A Comparative Study of Energy Storage Systems and Active Front Ends for Networks of Two Electrified RTG Cranes

Feras Alasali [1,2,*], Antonio Luque [1], Rayner Mayer [3] and William Holderbaum [1,4,*]

[1] School of Systems Engineering, University of Reading, Whiteknights, Reading RG6 6AY, UK;
     antonioluque.glasgow@gmail.com
[2] Department of Electrical Engineering, Hashemite University, Zarqa 13113, Jordan
[3] 9 Heathwood Close, Yateley, Hampshire GU46 7TP, UK; rayner@sciotech.demon.co.uk
[4] School of Engineering, Metropolitan Manchester University, Manchester M1 5GD, UK
[*] Correspondence: f.m.m.alasali@pgr.reading.ac.uk (F.A.); w.holderbaum@reading.ac.uk (W.H.);
     Tel.: +44-(0)118-378-6086 (W.H.)

check for
updates

Abstract: The global consumerism trend and the increase in worldwide population is increasing the need to improve the efficiency of marine container transportation. The high operating costs, pollution and noise of the diesel yard equipment is leading sea ports to move towards replacing diesel RTG cranes with electric Rubber Tyre Gantry (RTG) cranes which offer reduced environmental impact and higher energy efficiency. However, ports will require smarter solutions to meet the increased demand on the electrical distribution network due to the electrification of RTGs. This paper aims to highlight the peak demand problem in the two electrical cranes network and attempts to increase the energy saving at ports by using two different technologies: Energy Storage System (ESS) and Active Front End (AFE). This article introduces one of the first extensive investigations into different networks of RTG crane models and compares the benefits of using either AFE or ESS. The proposed RTG crane models and network parameters are validated using data collected at the Port of Felixstowe, UK. The results of the proposed RTG cranes network show a significant peak demand reduction and energy cost saving.

Keywords: energy storage system; RTG crane; active front end; energy savings

1. Introduction

According to trade statistic data from the World Shipping Council (WSC) 127.6 million twenty-foot container equivalent unit (TEUs) were exported and imported globally in 2014, a 4.3% increase from the previous year [1]. In 2015, ports worldwide reported about 9,000 calls for container ships and 1,000 calls for vehicle vessels per week [2]. The United Nations 2016 Review of Maritime Transport report shows that the world gross domestic product expanded by 2.5% compared to 2014 and the world seaborne trade expanded by 2.1% [3]. To face the accelerated growth of the world seaborne trade, ports need to improve the efficiency of handling operation by installing significant infrastructure. Port facilities to complete the container handling process from land to sea or conversely are costly to build and operate. During the handling process of the container terminal, fuel is consumed and CO_2 emitted by the different handling and transfer equipment. The high operating costs, pollution and noise emissions associated with the diesel yard equipment's, is leading sea ports to move towards replacing diesel rubber tyred gantry (RTG) cranes with electric RTG cranes which are more environmentally friendly and have higher energy efficiency. The use of electrical compared to diesel RTGs can reduce the CO_2 emissions by 60–80% and the maintenance costs by around 30% [4].

In ports, during highly intensive working, significant peaks of inrush currents will be seen in the primary and secondary substations which could lead to temporary shutdown of the port terminal. Thus, the traditional low voltage (LV) network reinforcement solutions to meet these peaks or the new demand increases due to electrifications of crane are effective but commercially expensive. This solution focuses on reinforcing the LV network by upgrading or replacing existing network components such as cables and substations [4,5]. Reducing the electric load on the distribution network would help to reduce the infrastructure reinforcement costs and carbon emissions at the electrical supply side. Recently, researchers worldwide are drawing attention to those industrial electrification problems that ports with RTGs could face if these were converted from diesel to electric operation.

The literature introducing the potential impact of using energy storage systems (ESS) to support the diesel and electric RTG cranes is beginning to appear [6–11]. For example, Flynn et al. [10] developed a hybrid energy source model for an RTG crane including a flywheel energy store. The results in [10] show a significant amount of power saving and reduction in fuel consumption of around 20%. In another study, Pietrosanti et al. [5] introduced an optimisation strategy to control the flywheel power for an RTG crane system. The simulation results show a reduction in peak demand around 38%. Kim et al. [12] used a supercapacitor energy storage to reduce the peak demand and gas emissions in an RTG crane system with savings in fuel consumption by 30% and 40% in CO_2 emissions. A proposed supercapacitor energy store, in [12], used an indirect control method to find an optimal load sharing regime between the hoist motor and the energy store. The simulation analysis showed that the supercapacitor energy storage is suitable for transient peaks due to its high-power density.

On the other hand, active front ends (AFEs) are mainly used to increase the power quality level in low voltage networks by reducing the total harmonic distortion and increasing the power factor and keep it within the limits [13,14]. Currently, crane manufacturers are designing new models of electrified RTG crane equipped with AFE technology. These new designs aim to improve the distribution network power quality at ports compared to passive filter system [13,14].

The research reviewed has introduced various studies on energy savings for a single RTG crane system operation by investigating the benefits of installing different types of energy storage devices (batteries, supercapacitors and flywheel) to reduce fuel consumption and gas emissions. The literature shows that the ESS is beneficial for reducing the peaks; accordingly, it is significant to investigate the ESS performance on a network of more than a single RTG crane. This study aims to decrease the demand on substation peak and the electricity bill at ports. In addition, unlike studies which have mainly used ESSs to increase energy saving in a single RTG crane system, this study investigates and analyses using the operational benefits of adding AFEs in an RTG cranes network. This paper attempts to fill the gap in the literature and compare two technologies either ESS or AFE on the electrical distribution network that feed two electrified RTG cranes. Therefore, this work has the following key contributions:

(1) A network of two electrified RTG cranes model is developed to investigate and analyse the power flow and peak demand at a port's electrical network. This will contribute to the limited literature focused on energy savings in network of RTG cranes.

(2) ESS and AFE models are developed and the peak demand reduction and energy cost saving at a port's electrical network are compared.

The structure of this paper is organised as follows: the RTG crane network topology is described in Section 2. A case study of a RTG crane network is introduced in Section 3. Section 4 discusses the test results of different networks of RTG crane models. Finally, a summary of the work is presented in Section 5.

2. RTG Crane Network Topology

This section aims to address the RTG's system topology and introduces the power system structure of a network of cranes. An electrified RTG, as shown in Figure 1, has been retrofitted to be powered by

the low voltage network at the Port of Felixstowe. This crane was manufactured by Shanghai Zhenhua Heavy Industries (ZPMC, Shanghai, China) [5,7,9]. This RTG crane has three main types of motors to drive the crane and move containers, as follows:

- Four electrical machines called gantry motors, which move the gantry around the container stack.
- One or two hoist motors which raise the container and are capable of raising containers weighing up to 40 tonnes fully loaded. The hoist motor(s) connect to a spreader through a cable reel by a head block and spreader which can weigh between 8 to 12 tonnes, which can result in a total hoisting weight of 52 tons.
- Two trolley motors which aim to move the cabin and hoisting unit, with or without the full loaded container, across the span of the crane.

Figure 1. An electrified Rubber Tyre Gantry (RTG) crane at the Port of Felixstowe, UK [7].

The power source for the RTG cranes (diesel or electricity) is sized to provide the power required to allow different moving modes and tasks. The highest percentage of the energy is consumed by the hoist motor(s) in lifting containers rather than the moving the gantry or the trolley [5,6].

2.1. Energy Analysis of RTG Crane System

The power which is fed into the RTG crane system is rectified through a diode converter, which converts alternating current (AC) into direct current (DC) power but only allows unidirectional flow, as seen in Figure 2. This process aims to protect the electrical distribution side from voltage mismatches or high harmonics produced from the regeneration due to electrical braking in the hoist and trolley motors. The DC power is delivered through a DC bus to the RTG motors through a voltage source converter (VSC) [13,14]. Thus, while lowering the container, the hoist motor works under generating conditions with the generated power passing to the DC link which increases the DC voltage level. Typically, in an RTG crane system, if the DC voltage reaches 750 V, a brake chopper is activated allowing excess energy to be dissipated through a set of brake resistors. To absorb the excess energy produced during the lowering of the container, an energy storage system can be attached to the DC bus, whose energy can then be used to help lift the next container. In the literature, the ESS solution in RTG cranes is mainly focused and used to save energy on a single RTG system [5,8].
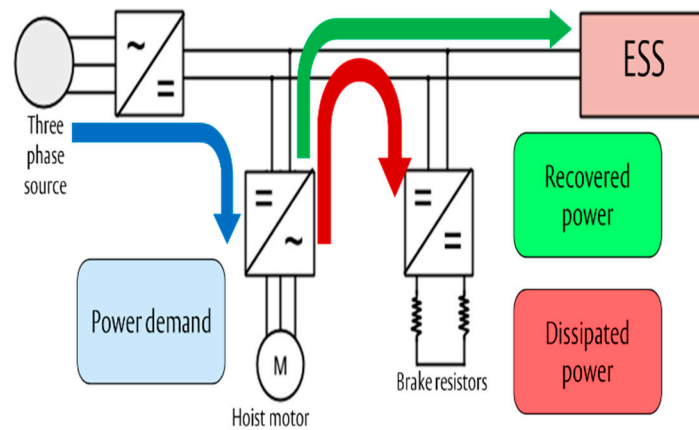
Figure 2. The consumed, dissipated and recovered power flow directions at an RTG system with ESS.

2.2. Network of RTG Cranes: Power System Structure

The electrical grid is a hierarchal network of synchronised and interconnected power supplies and consumers distributed over a wide geographic area. Firstly, the power station generates the electricity and steps-up the voltage to 230 kV or 400 kV (European system) to reduce the losses in the transmission stage. The electricity is then distributed to consumers by step-down voltage transformers and the distribution network. In the first stage, the voltage is stepped down to 33 kV then 11 kV (medium voltage) and finally to the low voltage (LV) network level of 415 V [7,9].

This paper will focus and study two RTG cranes network with and without ESS or AFE. Figure 3 represents a real electrical single line diagram at the Port of Felixstowe, UK, which is typical of a two crane network topology and configuration. The primary substation is a step-down station from 33 kV to 11 kV, and is split across the medium voltage network for the port. A secondary step-down substation with 11 kV input and 415 V output provides the RTG cranes with the required power through the LV cables and conductor rail, as shown in Figures 3 and 4 [7,9].
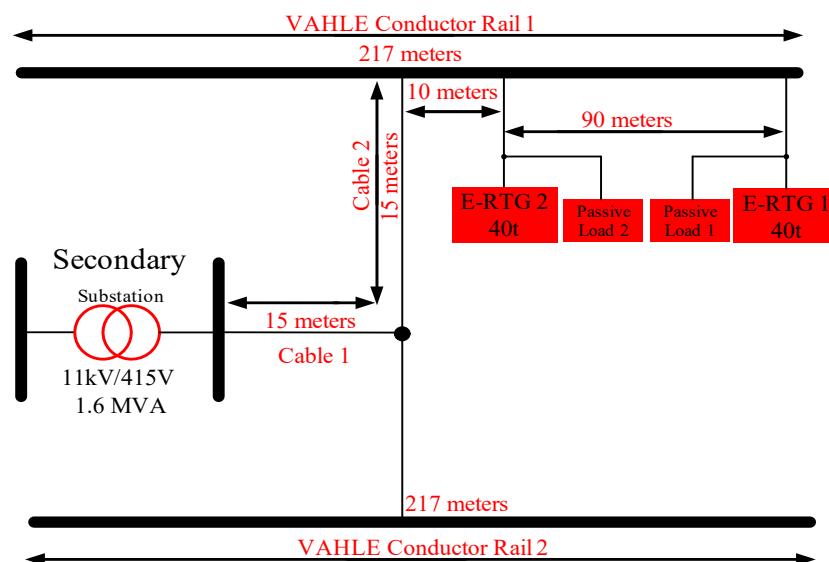

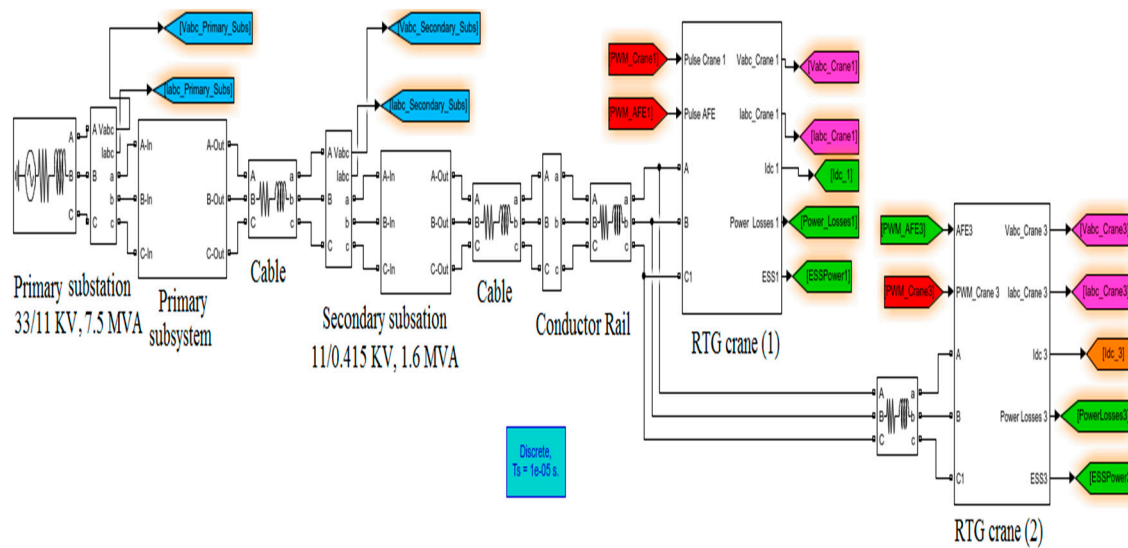**Figure 3.** The structure of two RTG cranes connected in series to the secondary substation.

Figure 4. Simulink model of a network of two RTG cranes.

The step-down transformer from 11 kV/ 415 V provides the cranes with power through 30 meters of low voltage cables and 217 meters of conductor rail bar. The network of two RTG cranes has been developed to investigate the ESS performance during high power demand with the two cranes connected in series 90 meters apart. In this paper, the series connection of two RTG crane has been chosen as a worst-case scenario with higher peak demand, voltage level and harmonics on the conductor bar or cable connections compared to parallel connection on two conductor rail bars. Table 1 presents the main characteristic parameters of the electrified crane system. These parameters were used to operate the two crane network model in this paper.

Table 1. Key parameters of the electrified RTG crane model [13,14].

Parameter	Value	Unit
Hoist motor power	200	kW
Trolley motors power	2×15	kW
Container Weight	40	tonnes
Spreader mass	11	tonnes

2.3. RTG Cranes Network Modelling

The cranes network, including the electrical distribution network and RTG crane elements, has been developed in MATLAB/Simulink. The network of cranes model, as seen in Figure 4, consists of three main components as follows:

- Primary substation: is an ideal three-phase source for the RTG crane system. The feeder substation (11 kV/ 415 V) provides the necessary power through a low voltage cable which supplies 415V to two cranes via a conductor rail bar. The key numerical parameters of the electrical network components are presented in Table 2 [7]. The parameters of the RTGs network (Section 2.3, Table 2) have been validated using data collected at the Port of Felixstowe, UK.
- RTG crane system: the RTG crane model including the electrical and mechanical components was developed [5,13,14] to study the operating cycle at the Port of Felixstowe. In this study, this model has been extended to include two electrified cranes. The RTG crane system includes induction motors (hoist and gantry) rated at 200 kW and two trolley motors rated 15 kW which are connected to the DC bus.
- The benefits of using either the ESS or AFE on a network of two cranes model were investigated by analysing the energy consumed through the entire network compared to actual demand without

using ESS or AFE. In addition, DC/DC converter aims to maintain the voltage level in the RTG crane system and ESS.

○　　Energy storage systems

ESSs collect energy regenerated during the lowering mode until they are fully charged with the remaining energy being dissipated via dump resistors. The main numerical parameters of the ESS are specified in Table 3. The energy store considered is a flywheel storage device powered by a 150 kW switched reluctance motor and stores up 3.6 MJ of energy [5,13]. In this study a power profile for hoisting the maximum container weight of 40 tonnes is used as it requires the highest level of power to move this container (250 kW). In general increasing the size of the ESS can help to store all regenerated energy so increasing energy saving. However, the higher power density and bigger ESS size will increase the capital cost and for the Port of Felixstowe the average mass of container lifted (including head block and spreader) is only 27 tonnes [13,14]. So this ESS has been sized for lifting this average mass in order to reduce the cost and size of ESS [13,14]. The distribution of container weights at Port of Felixstowe is discussed in Section 4.

○　　Active front ends

The AFE as a bi-directional converter which will allow the regenerated power to be fed back into the electrical network of the port terminal and so could be used by another crane. In this paper, the regenerative energy during the lowering mode can be used to reduce the peak demand during hoisting mode if the AFE is modelled as a bi-directional switch [13,14]. The LV power which is fed into the RTG crane is rectified through a diode converter, which converts alternating current (AC) into direct current (DC) power but only allows unidirectional flow. This process aims to protect the electrical distribution side from voltage mismatches or high harmonics produced from the regeneration due to electrical braking in the hoist and trolley motors. The regenerative energy is then wasted as heat in the dump resistors.

In order to reduce the wasted energy and increase energy saving, the AFE is modelled using a voltage source converter (VSC) based on a PI controller. The VSC in Figure 6 has been developed to transfer power between the electrical power network and the ccrane's power system. The control model aims to regulate the DC voltage at each RTG crane bus system by setting a reference value which helps to minimise the regenerative power that goes to the dump resistors and also protects the network from any electrical problems that might occur.

Table 2. Parameters of the cranes network [7].

Section	Components	Rating
Power source.	Secondary transformer.	11 KV/415 V 1.6 MVA
Distribution	Cable 1	0.0754 ohm/km
	Cable 2	0.1240 ohm/km
	Conductor rail	0.0520 ohm/km

Table 3. Parameters of the ESS [13,14].

Parameter	Value	Unit
Power (s)	150	kW
Energy	3.6	MJ
Rated voltage	625	V
Rated current	200	A

3. RTG Cranes Network: Case Studies

To investigate the peak reduction and energy savings on the network, a study has been made of the behaviour of RTG cranes network with and without ESS or AFE when they work with a maximum container weight of 40 tonnes. A comparative evaluation of the performance of ESS will be determined by the following configurations:

- Two RTG cranes network equipped with an ESS (no AFE). In this model, the AC power can only flow into the DC bus through a diode rectifier power converter [9].
- A network of two RTG cranes with each AFE system rated 150 kW (no ESS). The AFE allows the regenerated power to be fed back into the electrical network of the port terminal by two VSC converters working in four power quadrants [13,14].

3.1. RTG Cranes Network with ESS

In this case study, the DC power system at the RTG crane model is connected to the low voltage network via a diode converter. The diode converter is commonly used in RTG crane applications to convert AC power into DC power, as shown in Figure 2, due to is economy and ease of design and implementation. This converter is unidirectional, and the power regenerated at the crane system must be removed within the crane structure. The energy storage system is active when the crane is lowering a container as the hoist motors generate and the VSC converter rectifies the output and feeds this into the crane system as DC power so the DC voltage level rises. The ESS collects the regenerated energy within the maximum storage capacity limits and the remaining regenerated energy is dissipated as heat through brake resistors [10,12]. The advantage of the ESS on the cranes is that the energy is locally stored in each crane and thus the ESS can easily supply energy to the hoist motors when the RTG crane is lifting the next container thus reducing the demand on the supply.

In a standard RTG crane, if the DC voltage level exceeds the voltage threshold (750 V) during the lowering phase, the brake chopper is activated which enables the regenerated energy to be dissipated as heat and reduces the DC voltage level in the DC link. With the incorporation of the ESS, its control system is assumed active at 625 V [5]. In this study, the set-point system charge and discharge of the ESS is based on the comparison between the reference DC voltage (Vdc-ref), equal to 625V and the measured voltage value of the DC link (Vdc-meas). When the DC voltage is equal to the set point (625 V), the charging mode of the ESS is activated and then the DC voltage is lower than 600, the ESS is in discharging mode [6]. The PI control system aims to charge the ESS during DC voltage variation by setting a reference voltage [5,6]. The PI controller, as shown in Figure 5, generates a control signal to charge or discharge ESS depending on where the crane is in its duty cycle.
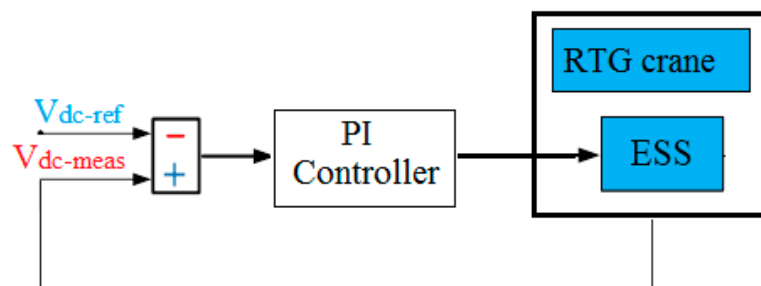

Figure 5. Control loop for the RTG crane system with ESS.

In this model, the useful stored energy will depend on the regenerated power from the hoist motor during lowering the container and the energy losses in the DC network and the conversion of the energy (AC/DC). In this case study, each ESS is set up to store and discharge up to 150 kW and 1 kWh in a maximum time of 25s. In this study, the weight of the container (40 tonnes) plus the weight of the spreader is 51 tonnes and the lifting time is set to 28 s to 30 s, which results in up to 250 kW

of power being regenerated. The main numerical parameters of the storage device are specified in Table 3 [13,14].

3.2. Active Front End (AFE)

The movement towards fully automated ports and electrified RTG cranes increase the benefits of using AFEs in the distribution network of RTG cranes. The AFE allows the recovered energy from lowering containers to be fed back into the port network [13,14] to feed neighbouring RTG cranes. This will help to reduce the substation peak and energy costs, as shown in Figure 6. The energy saving in the electrical network of a port will lead directly to a reduction in costs and CO_2 emissions. while reducing the stress on the port network and a further benefit of using AFE in a network of RTG cranes should be to keep the total harmonic distortion around 3% [14].
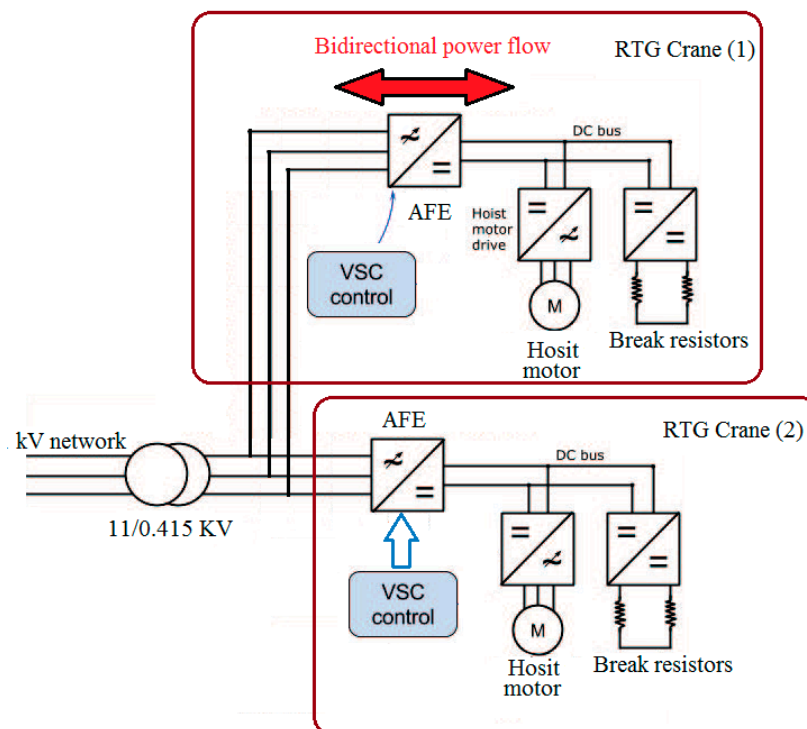

Figure 6. Block diagram of the AFE system.

In the RTG cranes network equipped with AFE scenario, the RTG cranes work simultaneously where the energy recovered during lowering container by one crane is immediately consumed by another crane in the network. In this paper, the AFE is modelled by using a voltage source converter (VSC) based on a PI controller. The VSC in Figure 6 has been developed to deliver the necessary interaction between electrical power network and the control power system. This VSC model is developed in [13,14] and in this paper the model has been updated for a network of two electrified RTG cranes. The control model aims to regulate the DC voltage at each RTG crane bus system by setting a reference value. This helps to minimise the regenerative power that goes to the dump resistors. In this case study, the VSC is a bidirectional power source converter which works in the four power quadrants. The major disadvantages of a VSC power converter is the power losses generated by the high frequency of the insulated-gate bipolar transistor (IGBT) switches and the associated cost.

However, this study focused on the energy saving and peak demand on the network and not on the economics of such converters. The PI control strategy applied to the VSC power converter which controls the performance of the hoist motor operation, is modelled in [13,14]. The VSC is based on an averaged model in order to maintain the power dynamics of the AFE from the interaction with the power system. This VSC model (averaged model) provides faster simulations, where the lifting cycle

is only between 28s to 30s. Furthermore, this model is not able to represent the harmonics and the power quality terms but focuses on the peak power, energy and cost savings in two cranes network by reusing the regenerative power.

4. Results and Discussion

In this section, the results from the two proposed scenarios for the RTG cranes network (ESS or AFE) are presented and discussed. The network of cranes with no ESS or AFE resulted in a significant amount of energy being dispersed in the brake resistors. The addition of energy storage increases the energy efficiency of the network of cranes by enabling this stored energy to be reused during periods of peak demand on the same crane whereas the AFE can transfer the recovered energy from one crane (lowering mode) to be used in reducing the peak demand and energy losses at the second crane during its lifting mode.

Figure 7 shows the power curve of the network of RTG cranes with and without storage. The RTG duty cycle can depend upon the operator (crane driver) behaviour [9] and there is usually a delay between lowering and raising a container. This very short delay will not have an effect on the energy saving. In addition, the power curve in Figure 7 shows two operation cycles:

- The first cycle from 0s to 60s. Here, the lifting mode in which energy is consumed during the lifting mode from 2 s to 32 s and lowering mode from 32 s to 60 s.
- The second cycle from 60 s to 120 s. Here, the lifting mode is from 62 s to 92 s and lowering mode from 92 s to 12 s.
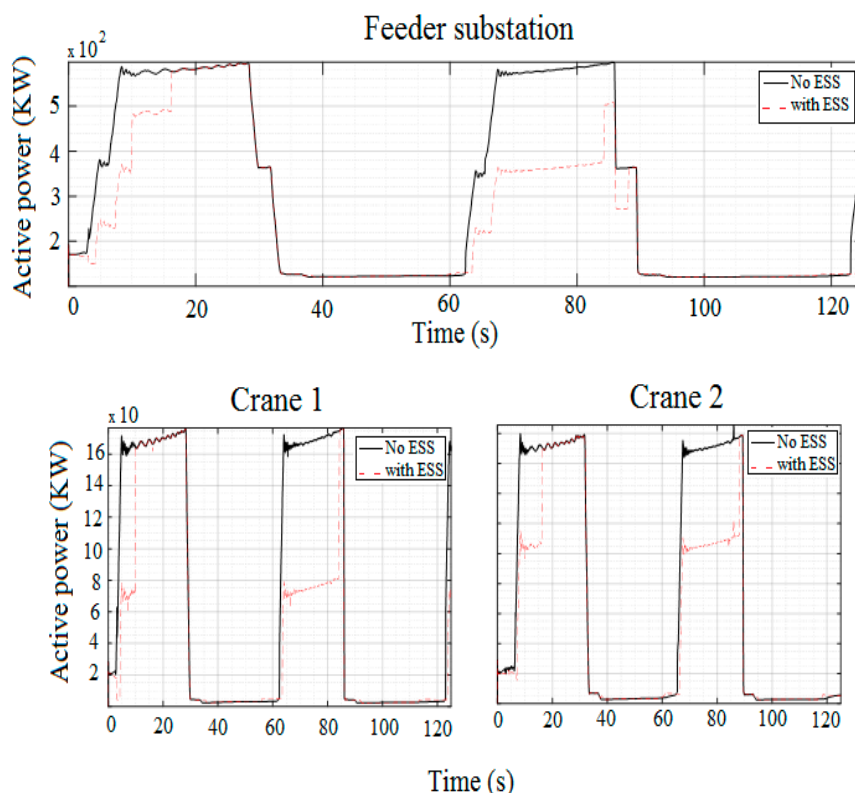

Figure 7. An example for the power flow of network of two RTG cranes without (black line) and with (red line) the energy storage system.

It is clear that the ESS helps to reduce the energy consumption by 30%, compared to no ESS model, during the both lifting periods by minimising the area of the peak power curve. The reduction in the energy consumption and peak demand in the feeder substation and on both RTG cranes can be clearly

seen in the second peak period from 62 s to 92 s (the second lifting period) compared to the first lifting period (from 2 s to 32 s) due to the ESS being not fully charged during the first lifting period. The ESS uses the recovered energy during the lowering mode of the first cycle (32 s to 60 s) to charge the ESS (fully charged) before starting the second lifting mode, which helps to decrease the peak demand and increase the energy savings. In Figure 7, the differences in the active power between the substation and cranes system is mainly related to the power network and converters losses.

Furthermore, the power losses through the resistor bank on the crane are decreased by around 80% and 55% for crane 1 and crane 2 respectively (Figure 8). The recovered energy in the ESS is around 75% of the energy generated during the lowering of the crane. The remaining 25% of the generated energy is dissipated by a brake chopper resistor so that the network of RTG cranes can increase energy saving up to 75%.
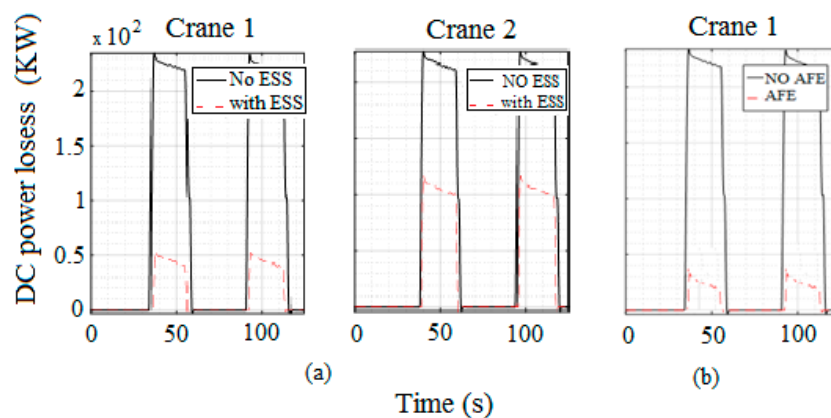

Figure 8. An example for the power losses of (a) the crane 1 and crane 2 (ESS model) and (b) AFE.

In this study, the size of ESS selected is based on the recovered energy generated from lifting weight of containers up to 27 tonnes in order to reduce the cost and size of ESS [13,14] (Figure 9) [15]. The 27 tonne container (middle between 25 and 30 tonne) has the highest frequency and therefore has been used to size the ESS. However, the ESS model in this paper aims to deal with the maximum of consumed and wasted energy. Therefore, the power curve generated by lifting 40 tonnes container (the heaviest load and worst-case scenario) is used to evaluate the benefit of using ESS in a network of RTG cranes.

The ability of transferring the regenerated hoist power into the distribution network via AFEs helps to decrease the peak demand and increase energy saving compared to the original RTG cranes network without ESS and AFE. The peak power reduction using ESS or AFE is presented in Table 4 as the percentage of time that the secondary substation is feeding more than 300 and 400 kW during an operation at crane cycle. The AFE model limits the peak power better than the ESS model due to the fact the regenerated power has been used across the network of cranes. This peak reduction helps to reduce the demand stress on the distribution network components while the use of AFE and ESS on a network of RTG cranes has a significant impact on reducing the voltage stress on the distribution network and the DC link. Figure 10 shows an example of the DC voltage level during the lifting and lowering container periods. The time of the voltage peak period is reduced for crane 1 and 2, as shown in Figure 10.
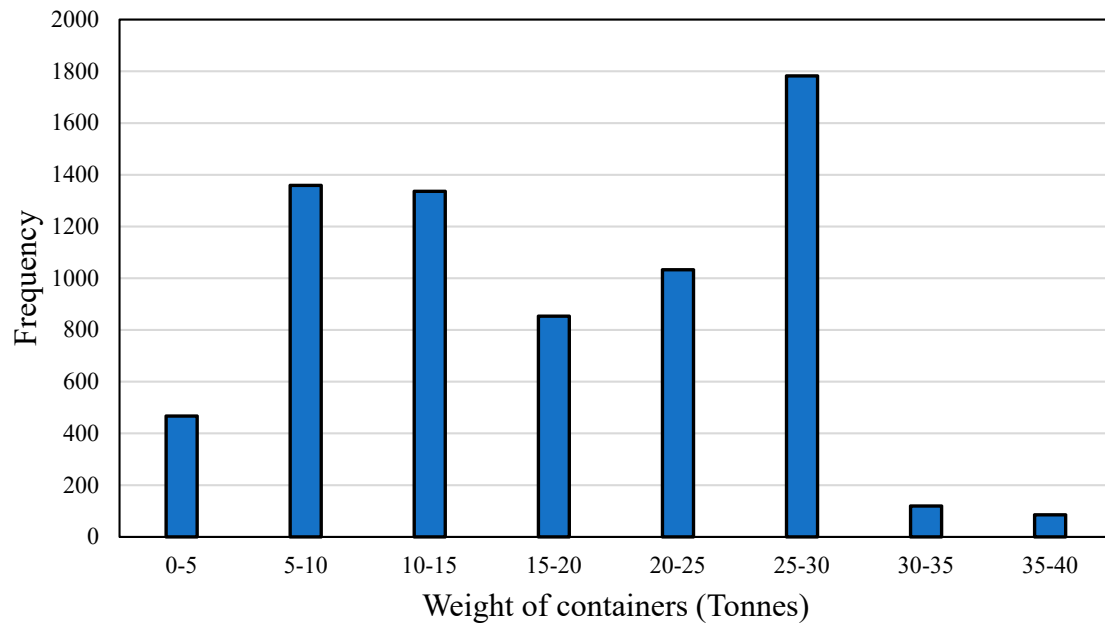
Figure 9. A histogram of the weight of containers for data collected at Port of Felixstowe over a period of four months.

Table 4. Percentage of time that the secondary substation for network of two RTG cranes output is over 300 and 400 kW.

Network Model Scenario	Above 300 kW	Above 400 kW
No ESS	50%	33%
ESS	36%	20%
AFE	30%	12%
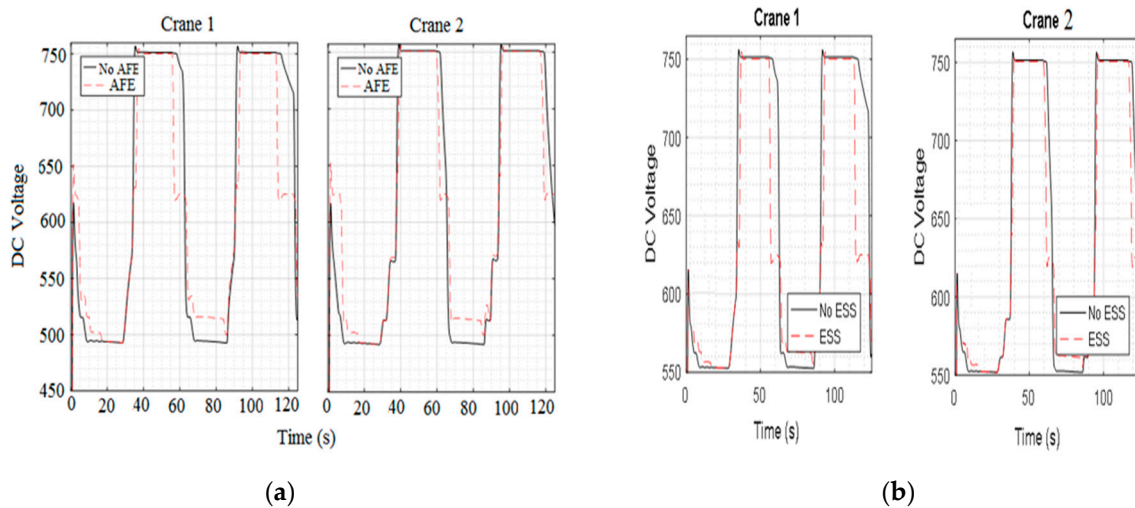
Figure 10. An example for the DC voltage curve of network of crane ((**a**) AFE model (**b**) ESS model).

This work attempts to assess the benefits of using AFE or ESS in a network of two RTG cranes. The AFE is modelled by using a VSC to regulate the DC voltage at each RTG crane bus system which helps to increase the energy saving by minimising the regenerative power that goes to the dump resistors. The ESS collects regenerated energy (until it is fully charged) during the lowing mode and then makes it available during the hoist mode so reducing the energy demand (Table 5). The AFE scenario for two cranes network outperforms the ESS scenario and achieves higher energy saving

as the AFE scenario achieves a 47% energy saving compared to 30% for the ESS model. In addition, the ability of transferring the regenerated power through the network of cranes helps to decrease the percentage of power losses (through brake resistors) from 35% in ESS scenario to 10% in AFE model.

Table 5. Percentage of reduction of energy consumption and power losses.

Network Model Scenario	Percentage of Reduction of Energy Consumption	Percentage of Power Losses Thorough the Brake Resistor
ESS	30%	35%
AFE	47%	10%

The energy saving in Table 5 can be directly translated to cost savings at ports. For example, in order to move more than 4 million TEUs each year, Port of Felixstowe, UK, operates 85 RTG cranes. These cranes work daily up to 18 hours for 350 days a year [16,17]. According to the Port's administration, the annual electricity energy costs for two RTG cranes is around £21,000. This significant reduction in energy consumption will reduce the port's operating costs. The energy saving of recoverable energy with 30% and 47% reduction for ESS and AFE models, could result in energy cost savings of £6300 and £9870 in electricity per year respectively.

Generally, both ESS and AFE can substantially reduce the power peak and energy demand and the final configuration will depend upon the port network and the frequency of container moves. For example, if the both cranes in the network are being simultaneously lowered the containers, there is regenerated energy from both cranes which need to be absorbed elsewhere (through the brake resistor as wasted energy) or else the fault level could rise. Here, the ESS solution can store the regenerated energy from both cranes and reuse it when it is required. The ESS ability to store all regenerated energy will depend on the size and charging and discharging rate of the ESS. In addition, the ESS is located at the DC bar of RTG crane, so there is no transformer or AC-DC-AC converting losses similar to AFE which will also increase the efficiency of using ESS at the network of RTG cranes.

In addition, the economics of using ESS or AFE will depend on whether there will be a significant credit for exporting the power back to the grid otherwise it would be better to store within the port for subsequent reuse. This would require the same network layout with a combination of AFE and ESS both at substation side as well as on the cranes. The series connection of two RTG cranes is the worst-case scenario with higher peak demand on the conductor bar or cable connections compared to parallel connection on two conductor rail bars, where the maximum number of cranes on the same conductor bar is two.

Based on the energy saving on low voltage network of two cranes, this study introduces a signification energy saving at port level and also a significant energy cost saving scenario by using a central ESS or AFE to feed a greater number of cranes. However, a central storage location on a higher level of voltage to feed all cranes at port and also the number of ESS will form part of our future work.

5. Conclusions

This paper investigates the behaviour of the power flows and energy saving for a two RTG crane network with different scenarios: energy storage system (ESS) and active front end (AFE). A model network of two RTG cranes has been simulated with the maximum container weight ratio (40 tonnes), to analyse the peak power demand and reduction in energy consumption using a MATLAB/Simulink model. Both scenarios ESS and AFE have a significant impact on reducing the energy consumption and the simulation results shows that the AFE scenario performs better than the ESS under the scenario described in the paper in terms of power losses and energy consumption. Furthermore, the reduction in energy consumption will also be beneficial for port terminal operators to reduce the energy operation costs and stress on the LV network as the predicted peak demand reduction will help to avoid the need to replace or upgrade a port's LV network components such as substations and cabling due to the electrification of cranes.

Abbreviations and Nomenclature

The following abbreviation are used in this paper:

RTG	Rubber Tyre Gantry
AFE	Active Front End
ESS	Energy Storage System
WSC	World Shipping Council
CO_2	Carbon dioxide
VSC	Voltage Source Converter
DC	Direct Current
AC	Alternating Current
LV	Low Voltage
P_{ESS}	Power energy storage
P_{Hoist}	Power of the hoist motor
P_{Losses}	Power losses at network
P_{dc}	Power transferred to DC bus system
P_{cap}	Power capacitor at VSC system
V_{dc}	DC voltage
i_{dc}	DC current

References

1. World Shipping Council. Trade Statistics. Online 2018. Available online: http://www.worldshipping.org/about-the-industry/global-trade/trade-statistics (accessed on 8 February 2019).
2. World Shipping Council. Ports. Online 2018. Available online: http://www.worldshipping.org/about-the-industry/global-trade/ports (accessed on 8 February 2019).
3. International Maritime Organisation. Statistical Resources—UNCTAD Review of Maritime Transport. Online. Available online: http://unctad.org/en/PublicationsLibrary/rmt2016_en.pdf (accessed on 8 February 2019).
4. Yang, Y.; Chang, W. Impacts of electric rubber-tired gantries on green port performance. *Res. Transp. Bus. Manag.* **2013**, *8*, 67–76. [CrossRef]
5. Pietrosanti, S.; Holderbaum, W.; Becerra, V. Optimal Power Management Strategy for Energy Storage with Stochastic Loads. *Energies* **2016**, *9*, 175. [CrossRef]
6. Niu, W.; Huang, X.; Yuan, F.; Schofield, N.; Xu, L.; Chu, J.; Gu, W. Sizing of Energy System of a Hybrid Lithium Battery RTG Crane. *IEEE Trans. Power Electron.* **2017**, *32*. [CrossRef]
7. Alasali, F.; Haben, S.; Becerra, V.; Holderbaum, W. Optimal Energy Management and MPC Strategies for Electrified RTG Cranes with Energy Storage System. *Energies* **2017**, *10*, 1598. [CrossRef]
8. Zhao, N.; Schofield, N.; Niu, W. Energy Storage System for a Port Crane Hybrid Power-Train. *IEEE Trans. Transp. Electrif.* **2016**, *2*, 480–492. [CrossRef]
9. Alasali, F.; Haben, S.; Holderbaum, W. Energy management systems for a network of electrified cranes with energy storage. *Electr. Power Energy Syst.* **2019**, *106*, 210–222. [CrossRef]
10. Flynn, M.; Mcmullen, P.; Solis, O. Saving Energy Using Flywheels. *IEEE Ind. Appl. Mag.* **2008**, *14*, 69–76. [CrossRef]
11. Alasali, F.; Luque, A.; Becerra, V.; Holderbaum, W. Energy Reduction and Peak shifting on a Network of Cranes. In Proceedings of the International Conference on Energy, Environment and Economics, Edinburgh, UK, 16–18 August 2016; pp. 137–143.

12. Kim, S.; Sul, S. Control of Rubber Tyred Gantry Crane with Energy Storage Based on Supercapacitor Bank. *IEEE Trans. Power Electron.* **2006**, *21*, 1420–1427. [CrossRef]

13. Luque, A.; Harrison, I.; Pietrosanti, S.; Alasali, F.; Holderbaum, W.; Becerra, V.; Mayer, R. Energy reduction on eRTG. In Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; pp. 1–6.

14. Pietrosanti, S.; Harrison, I.; Luque, A.; Holderbaum, W.; Becerra, V.; Mayer, R. Net Energy Savings in Rubber Tyred Gantry Cranes Equipped with an Active Front End. In Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016.

15. Port of Felixstowe. Ship 2 Shore Magazine No 29. Online 2018. Available online: https://www.portoffelixstowe. co.uk/press/ (accessed on 8 February 2019).

16. Papaioannou, V.; Pietrosanti, S.; Holderbaum, W.; Becerra, V.; Mayer, R. Analysis of energy usage for RTG cranes. *Energy* **2017**, *125*, 337–344. [CrossRef]

17. Harrison, I.; Pietrosanti, S.; Luque, A.; Mayer, R.; Holderbaum, W. Recording and analysing measurements from an RTG crane. *Measurement* **2018**, *125*, 284–293. [CrossRef]