Peak power reduction for electrified Rubber-Tyred Gantry (RTG) cranes using energy storage.

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Abstract

Ports around the world are moving towards using electrified RTG cranes to reduce greenhouse gases and energy consumption compared to diesel RTG cranes. This paper introduces the electrified RTG crane network with energy storage and the simulation model that will allow us to assessment the benefits from developing a control strategy based on load forecasting in crane network. To increase peak reduction and energy saving, this paper investigates the peak demand in electrifed RTG cranes and explores the contribution of crane load forecasting within a control strategy in peak reduction.The model describes the use of the collected data from the Port of Felixstowe to operate the simulation models and confirm the simulation's reliability. The analysis of the results shows that there might be benefit from developing an energy storage control strategy by using load forecasting output to reduce the peak demands.

1. Introduction

Recently, to reduce gas emissions, ports are shifting towards using electrified RTG cranes that are connected to the electrical grid [1]. Yang *et al.*[1] presented a single electrified RTG crane's performance comparing it to diesel RTG cranes. The results showed that the electrified RTG crane could achieve reductions of approximately 67% in gas emissions and energy savings of 86%.The energy storage technologies which have been used in RTG crane systems to increase energy saving and reduce the gas emissions. The energy storage system is typically located at the RTG crane to store energy during the lowering mode preventing it from being dissipated as heat through the break resistors. The energy storage regenerates the power during the lifting or hoisting mode in order to reduce the peak demand and increase energy savings. Batteries, supercapacitors and flywheel are the main type of energy storage systems which have been used in RTG crane systems. An energy storage control strategy that uses the reference value of power or voltage control has been widely used in RTG cranes systems to control the energy storage control or the dump resistors bank [2] [3]. However, the State of Charge (SoC) percentage has also been used to control the energy storage in [4] and Pietrosanti *et al.*[5] developed an optimal power management strategy to increase the energy saving in RTG crane systems. The following energy storage control strategies in RTG cranes examples are divided into three main categories: (i) Set point control system (ii) State of Charge (SoC) control system and (iii) power management strategy.

(i) Set point control system: controlling the DC link voltage in cranes system, utilising the recovered energy from break resistors, is one of the most effective control techniques

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used to increase energy savings [2] [6]. Kim *et al.* [6] developed a hybrid energy storage model that included battery and supercapacitor energy storage. The hybrid energy storage was connected to the DC link in the RTG crane system through a DC/DC converter. The aim of this hybrid model was to increase the life time of the battery system by using the supercapacitors for the transient peak charging and discharging. However, the proposed control strategy in [2] and [6] did not help to select the significant peak demand or develop schedule control model. The schedule control is aim to increase the lifetime of energy storage by reducing unnecessary charging and discharging periods.

(ii) State of Charge control system: in [4], state of charge percentage was used to control the battery energy storage. When the SoC of battery energy storage was less than 50%, the diesel generator in the RTG crane system tuned on to charge the battery and the diesel generator turned off when SoC was more than 80%. The hybrid energy source (battery and diesel engine) will feed the crane when the SoC is between 50% to 80%. When the SoC greater than 80% the hybrid model will operate with pure battery mode. In this control model, the minimum battery energy storage usage was determined for 30% SoC in order to increase the battery life time. However, [4] did not investigate the load profiles of RTG cranes over a long time period in order to select the significant peak level.

(iii) Power management strategy: in order to increase the energy saving and minimise the costs, Pietrosanti *et al.* [5] developed an optimal power management strategy. The objective of this strategy was to decrease the total cost of generated energy. The optimal control was designed to find the suitable storage output based on minimising the energy costs. The results of this paper showed an increase in energy savings and peak power demand reduction compared to a set point control strategy. The optimal control strategy in [5] aimed to minimise the energy cost and and only tested a one hour test cycle without investigating the significant peak points over long time periods. In addition, a significant improvement to this control strategy could be made by using the load forecast model in order to predict the significant peak points and minimise peak demand in line with minimising energy costs.

Overall, the control strategies for port applications have focused on energy saving and gas emission reduction for a single diesel RTG crane such as a diesel RTG crane in specific test cycles. In general, more investigations are required into electrified RTG cranes and how the control models in [2] [3] and [5] can be applied to electrified RTG cranes. In addition, the RTG crane application need more analyse to show the effects of located energy storage devices on the substation side. In addition, there are limited studies [5] on using different optimisation methods to increase the energy effciency of RTG cranes. The current control strategies researched for port applications and RTG cranes have not used the load forecasting methods to select the potential peak demand or to control the energy storage in RTG crane systems by using scheduling control system based on load forecasting.

2. Methodology

Electrified RTG cranes are used for container handling operation at ports and they are usually powered by a diesel generator [1]. In this paper the following two control strategies are applied in order to reduce peak demand and increase the load factor percentage by using peak shifting technique:

- Set point control: the reference value of power will be selected based on load factor calculations. The model will store the energy when the power falls below the reference value and discharge it when above the reference value.

- Scheduling control system: in this model load forecasting [7] will be utilised to create a charging and discharging schedule to reduce peak demand and increase the load factor.

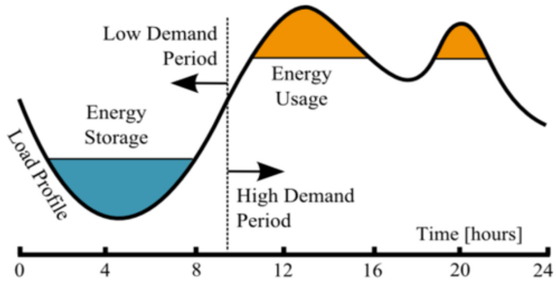
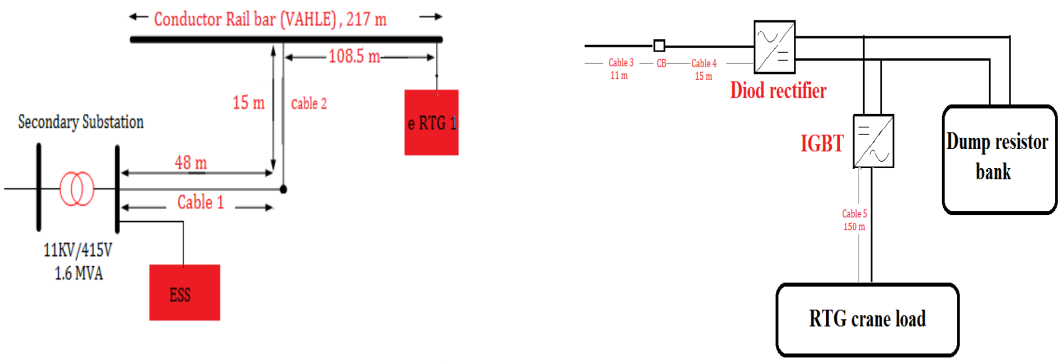


Figure 1: Peak shifting strategy [20].

2.1. *Electrified RTG crane*

The electrified RTG crane under analysis is currently used at the Port of Felixstowe and is manufactured by Shanghai Zhenhua Heavy Industries (ZPMC), shown in Figure 2. This crane is powered by the electric grid via a connection to a conductor rail bar of length 217 meters.The conductor bar is energised by a cable feeder from the secondary substation. The schematic diagram in Figure 3a displays the secondary substation (11kV/415V) as an energy source connected to a conductor bar via two cables and an energy storage system (ESS), as seen in Figure 3a. The conductor bar connects to DC bus link in the RTG crane system through cables 3 and 4 [8] [9].

Figure 2: Electrified RTG Crane.



(a) ESS located at substation side

(b) RTG crane system model

Figure 3: The network of electrified RTG crane schematic diagram [8][9].

2.2. *Control strategies for the energy storage system*

This paper presents two control methods for reducing the the peak demand over a day. The actual and predicted three-phase active power demand for electrified RTG cranes were used as input parameters to operate the crane simulation model. The set point control with a PI controller and scheduling control strategy have been developed in this paper.

2.2.1. *Set point control*

In this section a set set point controller has been developed. This controller uses a chosen reference power value and the actual power value to control the energy storage and it is widely used in industrial applications such as RTG crane operations [2] [5]. In this paper, the reference power value has been chosen based on the load factor (L.F). The load factor is the ratio used to assess the usefulness of the energy storage during peak demand period and and is expressed in equation 1:

$$L.F = \frac{\text{Average load}}{\text{Peak load in given time period}} 100\% \tag{1}$$

Based on the load factor calculations, the reference value for the power level was chosen as input for PI controller. The PI control with [-1,1] bounders have been used in [8], [9] and [10] for RTG crane control. The PI controller output limits are [-1;1] with a clamping anti-windup method have been used to avoid saturation problems [11]. In this paper the set point control, as seen in Figure 4, is a PI controller generates a control signal value between 1 and -1 based on the integral of the error and the instantaneous error of the power crane demand with respect to the chosen reference value [10][11].

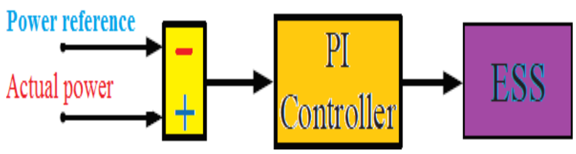


Figure 4: PI controller for the set point control strategy

2.2.2. *Scheduling control strategy*

One of the most popular and effective energy demand management methods is load shifting which determines and calculates the peak demand and peak demand reduction based on an objective target. In order to create a more effective control strategy, load forecasting is widely used in power systems for peak shifting, saving energy, and minimising energy costs in different application levels such as in low voltage distribution networks [12][13] , renewable energy generation [14][15] and electric vehicle charging [16]. In this strategy, the significant peaks based on the forecast load profiles were identified based on load forecast profile received from the forecast system. A charging and discharging routine is ten developed with the aim of controlling the energy storage system together with the real-time operation through the calculation of the energy storage discharge target.

3. Modelling

3.1. *The electrified RTG crane with an energy storage system.*

This subsection presents the development of a MATLAB Simulink model designed to describe the behaviour of the electrified RTG crane network at the Port of Felixstowe with energy storage. This model uses the actual three-phase active power collected at the Port of Felixstowe during the period from the 1^{st} to the 10^{th} of October,2016 to operate the electrified RTG crane.

The energy storage system was modelled by using generic storage Simulink blocks, a type of energy storage defined by energy capacity, power rating and efficiency.

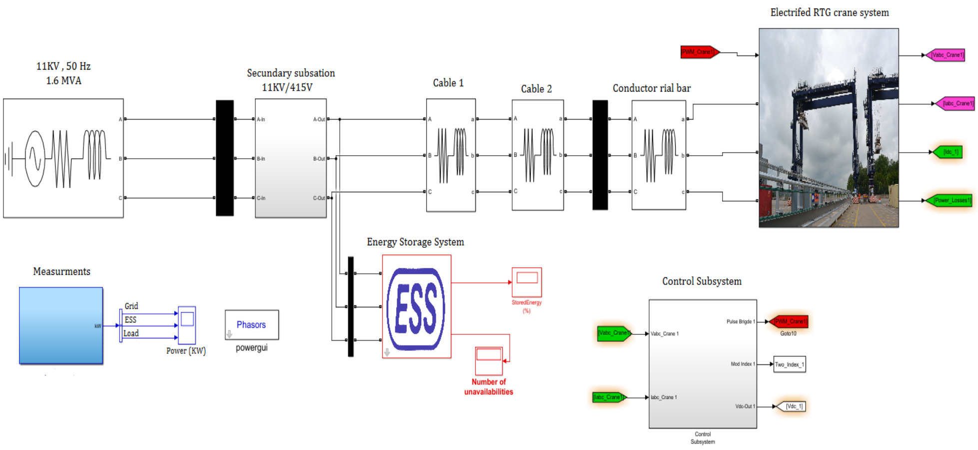


Figure 5: The electrified RTG crane MATLAB Simulink model [8]

3.2. *Set point control*

In this paper, the reference power value has been chosen based on the load factor calculations. In order to operate the energy storage economically and effectively, we aim to a high load factor which translates into a relatively low peak demand. Table 1 presents the daily and overall load factor and the maximum three-phase peak demand values.

Table 1. Daily and overall load factor.

Day	Maximum peak demand (kW)	Load factor
1	652	40.5%
2	474	44.3%
3	628	41.8%
4	508	38.2%
5	566	40.6%
6	426	42.5%
7	709	22.2%
8	669	26.0%
9	559	38.3%
10	366	31.1%
Overall	709	29.0%

Due to the neutral operation of RTG crane there is a big gab between the average power and peak powers in given time period[7]. In order to increase the overall load factor from 29% to an overall load factor target of 50%, it was necessary to reduce the peak demand to a peak demand of around 400 kW. In [17],[18] and [19], a typical load factor range for the electrical distribution network was presented between 50% to 70%. The chosen reference value for the set point control is 400 kW in this paper based on the load factor calculation.

3.3. *Scheduling control strategy for power shifting*

The new basic control model creates a discharge and charge schedule based on the load forecast profile. The the load forecast profile has been developed in [7]. The peak was considered significant if demand $>$ 400 KW and the energy storage started discharging when the load was more than 400 KW. In order to create the control schedule and maximise the load factor improvement, the energy storage charging target (CT) was calculated, as described in Equations 2 and 3.

$$SE_n = SE_n\%.SR \tag{2}$$

$$CT_n = SR \times SE_n \tag{3}$$

where SE_n is available stored energy at time step n (n = 1,2,......,24), $SE_n\%$ is stored energy percentage at time step n, SR is energy storage rating, CT_n is the hourly energy storage charging target at time step n and n is the hour of the day (n = 1,2,......,24). In this report, the peak was considered significant if demand $> 400\ KW$. The control schedule used the energy storage charging target to create the charging schedule and calculate the charging magnitude (CS_n) in advance based on load profile forecast as given by:

$$PG_n = LF_n + CT_n \tag{4}$$

$$CS_n = \begin{cases} CT_n, & \text{if } PG_n \leq 400KW \\ 400KW - LF_n, & \text{if } PG_n > 400KW \end{cases} \tag{5}$$

where PG_n is the expected hourly power grid demand at time step n, LF_n is the hourly load forecast value at time step n and CS_n is charging magnitude at time step n and n is the hour of the day (n = 1,2,......,24). The control schedule ensures that the summation of the charging power amount and load demand value do not exceed the power reference value (400 kW) which helped to increase the load factor improvement. In other words, the control schedule divides the charging target power amount over the subsequent load hours until the next peak point does not exceed the power reference level. This control included a function block which was created based on the equations 2 to 5. The load profile forecast is based on artificial neural networks (ANN) and was developed in [7].

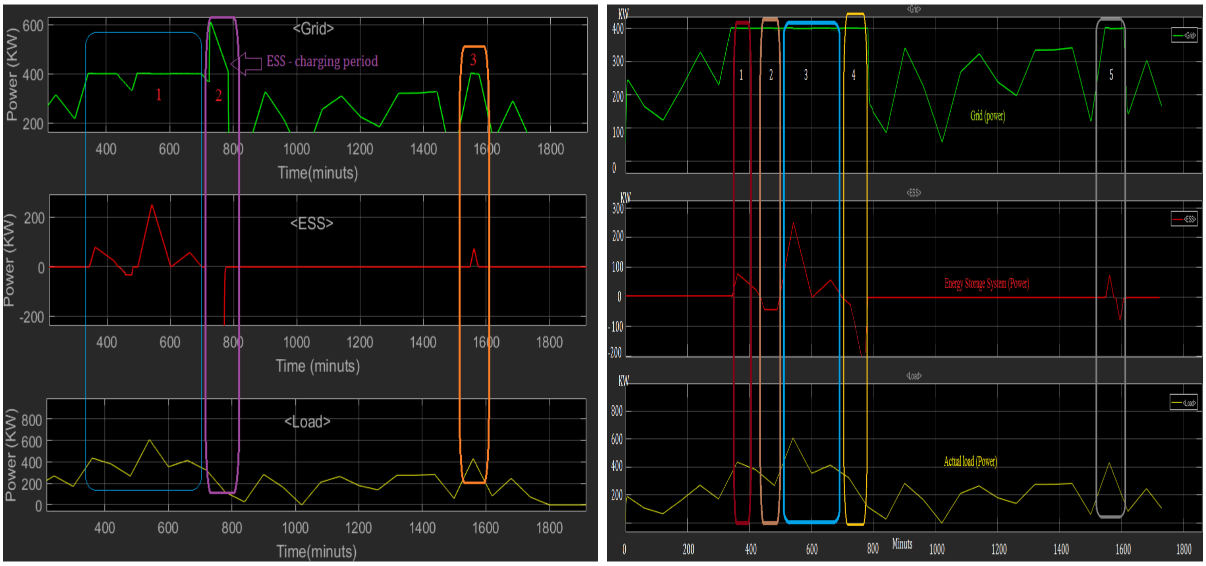
4. Results and discussion

The control models in this paper use the actual and ANN forecast model output presented in [7] for the period from the 1^{st} to the 10^{th} of October, 2016 to operate the electrified RTG crane with an energy storage model. The comparison of the control models is shown in Table 2. This table presents and summarises the comparison between set point control, scheduling control strategy and the load factor target. Table 2 shows that the scheduling control model performs better than the set point control with the largest peak value of 476kW compared to 663KW based on the operation data set for the period 1^{st} of October to the 10^{th} of October, 2016. The scheduling control model (PG_n) had a higher daily load factor improvement of 25.6%, which is equal to the load factor target. The set point control has a negative load factor improvement due to charging the energy storage incorrectly. The scheduling control (PG_n) does not reach the target value due to missing one peak point (476 kW) because the energy storage was not able to feed the necessary power.

Table 2. Comparison between set point control, scheduling control, and load factor target.

	Set point control	**Scheduling control**	**Target**
Maximum power grid	663 KW	476 KW	400 KW
Overall load factor	1.9%	14.3%	22.5%
Maximum daily load factor improvement	16.1%	25.6%	25.6%
Minimum daily load factor improvement	- 2.0%	2.8%	2.8%

From Figure 6a for the set point control, the charging of the energy storage might take place when the grid demands between 300kW and 400kW, as seen in box 2. Then the load on the grid will increase to above 600kW and create a new peak demand and reduce load factor improvements compered scheduling control. The Figure 6b shows that the scheduling control model has successfully reduced the four peak points to 400 KW, a seen in Figure 6b boxes 1,3 and 5. The first peak reduction (box 1) was 58 KW, reducing the peak power from 458 KW to 400 KW. Then the energy storage was charged by 58 KW, as seen in Figure 6a (box2) without creating any new peaks.



(a) Set point system

(b) Scheduling control

Figure 6: The simulation test results for the grid power, ESS power and RTG crane load in KW.

5. Conclusions

This paper has outlined the a set point control model and a scheduling control model in order to reduce peak demand over a ten-day period for an electrified RTG crane. It has described the control models' parameters and how the reference power level was selected. The performance of the two control strategies was evaluated by calculating the load factor on the grid. The scheduling control model has shown a better performance during the ten-day testing period compared to the set point control model. The scheduling control model showed significant signs that load forecasting may be helpful for the creation of a control model for a network of cranes. The results of the peak demand reduction and load factor improvement is related to data collected from a single electrified RTG crane over a specific period.

Acknowledgments

The authors are grateful to the Port of Felixstowe staff for providing the RTG crane data.

References

[1] Yang, Y. and Chang,W. (2013). Impacts of electric rubber-tired gantries on green port performance. Research in Transportation Business and Management . Volume 8, October 2013, Pages 67–76.

[2] Zhao, N., Schofield, N. and Niu, W. (2016). Energy Storage System for a Port Crane Hybrid Power-Train. IEEE Transactions On Transportation Electrification. Vol. 2, NO. 4, December 2016

[3] Flynn,M., Mcmullen, P. and Solis, O. (2008). Saving energy using flywheels. IEEE Industry Applications Magazine . Volume: 14, Issue: 6, November-December 2008.

[4] Niu,W., Huang, X., Yuan, F.,Schofield, N., Xu,L., Chu, J. and Gu,W. (2016). Sizing of Energy System of a Hybrid Lithium Battery RTG Crane. IEEE Transactions on Power Electronics, 2016.

[5] Pietrosanti, S.,Holderbaum, W. and Becerra, V. (2016). Optimal Power Management Strategy for Energy Storage with Stochastic Loads. Energies. doi:10.3390/en9030175, 2016.

[6] Kim, S. and Sul, S. (2006). Control of Rubber Tyred Gantry CraneWith Energy Storage Based on Supercapacitor Bank. IEEE Transactions On Power Electronics. Vol. 21, NO. 5, SEPTEMBER 2006.

[7] Alasali, F., Haben, S., Becerra,V. and Holderbaum, W. Analysis of RTG Crane Load Demand and Short-term Load Forecasting. *International Journal of Computing, Communications and Instrumentation Engineering (IJCCIE)*. ISSN 2349-1469, EISSN 2349-1477, Vol. 3, Issue 2, 2016.

[8] Alasali, F.; Luque, A.; Becerra,V. and Holderbaum, W. "Energy Reduction and Peak shifting on a Network of Cranes" in International conference on Energy, Environment and Economics, ISSN 2059-2353, 16-18 August 2016, pp 137-143.

[9] Luque, A.; Harrison, I.; Pietrosanti, S.; Alasali, F.; Holderbaum, W.; Mayer, R. and Becerra, V. "Energy Reduction on eRTG" in Environment and Electrical Engineering Conference (EEEIC), June 2016.

[10] Pietrosanti, S., Luque, A., Harrison, I., Holderbaum, W. and Becerra, V. (2016) Net Energy Savings in Rubber Tyred Gantry Cranes Equipped with an Active Front End. Environment and Electrical Engineering Conference, June 2016.

[11] Johnson, M. and Moradi, M.(2005) PID Control , N ew Ideentification and Desgin Methods. Springer. ISBN-10:1-85233-702-8, ISBN-13:978-1-85233-702-5, 2005.

[12] AboGaleela, M., El-Marsafawy, M., El-Sobki, M. (2013). Optimal Scheme with Load Forecasting for Demand Side Management (DSM) in Residential Areas. Energy and Power Engineering . doi:10.4236/epe.2013.54B171 Published Online July 2013.

[13] Bennett, C., Stewart, R. and Lu, J. (2015). Development of a three-phase battery energy storage scheduling and operation system for low voltage distribution networks. Applied Energy. Volume 146, 15 May 2015, Pages 122–134, 15 May 2015.

[14] Zhang, Y., Liu, B., Zhang, T. and Guo, B. (2014). An Intelligent Control Strategy of Battery Energy Storage System for Microgrid Energy Management under Forecast Uncertainties. International Journal of Electrochemical Science. Vol. 9, 2014.

[15] Reihani, E., Motalleb, M., Ghorbani, R. and Saoud, L. (2016). Load peak shaving and power smoothing of a distribution grid with high renewable energy penetration. Renewable Energy. Volume 86, Pages 1372–1379, February 2016.

[16] Amini, M., Kargarian, A. and Karabasoglu, O. (2016). ARIMA-based decoupled time series forecasting of electric vehicle charging demand for stochastic power system operation. Electric Power Systems Research. Volume 140, Pages 378–390, November 2016.

[17] Saadat, H. (2010). Power System Analysis, Third Edition. PSA publishing . ISBN: 978-0-9845438-0-9, 2010.

[18] Dogan, A., Kuzlu, M., Pipattanasomporn, M., Rahman, S. and Yalcinoz, T. (2015). Impact of EV Charging Strategies on Peak Demand Reduction and Load Factor Improvement . Electrical and Electronics Engineering (ELECO), 9th International Conference, 26-28 Nov. 2015.

[19] Douglass, P. , Garcia-Valle, R., Østergaard, J. and Tudora, O. (2014). Voltage-Sensitive Load Controllers for Voltage Regulation and Increased Load Factor in Distribution Systems. IEEE Transactions On Smart Grid . VOL. 5, NO. 5, September 2014.

[20] Sabihuddin, S. , Kiprakis, A. and Mueller, M. A Numerical and Graphical Review of Energy Storage Technologies. Energies 2015, 8(1), 172-216; doi:10.3390/en8010172