TAMPERE POLYTECHNIC - UNIVERSITY OF APPLIED SCIENCES
Electrical Engineering Study Program
Electrical Power Engineering

Engineering Thesis

Maiju Tuomi

VARIABLE SPEED GENERATOR – A WAY TO LOWER FUEL CONSUMPTION OF A STRADDLE CARRIER

Thesis Supervisor	MSc Lauri Hietalahti
Commissioning Company	Kalmar Industries, Supervisor Jari Mäkelä

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ABSTRACT

The object of this thesis was to find out how a variable speed generator would lower the fuel consumption of a Kalmar straddle carrier. The research started by trying to locate companies that manufacture variable speed generators and to find out what kind of technology was used. A possible working cycle for a straddle carrier was created and the power required from different operating functions calculated. Same calculations were made on the future concept with a variable speed generator. By comparing the results of the present and future concept it was found that about 10% savings in fuel consumption could be achieved. These figures are only suggestive because straddle carriers work very differently in different ports i. e. the standby time of a straddle carrier and the number of containers handled per hour vary. The information the manufacturing companies were able to give out about their variable speed generators was not informative enough for Kalmar Industries’ purpose. More research will be done on this subject since the calculations showed that significant savings in fuel economy could be reached.

TAMPEREEN AMMATTIKORKEAKOULU
Sähkötekniikan koulutusohjelma
Sähkövoimatekniikka
Tuomi, Maiju

Konttilukin polttoaineen kulutuksen alentaminen muuttuvakierroksisen generaattorin avulla

Tutkintotyö 36 sivua + 4 liitesivua
Työn ohjaaja DI Hietalahti Lauri
Työn tilaaja Kalmar Industries Ltd, valvojana Jari Mäkelä
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Hakusanat diesel, energia, magnetointi, muuttuvakierroksinen generaattori, konttilukki, polttoaineenkulutus

TIIVISTELMÄ

Tutkintotyön tavoitteena oli selvittää kuinka käyttämällä muuttuvakierroksista generaattoria konttilukissa voisi alentaa polttoaineen kulutusta. Aluksi etsittiin yrityksiä, jotka valmistavat muuttuvakierroksisia generaattoreita tarkoituksena ottaa selville eri tekniikoista, joita valmistajat käyttävät. Konttilukille luotiin kuvitteellinen toimintasykli ja eri toiminnoille laskettiin niiden tarvitsema teho. Samanlainen sykli luotiin koneelle jossa olisi käytössä muuttuvakierroksinen generaattori. Näiden syklien mukaisia polttoaineenkulutuksia vertaamalla, käyttämällä muuttuvakierroksista generaattoria perinteisen kestomagnetoidun tahtigeneraattorin sijasta, päästäisiin noin 10% pienempään polttoaineen kulutukseen. Laskennalliset tulokset olivat kuitenkin vain suuntaa antavia, sillä todellinen kulutus riippuu täysin satamasta, käsiteltävien konttien määrästä ja seisonta ajoista. Yritykset, joihin otettiin yhteyttä, eivät pystyneet tarjoamaan tarpeeksi konkreettista tietoa generaattoreistaan joten tutkimus tältä osin jäi vielä vajaaksi. Laskelmat kuitenkin osoittivat, että muuttuvakierroksisen generaattorin avulla saavutettaisiin merkittäviä säästöjä polttoainekustannuksissa, joten tutkimustyötä tullaan jatkamaan.

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LIST OF SYMBOLS USED

A	Area
AVR	Automatic Voltage Regulator
B	Fuel consumption
b_e	Fuel consumption
C	Drag coefficient
η	Efficiency coefficient
E_k	Kinetic Energy
E_{mv}	Voltage created by a magnetic current
ESC	Kalmar EDRIVE Straddle Carrier
ESC W	Kalmar EDRIVE Straddle Carrier with fully electrical drive functions
F_{air}	Motion resisting air resistance
F_{cons}	Fuel consumption
F_{roll}	Motion resisting force of rolling friction
g	Acceleration due to gravity
K	Kinetic energy
I_r	Magnetic current
m	Mass of a particle
Φ_m	Magnetic flux
ρ	Density of air
PMG	Permanent Magnet Generator
RMI	Remote Machine Interface
RTG	Rubber Tyre Gantry Crane
μ	Coefficient of rolling friction
v	Velocity
VSG	Variable Speed Generator

1 INTRODUCTION

The objective of this thesis is to find out how much a variable speed generator can lower the fuel consumption of a Kalmar straddle carrier. Customers are always interested in lowering the operating costs, but they also need to now that the product maintains its efficiency. At the moment, Kalmar straddle carriers are as efficient as they can in means of safety but to keep up with the market Kalmar needs to think of ways to improve their products.

A straddle carrier spends a big part of its working hours waiting and queuing but it also needs to do fast accelerations and drive at full speed with a full load. The conventional fixed speed generator used at the moment rotates at a constant rotational speed of 1800 rpm. A variable speed generator is able to vary the rotational speed from about 800 rpm to 2200 rpm. This thesis is about finding out how much output power is required during different operating functions such as driving at a constant speed, hoisting a container and when the straddle carrier is on standby. The idea is to calculate the fuel consumption when using a variable speed generator and compare it to the fuel consumption at the moment. A variable speed generator is new technology so a part of this thesis is to find out which companies manufacture such generators and what is the technology used.

Since it is important for the customer to keep the operating costs as low as possible and to keep the port as environmentally friendly as possible Kalmar will also do research on energy storage. It would be a way to use the energy being released during lowering the container and decelerating. In this thesis, there are calculations on the amount of energy that could be stored but the actual research on the energy storages will be done in the near future by Kalmar Industries.

2 KALMAR INDUSTRIES

2.1 General Information of Kalmar Industries

Kalmar Industries is a company that manufactures container and material handling products. The products are manufactured in Sweden, Finland, the Netherlands, the USA and China. Products include ship-to-shore cranes, harbour cranes, yard cranes, shuttle and straddle carriers (figure 1), reachstackers, heavy lift trucks and terminal tractors. Kalmar also provides services such as preventive maintenance, rental, financing, logistics advice, complete fleet management and spare parts. /6/

Figure 1 Kalmar ESC W Straddle Carrier /6/

Kalmar Industries is a part of the Cargotec group whose two other business sectors are Hiab and MacGREGOR. Cargotec is the worlds leading cargo handling solutions provider in ships, ports, terminals and local distribution. Cargotec's turnover in 2005 was 2,3 billion Euro and it had 7 500 employees in total. /6/

Kalmar Industries' turnover in 2005 was 1,1 billion euros and about 3200 employees. In Tampere, Kalmar has 730 employees. /6/

The factory in Härmälä started in 1936 building aircrafts and in ten years it became a part of Valtion Metallitehdas, Valmet. The factory focused on manufacturing industrial handling equipment. The material handling department became the main department of the company. The company has changed its name and owners during the past decades but it still is the world's leading company in material handling industry. It has been known as Kalmar Industries since 2002. /6/

2.2 The Straddle Carrier Family

The 7th generation Straddle Carrier Family includes four straddle carriers.

- Kalmar CSC Straddle Carrier
- Kalmar EDRIVE ESC Straddle Carrier
- Kalmar EDRIVE ESC W Straddle Carrier
- Kalmar SCH Shuttle Carrier

All of them share the same modular design system and most of the components are the same. This offers higher reliability and better technical and spare parts support within the Kalmar sales and support network. /10/

Kalmar CSC Straddle Carrier is the most common straddle carrier in the world. There are options of 3-high and 4-high versions with a Smoothlift hoist system with a lifting capacity of either 40 or 50 tons. /10/

Kalmar EDRIVE ESC Straddle Carrier offers 20% lower fuel consumption, lower operating costs, better acceleration and smoother operations. /10/

Kalmar EDRIVE ESC W Straddle Carrier like ESC model with full AC hoist and drive functions. It offers the customer an environmentally friendly option with less maintenance. /10/

Kalmar SCH Shuttle Carrier is for transporting the containers between yard stacking cranes (i.e. RTG) and ship-to-shore cranes. /10/

3 GENERATORS

3.1 Synchronous Generator

A synchronous generator is an electrical machine that changes mechanical energy to electrical energy and feeds it to the electrical power network. The mechanical structure of the generator depends on the power source. A diesel engine can function as a power source when using generator as a reserve capacity. In power plants, turbines are being used as the power source. /2/

The rotation rate n of a synchronous generator depends on the frequency f of the network and the pole pair p of the generator

$$n = 60\frac{f}{p} \tag{1}$$

where n is the rotation rate of the generator [rpm]
f is the frequency of the network [Hz]
p is the pole pair of the generator

Reserve capacity generators are either salient pole or non-salient pole machines depending on the rotors mechanical structure (figure 2). Salient pole machines are used when the rotational speed is slow (75 – 500 rpm) and non-salient pole machines when higher speeds are used. /2/

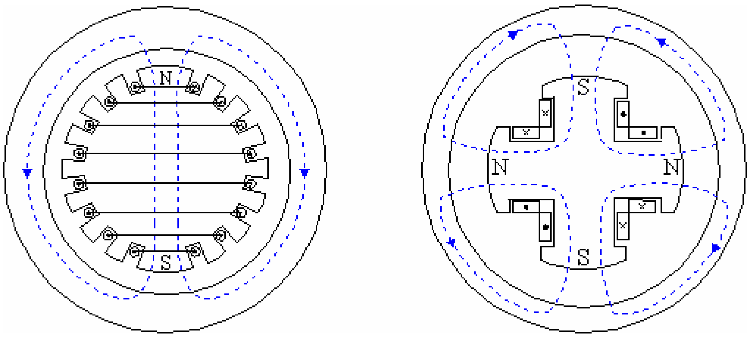

Figure 2 Structure of non-salient (left) and salient pole machines (right) /25/

Open circuit operation

Synchronous generator is on an open circuit operation when there is not any load current on the stator. DC current must be fed to the rotor winding to create a magnetic flux Φ or there needs to be permanent magnets on the rotor. When the amount of load on the generator increases the voltage E_m decreases. To keep the output voltage on a set value, more excitation current I_m needs to be fed to the rotor winding. This increases the magnetic flux which increases the output voltage as shown in equation 2. Only the magnetic flux can vary since the other factors are constant. /25/

$$E_m = \frac{2\pi}{\sqrt{2}} fN\Phi \approx 4{,}44 f_k fN\Phi \qquad (2)$$

where E_m is the phase voltage [V]

f is the frequency

N is the number of phase winding

Φ is the magnetic flux

The output voltage E_m changes in function of the magnetic current I_m as shown in figure 3. /2/

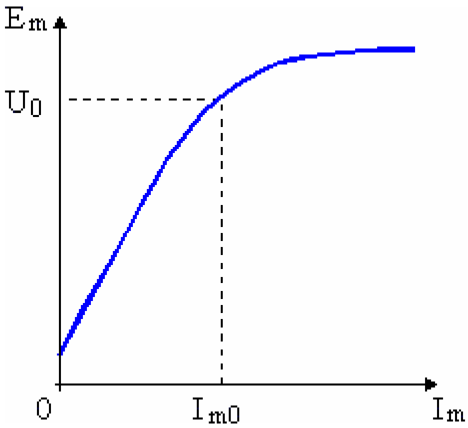

Figure 3 The voltage in function of the magnetic current I_m (U_0 and I_{m0} are the nominal values) /25/

Excitation

A synchronous machine needs a magnetic field to create an output voltage. Based on how the magnetic field is created in the machine, synchronous machines are divided into two main categories: slip ring machines and brushless generators. /2/

In the slip ring generator, excitation current I_m is being fed to the rotor winding through slip rings made of brass or steel. The magnetic power is taken from a separate DC source or from an AC source. When using an AC source to create the excitation current there needs to be a rectifier within the system. /2/

On the same axle with a brushless generator there is a small AC generator that creates the excitation current. A generator needs a control for the excitation for example an automatic voltage regulator (AVR). It keeps the generator's voltage at a set value regardless of load, temperature or frequency variations within certain limits. In figure 4, there is a picture of a brushless generator with an AC permanent magnet generator (PMG) to create the excitation power. /9/

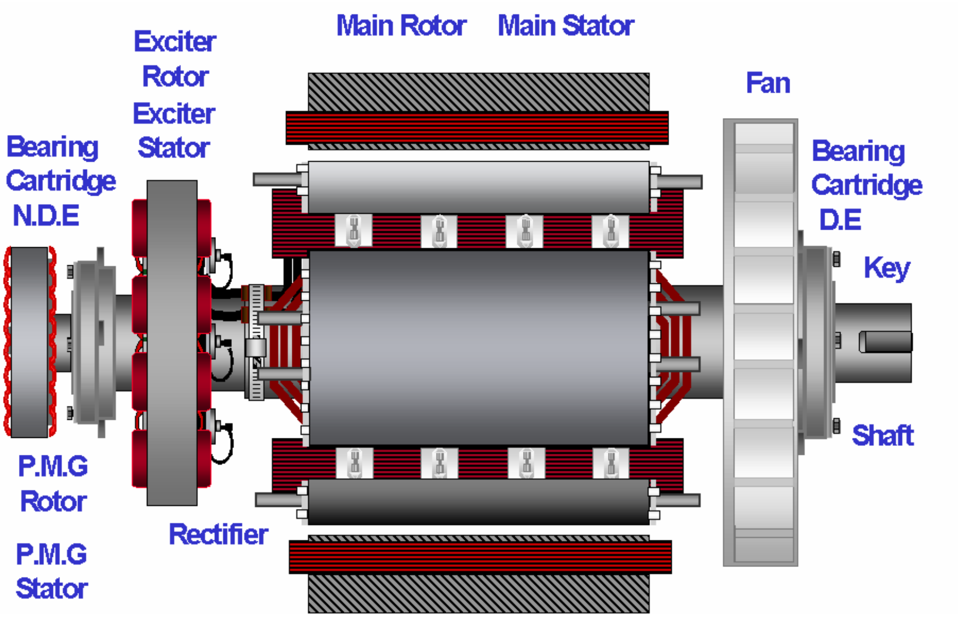

Figure 4 Mechanical structure of a synchronous PMG /21/

3.2 Power Unit in Kalmar Straddle Carrier

In Kalmar EDRIVE Straddle Carrier (ESC W) electricity is produced by a brushless generator (Stamford 420 kVA) and the mechanical energy for it is fed by a diesel engine (Scania 336 kW). In figure 5, the image shows the system in principle. There is an AC source that supplies power for the excitation of the generator through a rectifier. This current is rectified and controlled by the AVR, and fed to the field winding of the exciter. /1;10/

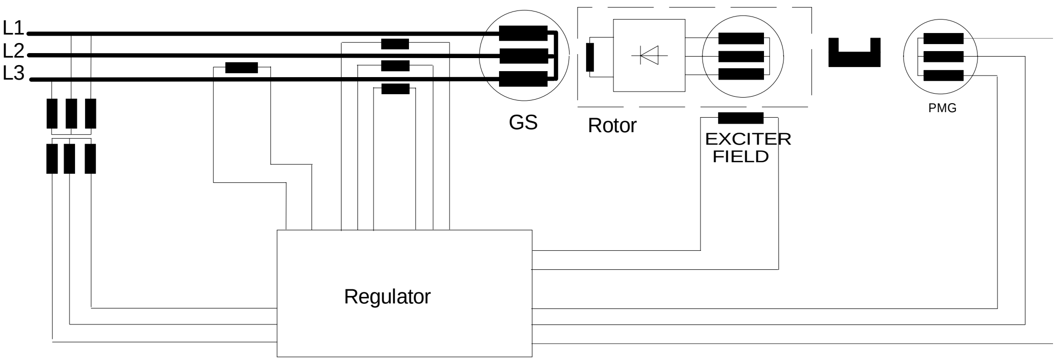

Figure 5 Basic voltage control loop, excitation from PMG /1/

3.3 A Variable Speed Generator

A Variable speed generator is different from a conventional fixed speed synchronous generator because it reacts to the load through a control unit. Conventional engine driven generators run at a fixed speed. A variable speed generator engine runs at the minimum RPM needed to produce the required output. The engine varies its rotational speed based upon the amount of load on the generator output. The engine runs slower when the demand is less and lowering the engine rpms indicates that less fuel is consumed and the acoustic noise is significantly lower. /19/

In a permanent magnet VSG, the magnets are on the rotor so excitation is not needed as in a conventional synchronous generator. A complete set including a diesel engine and a VSG needs a control unit that regulates both the diesel engine and the generator.

3.4 Variable Speed Generators in Wind Power Production

A common wind power plant includes a turbine rotating at a constant speed, a gearbox and an induction generator. The rotational speed of a turbine is about 10–30 rpm whereas a generator rotates at 1500 rpm so a gearbox is needed. The constant slow rotational speed of the turbine needs to be increased for the induction generator. Research has been made on how wind power production could be more efficient in means of capturing more energy. Using a variable speed instead of a constant rotational speed turbine, the captured energy can increase by about 6 to 15 percent. /18/

By using a direct driven system the turbine is directly connected to a slow speed generator so a gearbox is not needed. This means increased efficiency and reliability because a gearbox needs maintenance, less noise and less weight at the top. /18/

By using a synchronous generator at variable speed, a higher efficiency and power factor is achieved but it is impossible to connect a synchronous generator directly to the grid because the output power is not constant. It is possible to connect an induction generator directly to the grid but a large slip is needed to allow the rotational speed changes and that leads to poor efficiency. A frequency converter in the system enables the use of a synchronous generator by being able to keep the output frequency constant while the rotational speed can vary within certain limits. /18/

Tampere University of Technology has done a study on the possibilities of a system with a variable speed stall regulated turbine, a direct driven slow speed synchronous generator (axial flux permanent magnet generator) and a frequency converter connected to the grid. The generator was chosen since it has high torque, which is typically required from a slow speed generator. /18/

Axial Flux Permanent Magnet Generator

Electrical machines can be divided into three main categories based on their magnetic flux; radial flux, axial flux and transverse flux machines. The radial flux machines are the most common ones out of these three. The structure of an axial flux generator enables a large number of poles thus being suitable for wind power production. /18/

There are two main types of axial flux generators; machines with two rotor discs rotating around the stator and machines which have two stator discs and a rotor rotating between them. The most efficient design has a large radius but a small radial length since a large radius leads to a high torque. Studies have shown that the toroidal stator machine with two rotor discs and a stator in between is more cost efficient. /18/

In this type of machine, there are permanent magnets on both sides of the stator on the iron rings of the rotors so the rotors rotate around the stator. There is no need for any external magnetization and the machine is nearly maintenance free since there are no slip rings. In this kind of layout the outer radius is very large so it is challenging to try to keep the three disks close to one other and to keep the air gap length constant. /18/

3.5 A Variable Speed Integrated Generator by Newage Avk Seg

Stamford Power Generation offers variable speed integrated generators (V.S.I.G) with an output power from 5 kVA to 100 kVA. The output voltage is selectable within 110 V to 480 V at 50 or 60 Hz. The concept includes an engine, a generator and a power electronics converter as shown in figure 6. The variable speed technology enables maximum fuel economy for a specific load so it is an environmentally friendly option with short term economical advantages. The physical size of the package is smaller than with a conventional fixed speed generator. Due to the smaller rotational speed, the engine life is increased and the acoustic noise is lower. /22/

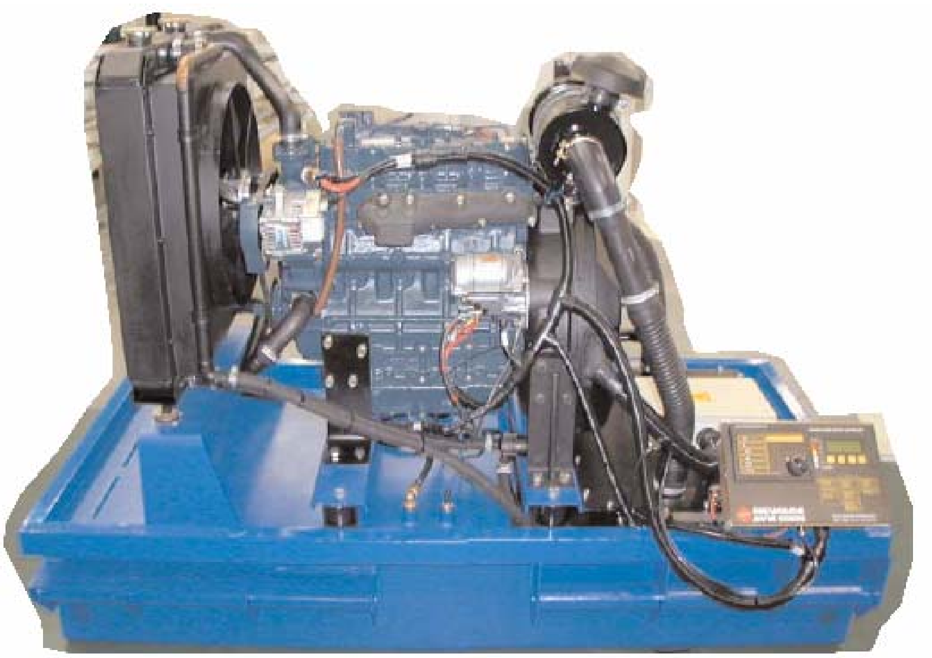

Figure 6 Stamford V.S.I.G /22/

The power flow principle of the V.S.I.G. is shown in figure 7. The engine driven generator feeds variable frequency, three phase power to the power electronics converter. This supplies fixed frequency single or three phase power to the consumer. The power electronics controller varies the engine speed according to the consumer load. /22/

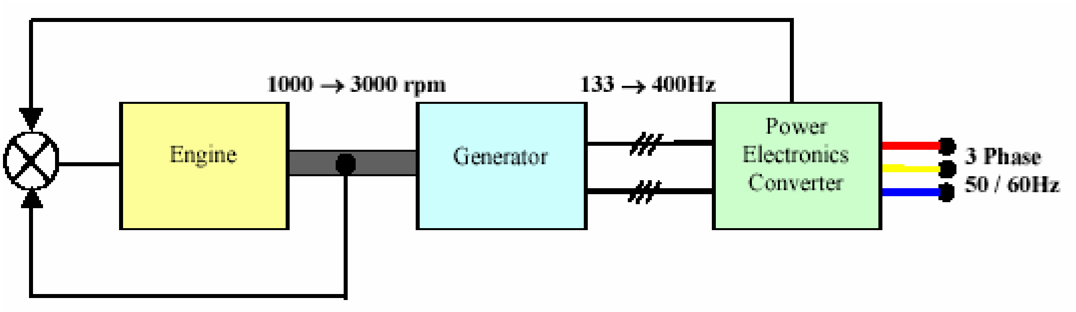

Figure 7 Power flow principle in Stamford V.S.I.G. /22/

The generator is a 16 pole, axial field, brushless permanent magnet type machine. It is practically maintenance free since there are no slip rings or brushes required. The rotor is constructed from two plates on which the 16 magnet poles are located. There is a wound toroid stator with slotless airgap winding. Figure 8 shows where the magnets are placed on the rotor plates. /23/

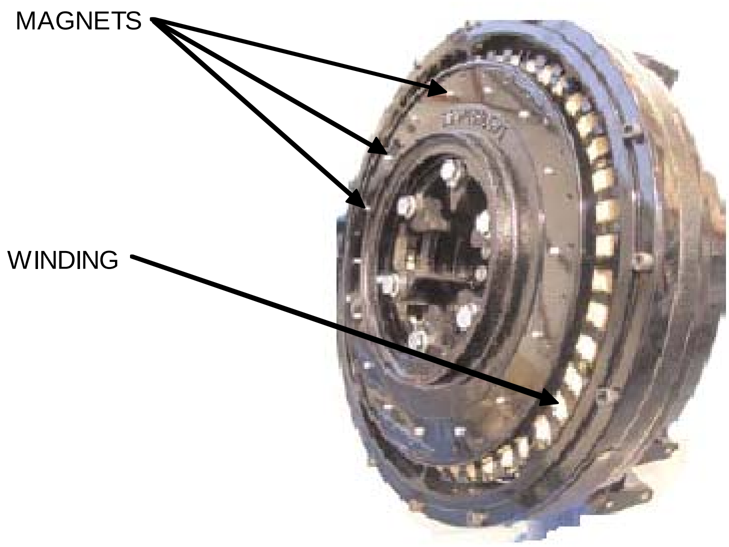

Figure 8 Stamford V.S.I.G. /22/

4 KALMAR ESC STRADDLE CARRIER – ELECTRICAL SYSTEM

4.1 Seventh Generation ESC Carriers

There are two types of 7th generation ESC Carriers: ESC (hydraulic Smoothlift hoisting system) and ESC W (electrical hoisting with winch). This thesis will focus on the fully electrical model ESC W. In figure 9 there is a picture of an ESC W Straddle Carrier and the main components listed below. In appendix 1, there is a main diagram for more detailed information. /9/

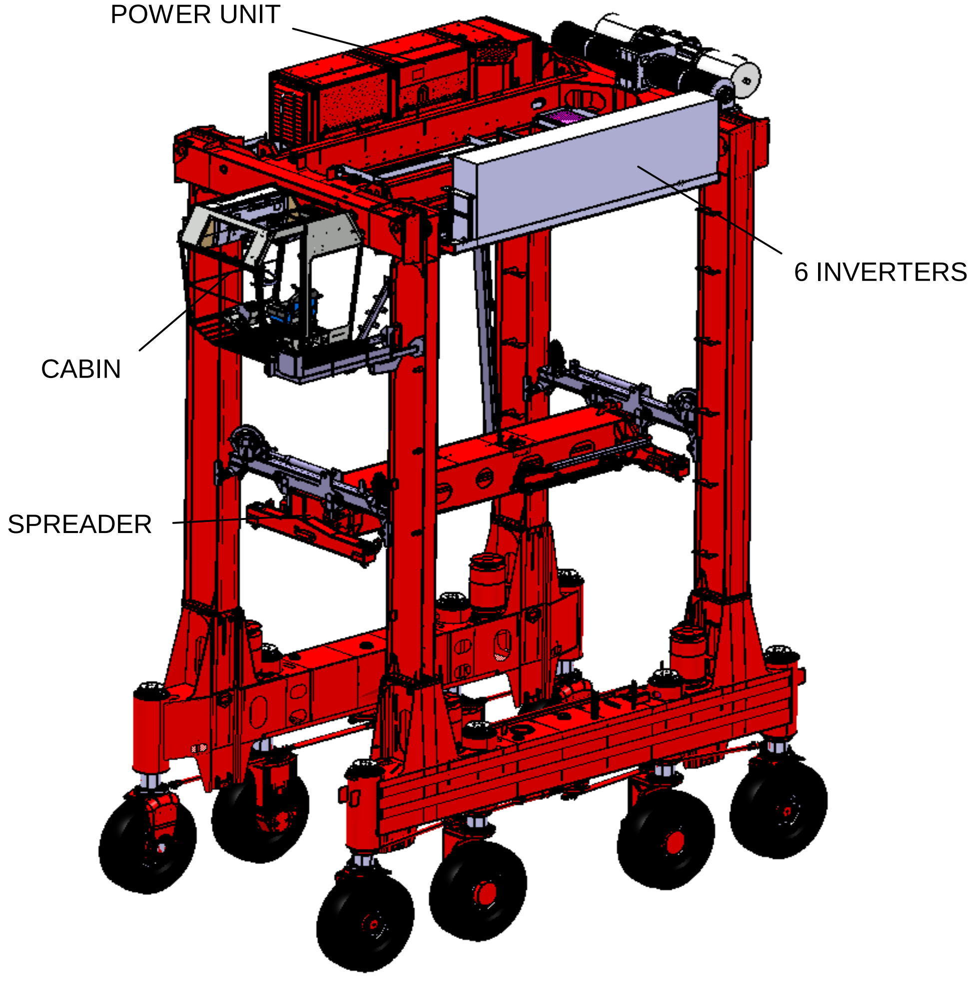

Figure 9. Kalmar ESC W Straddle Carrier

Power Unit (Figure 10):

- Stamford Generator 420 kVA, 440 V, 60 Hz
- Scania Diesel Engine 336 kW + 10 % short time overload, idle speed 1000 rpm, working speed 1800 rpm
- Diesel Control Unit

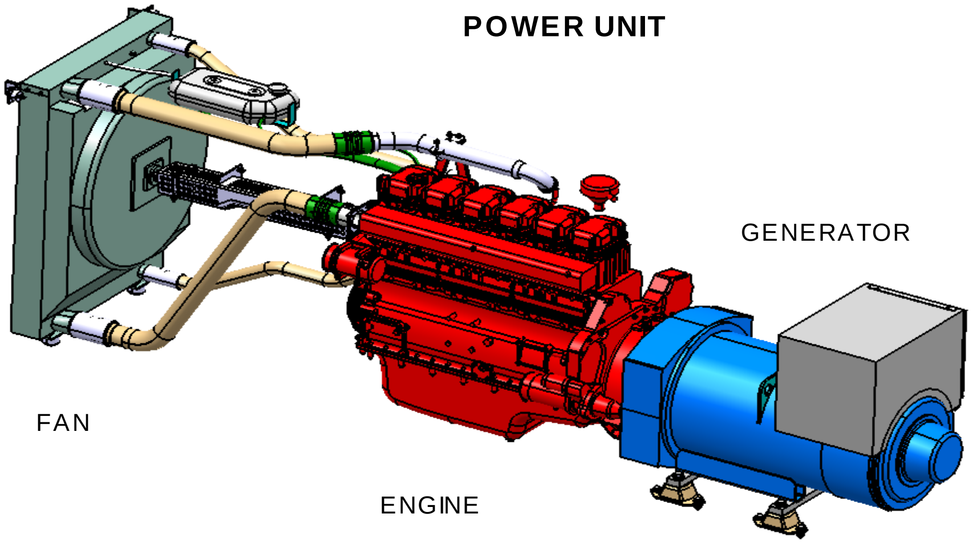

Figure 10 The power unit of a straddle carrier

Upper Frame EU440:

- 4 pcs 55 kW Inverters
- 2 pcs 75 kW Inverters

Motors:

- 4 pcs 55 kW Drive Motors
- 2 pcs 75 kW Hoist Motors
- 2 pcs 170 kW Braking Resistors and Brake Choppers

The dimensions of Kalmar Edrive Straddle Carrier ESC W 350 are in table 1 and a coherent picture of a ESC W in figure 11.

Table 1 ESC W dimensions /12/

Nominal dimensions	[mm]
Max overall height	13080
Lifting height max	9200
Overall width	5000
Inside clear width	3500
Overall length	9200
Pick-up height min	500
Turning radius inside	3630
Turning radius outside	9550

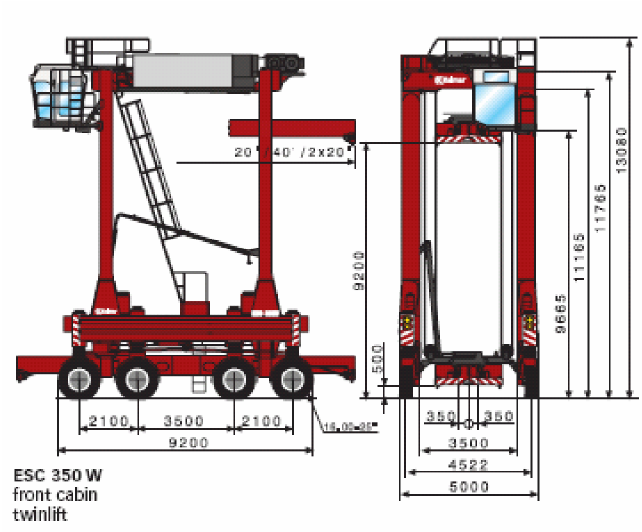

Figure 11 Dimensions of Kalmar ESC W /7/

5 MANUFACTURING COMPANIES

5.1 Information Received from Different Manufacturers

There are lots of companies that manufacture generators around the world. It is quite challenging to look for the ones who manufacture variable speed generators. Because it is such a new technology, companies are not necessarily advertising their variable speed generators. The few manufacturing companies found were contacted and some of them replied to an enquiry that was sent to them on behalf of Kalmar Industries. The enquiry included the information in chapter 5.2.

The received information about the generators was very general and the manufacturers were not able to send anything specific about the technology used in their products. Most companies found are from America so the distance makes it more difficult to keep in contact with the manufacturer. The companies found from the Internet were not previously known to Kalmar. So far, the most detailed information Kalmar has is about Stamfords V.S.I.G which was introduced in chapter 3.5.

Companies contacted

A list of all the companies who the enquiry was sent to /3;4;5;12;13;17;24;25/:

- Light Engineering, Indianapolis, USA
- Marathon Electric Manufacturing Corp, Wausau Wisconsin, USA
- Pronto Power, Sacramento, California, USA
- Turbo Genset, West Drayton, Middlesex, UK
- Bugatti Marine, Florida, USA
- Glacier Bay, Oakland, California, USA
- WEG S.A., Jaraguá do Sul, SC, Brazil
- GE Energy, Atlanta, USA

More detailed descriptions of the companies, how they replied and their contact details are in appendix 2.

5.2 Technical Requirements for Future Concept

The enquiry sent to the manufacturing companies presented in chapter 5.1 is in figure 12. It includes the main requirements but at this point of the whole research it is more important to find out what companies have to offer instead of finding the right one for a straddle carrier.

It is in Kalmar Industries best interests to start testing a variable speed generator while keeping the other components of the whole system the same. The converters being currently used are setting requirements for the generator in terms of voltage and frequency limits. Even though the rotational speed range only needs to be 1380 – 1920 rpm, Kalmar wants information about generators that can vary the rotational speed within the limits specified in the enquiry.

Variable Speed Generator for a straddle carrier

Power	250 – 350 kVA
Voltage	440 VAC (325 – 525 V)
Frequency	60 Hz (46 – 64 Hz)
Rotational speed	800 – 2100 rpm
Rated power factor	0.8
Insulation	Class H
Ambient temperature	min 50°C
Protection	minimum requirement IP22, IP34 preferred
cos φ	0.95

Figure 12 Enquiry sent to manufacturing companies by Kalmar Industries

6 POWER EVALUATION IN ESC

6.1 Theory about Automotive Power

Two forces oppose the motion of a moving vehicle: rolling friction F_{roll} and air resistance F_{air}. /28/

$$F_{roll} = \mu_r \cdot mg \quad (2)$$

where F_{roll} is the rolling friction
μ_r is the coefficient of rolling friction
m is the mass of a particle
g is acceleration due to gravitation

$$F_{air} = \frac{1}{2} C A \rho v^2 \quad (3)$$

where F_{air} is the air resistance
C is the drag coefficient that depends on the shape of the vehicle
A is the area of a vehicle
ρ is the density of air
v is the speed of the vehicle

The power P that an engine needs to overcome this resistance can be calculated by combining these two forces and multiplying it by the constant speed v. /28/

$$P = (F_{roll} + F_{air})v \quad (4)$$

where P is the power
v is the speed of the vehicle

When hoisting a particle into the air, energy is being stored in the system. When lowering the particle, potential energy is being released so in theory that energy could be taken into storage. The power P needed to do the work can be calculated when we have the systems mass m and the hoisting velocity v. /28/

$$P = mgv \qquad (5)$$

where m is the mass of a particle
g is acceleration due to gravitation
v is the hoisting velocity of a particle

The kinetic energy E_k of a particle depends on the particle's mass and velocity. /28/

$$E_k = \frac{1}{2}mv^2 \qquad (6)$$

where E_k is the kinetic energy of a particle
m is the mass of a particle
v is the velocity of a particle

Energy is being released during deceleration and the quantity is the difference between the final kinetic energy K_2 and the initial kinetic energy K_1. This energy can be stored. /28/

$$W = K_1 - K_2 \qquad (7)$$

where W is the work done by the net force on a particle
K_2 is the final kinetic energy
K_1 is the initial kinetic energy

Power means work done in a certain time period. The average power P_{av} is the amount of work done divided by the time t. /28/

$$P_{av} = \frac{\Delta W}{\Delta t} \qquad (8)$$

where P_{av} is the power
ΔW is the amount of work done
Δt is the time it takes to do the work

6.2 Power Calculations of a Straddle Carrier

Using equations 2 – 8 mentioned in chapter 6.1, and the technical specifications of an ESC W 350 straddle carrier, in table 2, the power needed from the diesel engine, during different functions, can be calculated. Containers can weigh anything between 2 200 and 40 000 kg. The calculations have been made using an average weight of 25 000 kg. /12/

Table 2 Technical values used in the power calculations /12/

Dead Weight	62000 kg
Container Weight	25000 kg
Spreader weight	10000 kg
Overall length	9,2 m
Container height	2,9 m
Max travel speed 0t/25t	8,33 m/s
Hoisting speed 25t	0,4 m/s
Hoisting speed 0t	0,5 m/s
Lowering speed 0/25t	0,3 m/s
η_{tot}	0,85
P_{max}	350 kW
g	9,8 m/s^2
μ_r	0,02
C (depends on the shape)	0,5
A (area seen from the front)	38,88 m^2
ρ	1,2 kg/m^3

The theoretical power value needs to be divided by the operating efficiency factor η_{tot}. Except when releasing energy (lowering a container and decelerating) the operating efficiency must be taken into consideration by multiplying the theoretical value with the efficiency factor.

Generator η = 0,98

Rectifiers η = 0,99

Inverters η = 0,98

Motors η = 0,97

Mechanical gear ratio η = ~0,92

Operating efficiency η_{tot} = 0,85

In table 3, are the different possible functions of a straddle carrier and the calculated power needed to perform such functions. The power values for acceleration and simultaneous functions are 350 kW because that is the maximum momentary power available. The power values calculated for deceleration and lowering are for future concept in case an energy storage will be taken into consideration. In chapter 8, there is a short description of the research Kalmar Industries has done on them so far.

Table 3 Calculated power values for different functions

Function	P / [kW]	P / P_{max} [%]
Acceleration (25t)	350,0	100,0
Constant speed 20 km/h (25t)	113,7	32,5
Hoisting (25t)	177,6	50,7
Acceleration and Hoisting (25t)	350,0	100,0
Acceleration (0t)	350,0	100,0
Constant speed 20 km/h (0t)	81,7	23,3
Acceleration and Hoisting (25t)	350,0	100,0
Constant speed 30 km/h and Hoisting (25t)	350,0	100,0
On standby	35,0	10,0
Decelerating to a corner 10 km/h (25t)	-71,3	0
Decelerating to 0 km/h (25t)	-94,9	0
Lowering a container (25t)	-87,5	0
Decelerating to a corner 10 km/h (0t)	-101,4	0
Decelerating to 0 km/h (0t)	-135,3	0
Lowering a container (0t)	-25,0	0

In chapters 6.3 and 6.4, there are possible working cycles for a straddle carrier with the clarifying functions described above. The number of containers handled per hour can be anything up to around twenty. One of the created working cycles is with only six containers handled in an hour (chapter 6.4) and the other one with twelve containers (chapter 6.3). It depends a lot on the driver and his experience, how busy the port is and the structure of the port how many containers a straddle carrier can handle per hour.

A system called Remote Machine Interface (RMI) has been installed to a few straddle carriers. It is for getting online information from straddle carriers and it has been measured from some of the straddle carriers in Kotka that the average time that it takes to move a container from one place to another is between 317 and 329 seconds. The measured average is from containers handled between 1.1.2006 and 8.24.2006. These measured values are very close to the created cycle where 12 containers are handled per hour (chapter 6.3).

The time a straddle carrier is on stand-by is a significant part of the total working time. Measurements made with RMI show that the average standby times are between 20 - 50% of the total working hours. In chapters 6.3 and 6.4, the standby time is shown at the end of the cycle, but in practise it happens during all the functions while waiting for a ship to dock and queuing among other things.

6.3 Working Cycle when handling 12 containers per hour

In figure 13 there is the working cycle of a straddle carrier when handling 12 containers per hour.

1. Accelerating to 30 km/hr (0t)
2. Driving 30 km/hr (0t)
3. Decelerating from 30 km/hr to 0 km/hr (0t)
4. Picking up a container (25t) and hoisting 0,5 m
5. Accelerating to 30 km/hr (25t)
6. Driving 30 km/hr (25t)
7. Decelerating from 30 km/hr to 0 km/hr (25t)
8. Lowering 0,5m (25t)
9. Accelerating to 30 km/hr (0t)
10. Driving 30 km/hr (0t)
11. Corner (decelerating from 30 km/hr to 10 km/hr and accelerating from 10 km/hr to 30 km/hr)
12. Driving 30 km/hr (0t)
13. Decelerating from 30 km/hr to 0 km/hr (0t)
14. Picking up a container (25t) and hoisting 0,5m
15. Accelerating to 30 km/hr (25t)
16. Driving 30 km/hr (25t)
17. Driving and hoisting 2,9m (25t)
18. Decelerating from 30 km/hr to 0 km/hr (25t)
19. Lowering 0,5m (on another container) (25t)
20. On standby (33,4% of total working time)

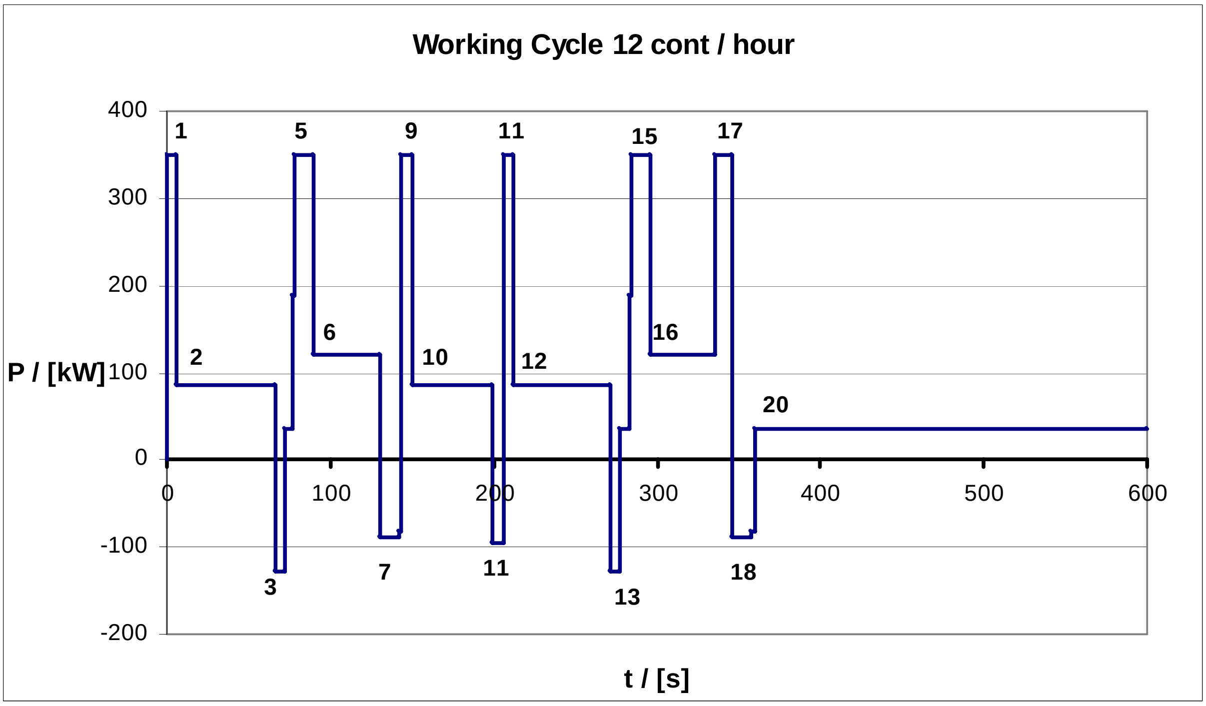

Figure 13 Working cycle of a straddle carrier (12 containers per hour)

6.4 Working Cycle when handling 12 containers per hour

In figure 14 there is the working cycle of a straddle carrier when handling 12 containers per hour.

1. Accelerating to 30 km/hr (0t)
2. Driving 30 km/hr
3. Curve (decelerating from 30 km/hr to 10 km/hr and accelerating from 10 km/hr to 30 km/hr)
4. Driving 30 km/hr (0t)
5. Decelerating from 30 km/hr to 0 km/hr (0t)
6. Picking a container (25t) and hoisting 0,5 m
7. Accelerating to 30 km/hr (25t)
8. Driving 30 km/hr (25t)
9. Corner (decelerating from 30 km/hr to 10 km/hr and accelerating from 10 km/hr to 30 km/hr)
10. Driving 30 km/hr (25t)
11. Driving and hoisting 5,8m (25t)
12. Decelerating from 30 km/hr to 0 km/hr (25t)
13. Lowering 3,4m (on another container) (25t)
14. Accelerating to 30 km/hr (0t)
15. Driving 30 km/hr (0t)
16. On standby (44,3% of total working time)

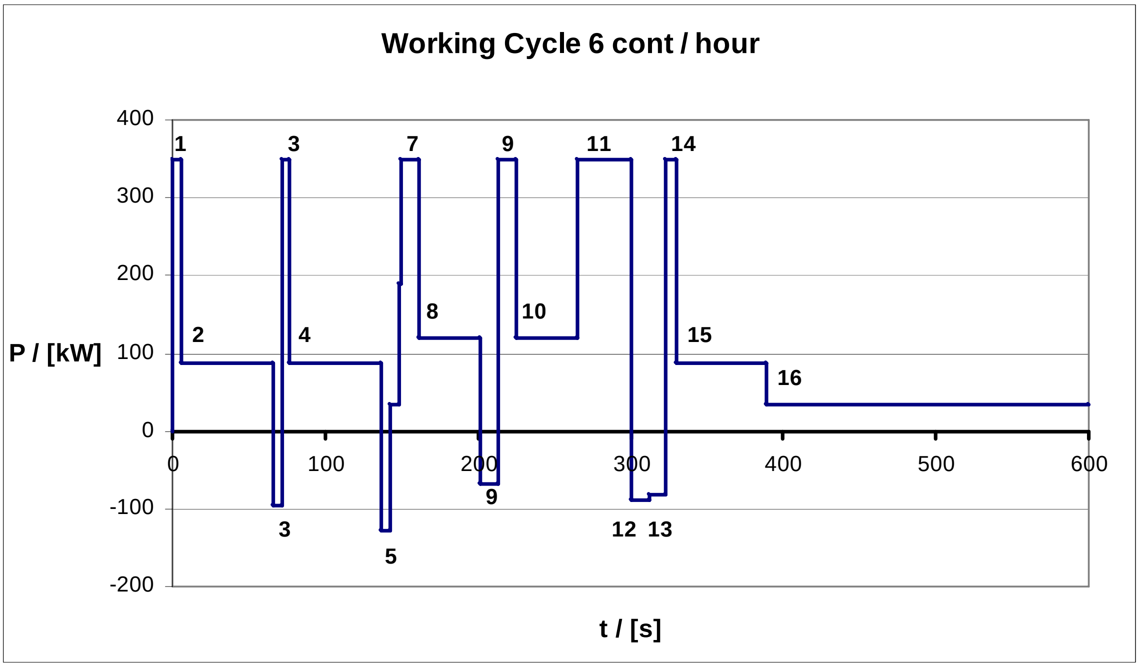

Figure 14 Working cycle of a Straddle Carrier (6 containers per hour)

7 FUEL CONSUMPTION ANALYSIS

7.1 Estimated fuel consumption with the present system compared with the consumption using a variable speed generator

The technical information of the diesel engine and the generator being used at the moment is in table 4.

Table 4 Technical specification of the generator and the diesel engine /12/

Stamford HCI 434F1	
Rated power kVA	420 kVA
Rated power kW	336 kW
Voltage	440 V
Frequency	60 Hz
Amps	551 A
RPM	1800
Enclosure	IP 22
Insulation	Class H
P. F.	0,8
Ambient temperature	40 °C

Scania 12 - litre engine	
Power	336 kW
Max power	370 kW
No. of cylinders	6 in line
Displacement	11,7 litres
Idle speed	1000 rpm
Working speed	1800 rpm

The amount of fuel needed to produce the required energy depends on the amount of electrical load. Kalmar has information on the engines fuel consumption which is shown in table 5 for the current system used and for the future concept. An engine's fuel consumption is normally given in g/kWh (b_e) but since the nature of this thesis is to do research on a specific working cycle of a straddle carrier the fuel consumption has been transformed to g/sec (B_1) by using formula 9. The l/hr (B_2) consumption has been calculated by using the information that the density of fuel is 840 kg/m^3. /11/

$$B(\text{g/sec}) = \frac{b_e(\text{g/kWh}) \cdot P(\text{kW})}{3600\,\text{sec}} \qquad (9)$$

The power a straddle carrier needs when it is on stand-by is about 35 kW but when using a VSG the losses are not as much because the fan is a significant part of the total. The required standby power would be about 25 kW with VSG. On the working cycles in figures 15a and 15b, the power is 35 kW but it has been taken in to consideration in the fuel consumption calculations as shown in table 5.

Table 5 Fuel consumption of ESC W 350 /11/

		Stamford HCI	VSG	Stamford HCI	VSG	Stamford HCI	VSG
P%	P / [kW]	b_e / [g/kWh]	b_e / [g/kWh]	B_1 / [g/sec]	B_1 / [g/sec]	B_2 / [l/hr]	B_2 / [l/hr]
100	350	218	217	21,19	21,10	90,83	**90,42**
50,7	177,6	223	217	11,00	10,71	47,15	**45,88**
32,5	113,7	226	210	7,14	6,63	30,59	**28,43**
23,3	81,7	235	208	5,33	4,72	22,86	**20,23**
10	35	240	-	2,33	-	10,00	**-**
7	25	-	220	-	1,53	-	**6,55**

In figure 15a the ascending curve shows the amount of fuel consumed over a period of ten minutes when two containers are handled. The curve shows that most savings are gained while a straddle carrier is on stand-by. In chapter 7.2, is an estimate of the economical savings that could be gained.

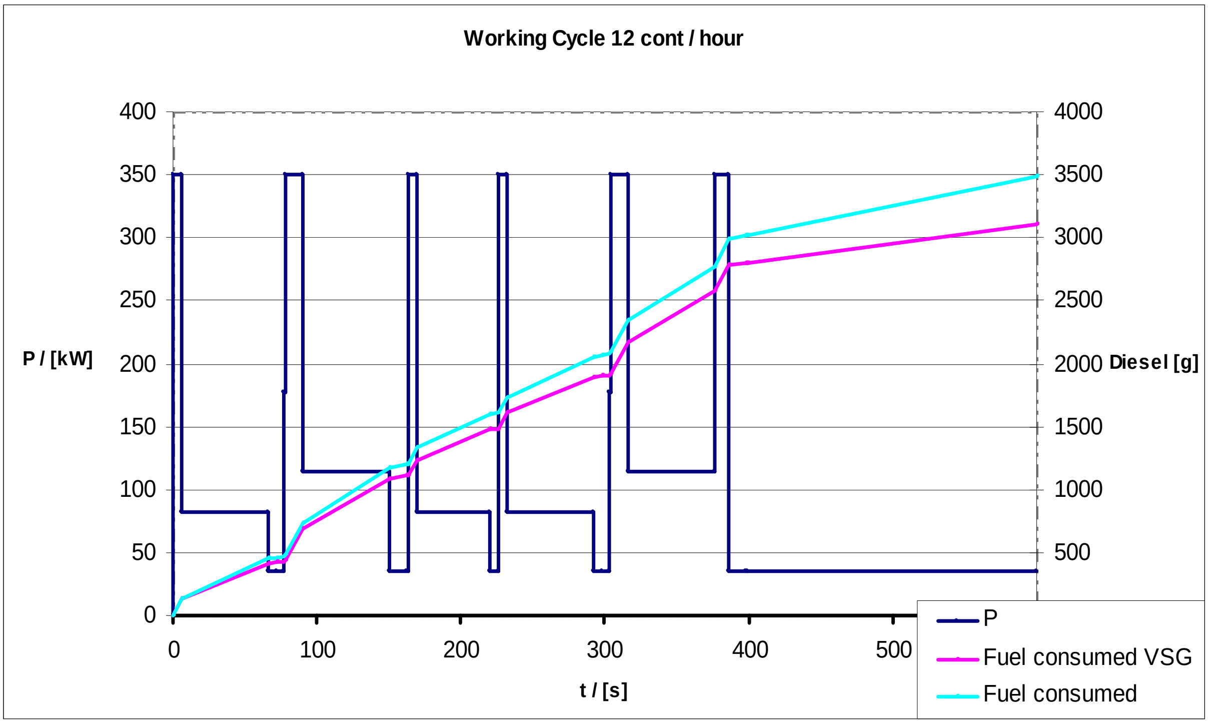

Figure 15a Fuel consumption curves with Stamford HCI and VSG when handling 12 containers per hour

In figure 15b the ascending curve shows the amount of fuel consumed over a period of ten minutes when one container is moved from one place to another.

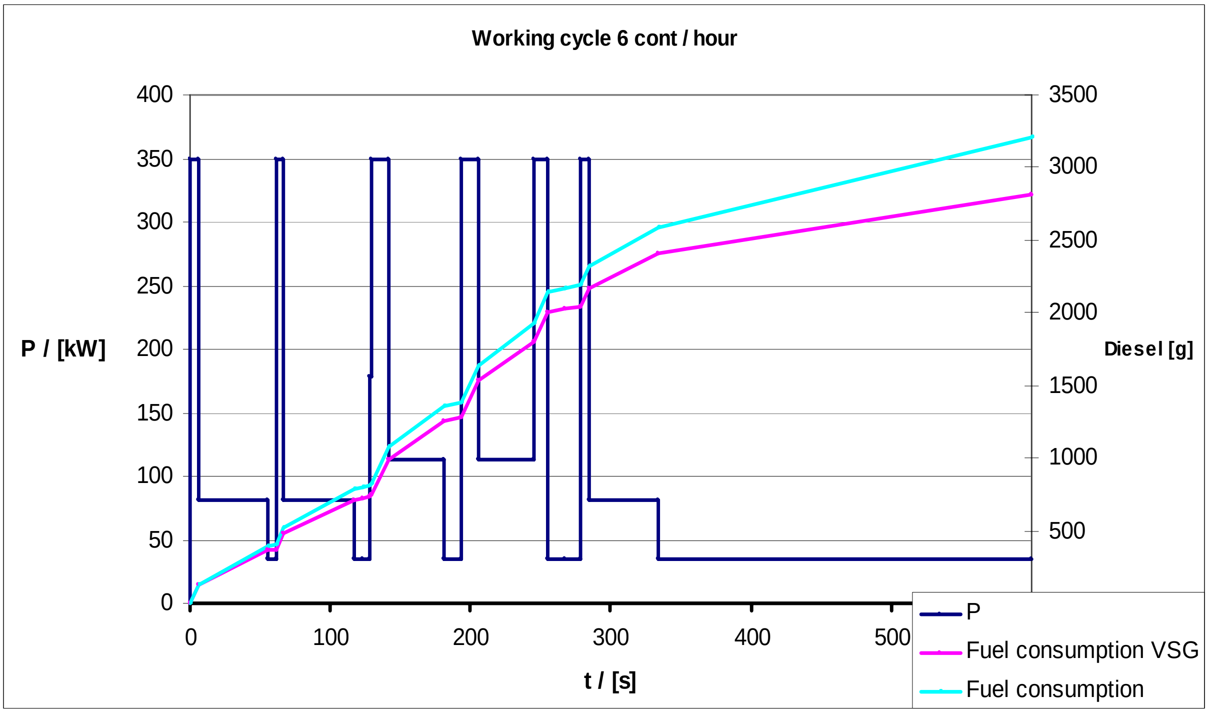

Figure 15b Fuel consumption curves with Stamford HCI and VSG when handling 6 containers per hour

The calculated fuel consumption figures in table 6 show that by using a VSG instead of a conventional fixed speed generator significant savings in fuel consumption could be achieved.

Table 6 Savings in total

	Stamford HCI B_2 / [l / hr]	VSG B_2 / [l/hr]	Savings [%]
12 cont per hour	24,91	22,22	**10,8**
6 cont per hour	22,90	20,09	**12,3**

7.2 Economical Savings

Calculations in chapter 7.1 show that the fuel consumption savings are around the calculated 10,8% and 12,3%. A straddle carrier in Belgium has about 5000 working hours per year and diesel costs about 1 euro per litre there. The savings in a year for the two working cycles are presented in table 7.

Table 7 Economical savings of a straddle carrier in a year

	hours per year	B / [l/hr]	€ per litre	€ per year	€ savings per year
12 cont per hour	5000	24,91	1	124550	**13 450**
12 cont per hour (VSG)	5000	22,22	1	111100	
6 cont per hour	5000	22,9	1	114500	**14 050**
6 cont per hour (VSG)	5000	20,09	1	100450	

8 ENERGY STORAGE

Energy storage makes it possible to reuse electrical energy. Kalmar Industries has approached a few companies that have found a way to store energy. Two types of storages were found – Flywheels and Ultra Capacitors. Companies are mostly prototyping but there are some already on the markets. /8/

Magnet-Motor manufactures a flywheel unit and it has been used in diesel electric urban busses. The manufacturer states the following:

“The magnetodynamic storage (MDS) is a flywheel storage unit with a vertical rotation axis. The rotor is a hollow cylinder primarily made of carbon fibre composite. For an optimum compact system design, the motor/generator (M/G) unit is integrated inside the hollow rotor. The MDS gains stored energy while the motor/generator unit runs as a motor, accelerating the rotor. The MDS feeds back energy when the M/G unit is switched to generator mode, thus reducing the rotor speed. /14/ “

The research done so far on the flywheels and ultra capacitor has given an idea of the capacities of the storages and some information of the prototype prices (table 8).

Table 8 General information on energy storages /8/

	Flywheels	Capacitors
Storage [MJ]	5,4 - 14	5,69 - 6,75
Peak Power [kW]	240 - 400	-
Protoype price [€]	80 000 - 150 000	45 000 - 100 000
Weight [t]	0,6 - 1,3	1 - 2,16

A system where energy could be reused is environmentally friendlier and it would lower the operating costs. More research of the energy storages will be done.

9 CONCLUSION

The object was to do research about variable speed generators; which companies manufacture such generators, what kind of technology is used and how would variable rotational speed lower the fuel consumption of a straddle carrier. The calculations based on the two created working cycles show that if a variable speed generator system would replace the current constant rotational speed system significant operational savings could be achieved. The calculated fuel consumption savings are about 10%.

The calculations are not accurate since the information about fuel consumption and about the operating efficiency is very general – not from manufacturer's documents. The power calculations do not take wind into consideration and the assumption is that a straddle carrier drives on the flat. Temporary rises on the ground or wind were not taken into consideration since the focus of this thesis was on the variable speed generator technology and how it effects on the fuel consumption.

In an ideal situation at least one of the companies contacted would have offered detailed technical information of a variable speed generator with the required output so more specific calculations could have been made. The technical information, offered by the manufacturers, was not informative enough for Kalmar Industries purpose so further research is needed. It is not only the operating costs but also the environmental issues that concern around the world which makes this research topical.

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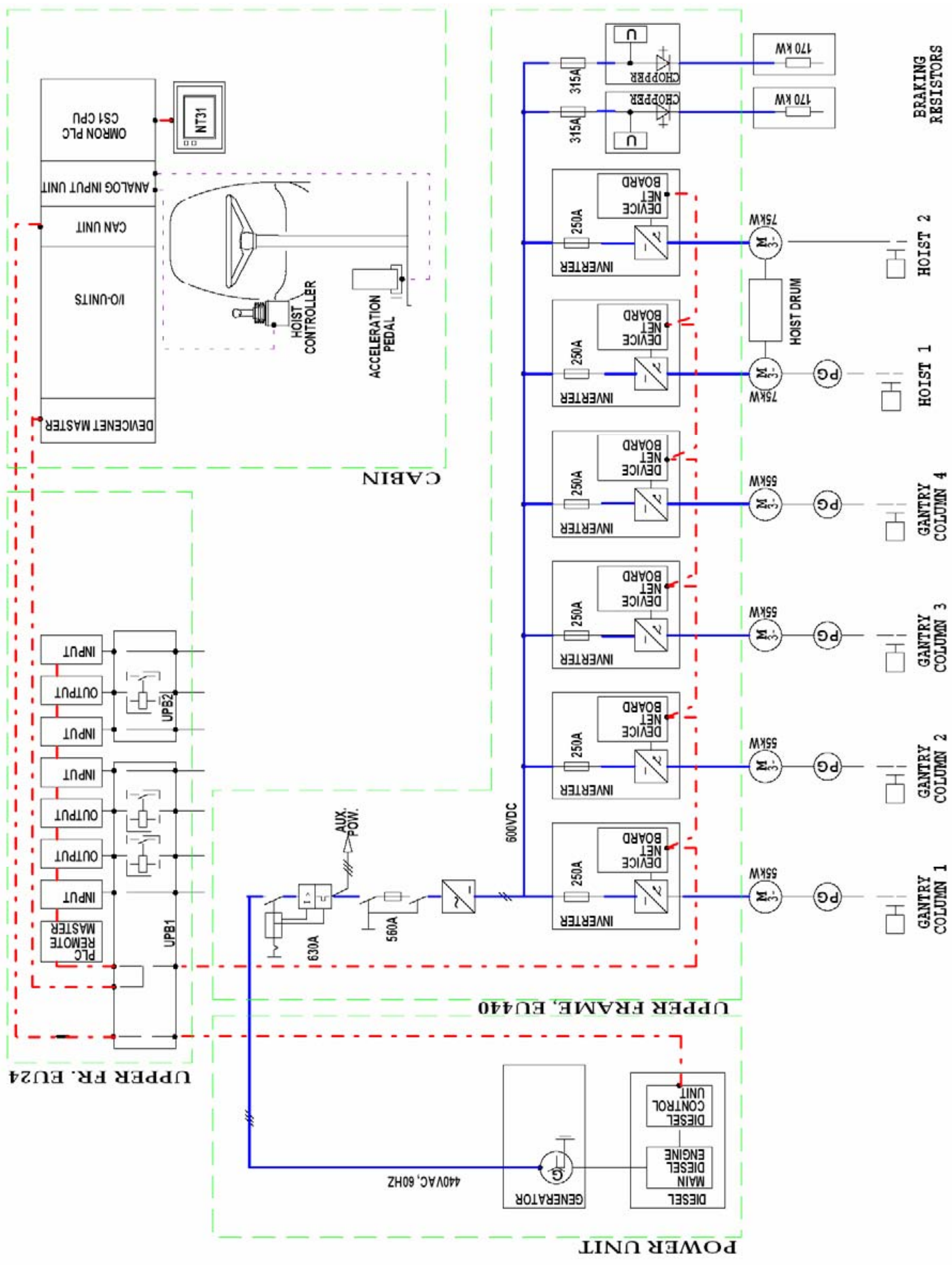
APPENDICES

1 Main diagram of ESC W 350

2 Company Information and Their Reply to the Enquiry

Main diagram ESC W



Company Information and Their Reply to the Enquiry

1. LE Inc

Light Engineering, Indianapolis, USA
Contact person Steve Stover, steve@lightengineering.com

LE Inc. manufactures variable speed brushless motors and generators. Enquiry was sent to them and they were able to offer a product called GenSmart G60L1 that produces 100 kW at a rotational speed of 2500 rpm. They are also working on the next version of this machine that has two active stators and it will produce over 200 kW at 2500 rpm. A 400 kW system is also under development and it will be available sometime in 2007. /24/

2. Marathon Electric Manufacturing Corp

Marathon Electric Manufacturing Corp, Wausau Wisconsin, USA
Contact person Mr. Barry Mills, barry_mills@btinternet.com

The company has a new product called Magna Smart, a variable speed generator featuring an enclosed design. Their generators are widely used around the world in industry, marine, agricultural, military and transportation applications world-wide. Marathon Electric replied to the enquiry but could not offer a generator with the required output. They sent some pictures of the Magna Smart but no detailed technical information. /16;15/

3. Pronto Power

Pronto Power, Sacramento, California, USA

Pronto Power manufactures high efficiency variable speed DC / inverter AC engine driven generators with an output of 200 – 300 kW. Pronto Power generators have been used in buildings, businesses, hospitals, schools, emergency centres, commercial and pleasure vessels, RV's, busses, and highway trucks. /19

4. Turbo Genset

Turbo Genset, West Drayton, Middlesex, UK

- Turbo Genset's Variable Speed Generator (VSG) consists of a reciprocating engine coupled to either a permanent magnet generator or a wound field synchronous machine. The VSG can produce power up to 130kW. /26/

5. Bugatti Marine

Bugatti Marine, Florida, USA
Contact person Mr. John F. Rodrigues, John.Rodrigues@YachtBoutique.com

Bugatti Marine specializes in custom-built marine equipment under the Bugatti Marine and Bentley Marine name brands and they offer variable speed turbo gensets, as well as variable speed diesel gensets. The units can be either air-cooled or liquid cooled (ethylene glycol) and the required 250 – 350 kVA output is possible. They replied to the enquiry, sent information on their products and will be able to offer more detailed information later if Kalmar Industries is interested in what Bugatti Marine has to offer. /3;20/

6. GLACIER BAY

Glacier Bay, Oakland, California, USA
Contact person N. Bruce Nelson, nbn@glacierbay.com

Glacier Bay replied to the enquiry and the company does manufacture variable speed diesel gensets, but they are designed to output dc rather than ac power. They also manufacture dc motors to match with a system called OSSA Powerlite. If a dc system is an option for Kalmar Industries they might have a solution but the generators will not meet Kalmar Industries technical specifications directly. /17;5/

7. WEG

WEG S.A., Jaraguá do Sul, SC, Brazil

The company is the largest electric motors manufacturer in Latin America but it is not certain that they manufacture variable speed generators since they did not send a reply to the enquiry. /27/

8. GE Energy

GE Energy, Atlanta, USA

GE Energy produces wind turbines and offers different kinds of energy solutions but they did not reply to the enquiry so no information of their products was available. /4/