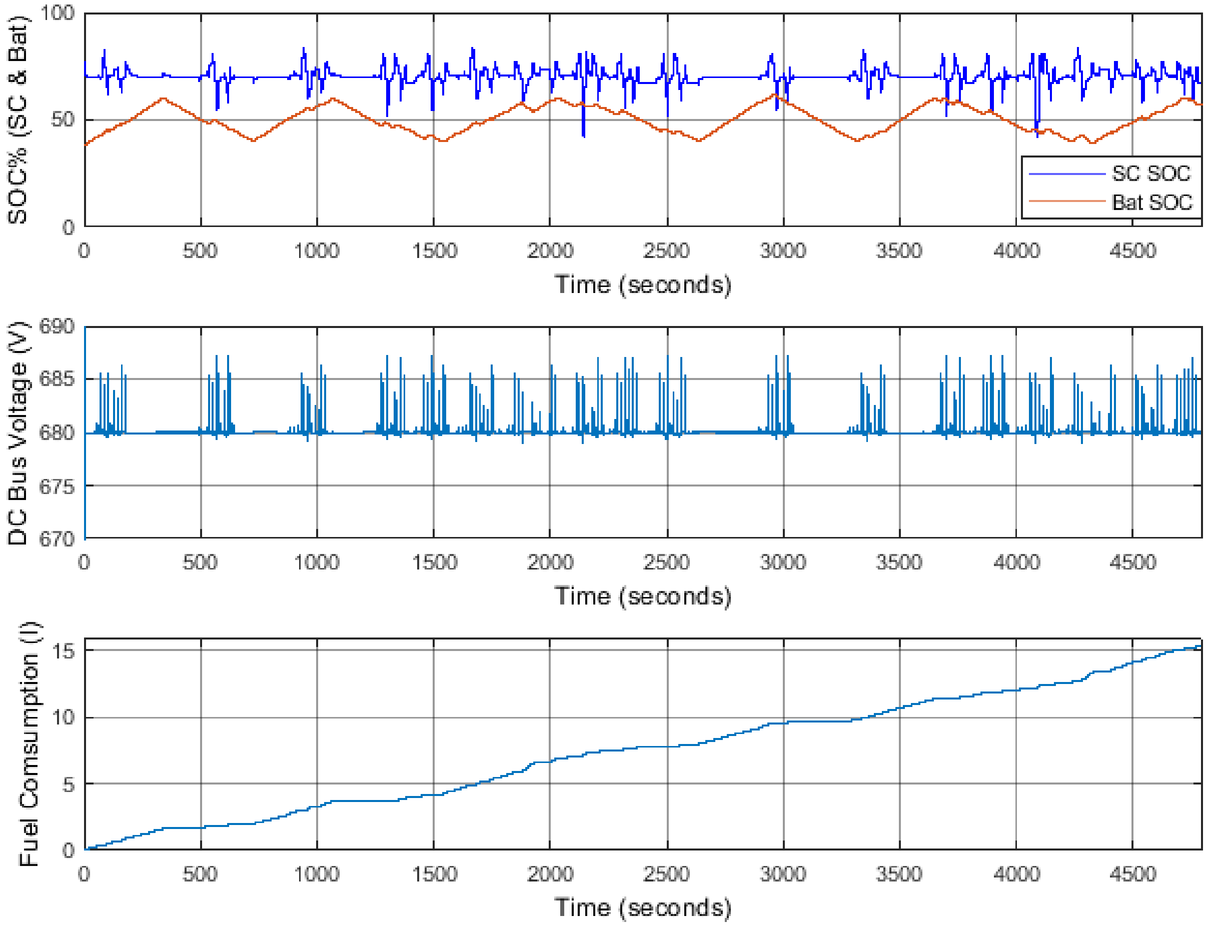

FIGURE 9. SOC variations, DC bus voltage and cumulative fuel consumption.

compared system. The system discussed in [19] charge and discharge battery bank with high transient and steady state currents (beyond the accepted safe operating current limits recommended by the manufacturer) resulting in an increased battery internal temperature which cannot be controlled by the active cooling system due to its large time constant. Therefore, continuous heavy operation for 7-8 hours needs at least 2-3 hours to settle the system temperature. During above period crane is switched over to conventional mode (bypassing battery system) with de-rated performance where VSDG operates as a constant speed diesel generator resulting in low fuel efficiency.

This reduction in fuel consumption in the proposed system is mainly due to the advanced energy management strategy and the integration of SC bank which eliminates the high temperature rise in battery bank by controlling charge/discharge currents and enabling SC bank to response transient demands more efficiently due to low internal resistance which makes hybrid system to operate continuously.

VI. CONCLUSIONS

The proposed power supply system has a simple and compact DC micro grid topology with a battery bank and SC bank connected to DC-link through bi-directional DC/DC converters and a variable speed diesel generator feeding to the DC-link through an active front end unit. In this study, variable speed diesel generator follows the demand filtering power peaks. The battery SOC is maintained within a narrow predefined SOC region minimizing the energy losses due to round trip operation.

This is a unique feature of this work. The battery SC and VSDG capacities are sized based on the load profile. The proposed state machine control strategy is used to control the power flow according to demand. The operation of battery system under safe limits and controlling its SOC under narrow band increase the life expectancy of the battery bank. The simulation results have shown that 27% reduction in fuel consumption per move when comparing the proposed system with actual system having same VSDG capacity and battery capacity [19] as in the proposed system. The problem due to high initial investment of the SC DC/DC converter can be mitigated by further improving the system.

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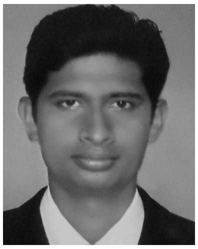

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