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WARD LEONARD CONTROL SYSTEM

Thesis

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ABSTRACT

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Ever since electric motor drives have been invented, there has been a need for accurate speed control system for them. One solution for this problem was invented by Mr. H. Ward Leonard in 1891. It was a control system that used rotating machines to alter the speed of the working motor.
The Ward Leonard connection had been used in excavators, elevators, in marine solutions and in a few locomotives. Today this system has been replaced by smaller, less expensive and more efficient ways to control motors. Ward Leonard system can still be found in very large applications where using other methods to control motors would be difficult and expensive.

Key words
Ward Leonard, Ward Leonard drive, DC motor, DC generator

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Työelämäohjaaja
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Aina sähkömoottorin keksimisestä lähtien on ollut tarve tarkkaan nopeuden säätelemiseen. Yhden ratkaisun tähän ongelmaan kehitti H. Ward Leonard vuonna 1891. Se oli ohjausjärjestelmä, joka käytti pyöriviä sähkökoneita työkoneen nopeuden muuttamiseen.
Ward Leonard ohjausta on käytetty hisseissä, nostureissa, merisovelluksissa ja junissa.
Myöhemmin tämän järjestelmän ovat korvanneet suuntaajien käyttöön perustuvat järjestelmät, jotka ovat halvempia. Ward Leonard järjestelmän voi kuitenkin vielä löytää muutamista suurista järjestelmistä, missä muiden sovellusten käyttö olisi joko vaikeaa tai todella kallista.

Asiasanat
Ward Leonard, Ward-Leonard ohjaus, DC-moottori, DC-generaattori

ABSTRACT

TIIVISTELMÄ

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1 INTRODUCTION

This thesis has been made in collaboration with Central Ostrobothnia University of applied sciences Ylivieska unit, and University of Applied Sciences Aachen.

All the measurements and the majority of the research are made as a common project with Konsta Luukkonen. The project was assigned by the two schools of Ylivieska and Juelich during our student exchange in Juelich. While we were in Juelich, we were instructed by Volker Muskat and Boris Neubauer.

The objective of this work was to research the Ward Leonard motor control system, where it has been used, and where it is still in use and also do background research of its origins, its theory and its applications. Finding reliable information about this speed control system was rather complicated. Most of the books that should have handled the Ward Leonard connection actually mentioned it only by few words. The Ward Leonard control system is a rather old way to control DC machines so most of the information that we found was more than 70 years old. This why it was hard to figure out that these systems are still in use at the present day.

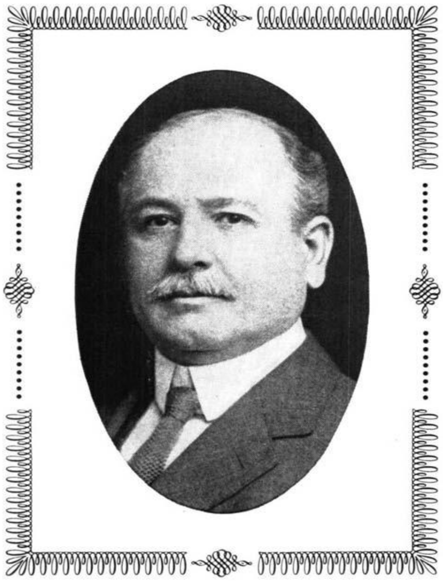
At the end of this research we performed measurements with a Ward Leonard setup under laboratory conditions. The results of these experiments are enclosed. Also the formula which is mentioned in section 4 is displayed at the end of the thesis.

In this work one can also find some background information about DC motors and generators and their principles. We hope that this research is useful to anyone who is interested in the Ward Leonard control system.

2 HISTORY OF WARD LEONARD DRIVE

In this chapter we look at the early days of the Ward Leonard connection. And also it´s applications that followed as the years come by.

2.1 H. Ward Leonard



GRAPH 1. Mr. Ward Leonard

Mr. Ward Leonard was born in 1861 in Cincinnati, USA. He graduated from the Massachusetts institute of technology at age of 22. A year later he became associated with Thomas A. Edison when he was joined a group of four engineers to introduce the new Edison power-station system. He was appointed superintendent of the Western Electric Light Co. in Chicago at the age of 26. Because of Mr. Ward Leonard´s background in power-station work he thought differently about the problems in electrical drive control than most of his competitors at the time. Actually he was more concerned about the economy of the power-station operation and distributing systems than were the railway engineers of that time. Mr. Ward Leonard died suddenly at an AIEE banquet in New York on the 18th February 1915. Mr. Ward Leonard made over 100 inventions during his lifetime. (K.A. Yeomans 1968,144-148)

2.2 First Years of Ward Leonard Control

The Ward Leonard control system was invented by American electrical engineer caller H. Ward Leonard in 1891. So, as you see, this invention is almost as old as the history of applied electrical engineering. Ward Leonard control was a very popular way to control the speed of electrical machines in the decades between 1900´s and 1960´s but the way to its greatness wasn´t always so easy and this new invention faced hard criticism of its technical and commercial value.

Ward Leonard first described his system in an article in Electrical World in November 1891. A few months later his system was presented in the paper to the 9th general meeting of the American Institute of Electrical Engineers in June 1892. At this meeting a wide range of papers on electric circuit theory, on power station management, on electro-technical education and on mining and traction applications was discussed. In the late 19th century the development of electrical machines was quite rapid and DC motors were found useful in a variety of machine drives, cranes and electric traction systems. Actually the first commercially successful municipal-transport system was developed by F. Sprague in 1887.

The Ward Leonard system was proposed as an answer to the current problems in applying electric motors to traction duties. The series motor was successfully developed by Sprague for this application as a robust and reliable machine. Series motors were also capable of withstanding the abuse and hard conditions that occur in municipal street-car operation. The problem was that series motors took heavy currents when starting or when crawling heavy loaded up steep gradients and this caused severe fluctuations in the power station loadings. Also the rheostat control of series motor was inefficient. It was also tried to apply a variable-ratio transmission in street-cars to achieve better efficiency at starting and at low speeds but those attempts ended up in failure.

Ward Leonard´s arrangement was proposed as a variable ratio power convertor using the basic principle that the maximum efficiency of a motor is achieved when “voltage varies as speed, and current varies as torque”. This how high torque can be made for starting without excessive power demand.

Ward Leonard claimed that the advantages of his control system compared to series motor drives were increased efficiency, reduced space, size and cost of the control switches and rheostats. It also made savings in power stations because of the steadier load. The disadvantage was the higher cost of the equipment but it was estimated that the total cost of the transport system would be less.

Ward Leonard´s control system faced hard criticism. It was said that Ward Leonard control wasn´t as efficient as it was claimed to be and some thought that the maintenance costs and the building expenses were high. Actually his control system wasn´t ever widely adapted for locomotive use, maybe because series motor worked properly, even though they had disadvantages like limitations in efficiency, need of space for rheostats and inability to recover power by regeneration.

Actually Mr. Ward Leonard visited France and England in 1895. In France he wrote a report about the Heilmann locomotive that actually used the Ward Leonard connection but with the prime mover being a steam engine. It showed that the generator didn´t spark disastrously and the commutator stayed in good condition in this kind of use and that it didn´t break down easily like some critics said. (K.A. Yeomans 1968,144-148)

2.3 First applications of Ward Leonard control

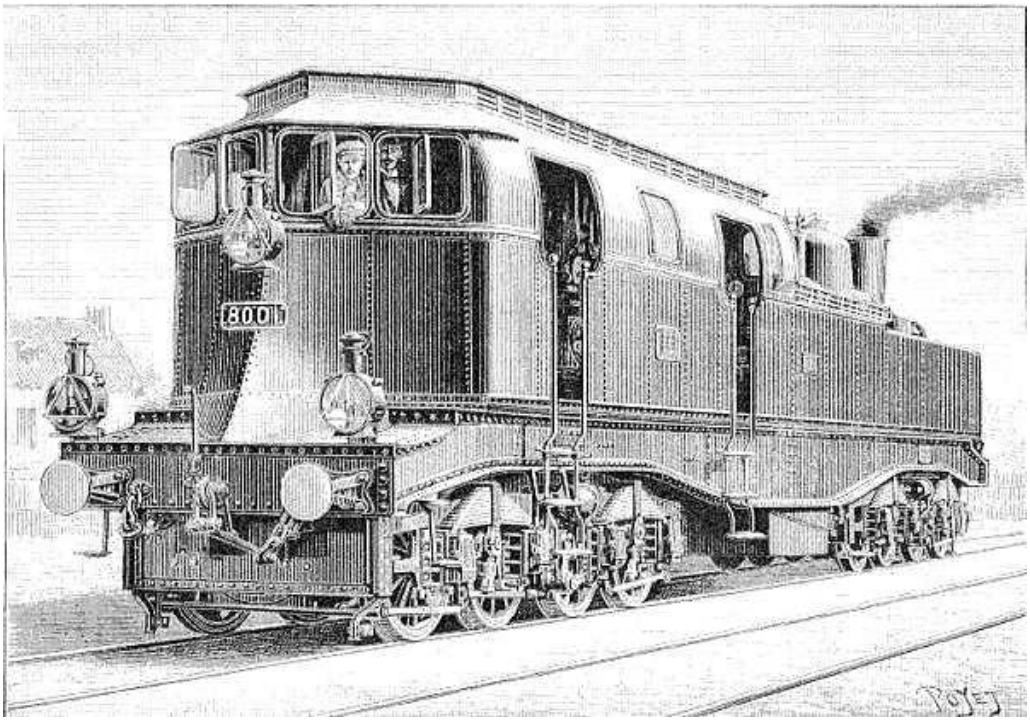
The drive had been first devised in 1891 to drive a 30 hp Calico printing press. All previous attempts to try to apply an electric motor to this press failed because of the high starting torque needed and because the factory´s power plant could not supply very large currents. Before that, the printing press had been driven by two cylinder steam machines and it was thought to be impossible to drive this press with an electric machine. However, when a separately excited generator was used to supply individual press motor, a perfect drive was achieved. Actually the effect on the factory´s generating plant was so low that the power plant´s steam engineer did not believe that press was turned on because no big changes happened in the steam indicators. The Calico printing press achieved a 25% increase in production because of its good control characteristics and steady speed regulation at low speeds.

Another early application of Ward Leonard control was in gun turret control in marine use. Turrets had formerly been controlled by steam cylinders and during tests both hydraulic and rheostatic controlled series motors had been found to be unsuitable for this use. Old steam controlled turret control was quite slow and not very accurate. The Ward Leonard control enabled 23 individual stops and starts in 20 seconds with turret rotation of only 1˚, so it was a quite remarkable innovation for war technology. This technology was adopted by US Navy and it was widely acclaimed in other countries.
(K.A. Yeomans 1968,144-148)

TABLE1. Applications that had the Ward Leonard system in 1896

Application	Power (hp)
Travelling Cranes	1-50
Lifts	5-40
Mine Hoists	10-125
Gun Turrets of Warships	30
Billet Shifter in Rolling Mill	30
Heilmann Locomotive	8x50
Cloth-printing Press	25
Newspaper Press	50
Drilling Machine	5

2.4 Heilmann Locomotive

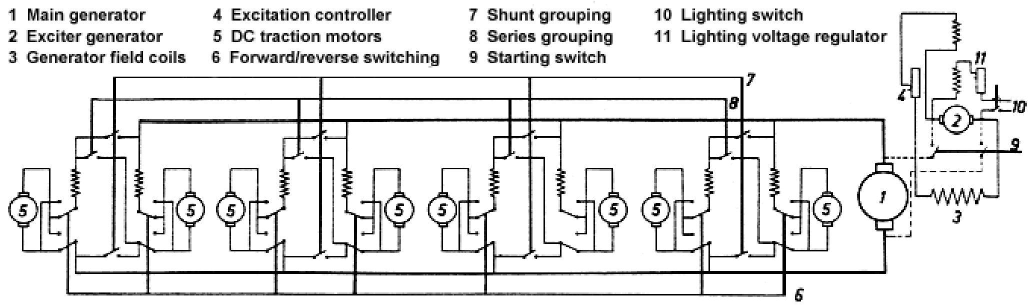


GRAPH 2. Heilmann Locomotive (The Heilmann Locomotives 2007)

The first Heilmann locomotive prototype was build during 1892-1893. This locomotive was an electrified steam locomotive which used a Ward Leonard drive system to control drive motors. A steam engine was the prime mover which ran the prime generator and the smaller exciting generator which produced the exciting power for the prime generator and drive motors. Before the inventors of this locomotive started to build it, they did some research on whether they should use AC or DC power in the locomotive. In no time it became clear that they should use DC in the locomotive because it is easier to control and the prime mover could run at a constant efficient speed. The locomotive had 4 axle bogies, which meant 8 axles, and each axle was powered by 60 hp DC-motor. Later in 1897 there were built two big Heilmanns. These locomotives had two main generators running drive motors. The steam engine was also larger.

The Heilmann locomotives were built in a time where nobody was sure which traction and power system was best suited for railway work. Still the Ward Leonard system was never widely used in locomotives, maybe because it needed a lot of space because of the motor-generator set.

We know that Hungarian railways have a few electrical locomotives that use Ward Leonard drive systems. These 30 V41-class locomotives were built in the late 1950´s with Ward Leonard control because there were some problems in Hungarian industry in providing a well working electrical rectifier for railway use. They also had problems with applying AC-power to locomotive at that time so the temporary solution was the Ward Leonard system. The next picture shows a simplified electrical circuit of a large Heilmann locomotive.
(Michael C. Duffy 1990; The Heilmann Locomotives 2007; Imre Jàkli 1997)



GRAPH 3. Electrical circuit of Heilmann locomotive
(The Heilmann Locomotives 2007)

2.5 Electric Lifts

Because of the good and smooth controllability of the Ward Leonard drive it was taken into use in elevators quite early. Elevators were at the time in a state of rapid development and the Ward Leonard system fulfilled the demands that elevator companies had set. At first, also in elevator use, the Ward Leonard set was criticized because of its inefficiency and power losses when the motor-generator set was idling but those losses are less significant when the work rate required of the drive is high and when starts are frequent. The Ward Leonard drive drove elevators so smoothly that even the critics had to admit that the starting and stopping of the elevator was "extremely pretty". With this system elevators ran at medium elevating speed which was about 250 ft/min.

The Ward Leonard system was also used in the mining industry as a driving system for mine hoists. When the Ilgner flywheel system was introduced in 1903 the Ward Leonard system came into general use. Because of its large flywheel system the effect on the power-stations of fluctuating loads in winders was minimized. This minimization of effects was important because normally the main load of power-stations near mines were the winder motors.

In Europe the introduction of Ward Leonard drives was expedited during the Paris Exposition of 1900. There was a moving pavement which was controlled by a Ward Leonard system. The Ward Leonard drive was chosen to drive that pavement because every else controlling method had failed.
(K.A. Yeomans, 1968, 144-148)

2.6 Ward-Leonard control system in excavators

Large machine shovels started to be used in mining at the early 1900´s. At first these machines were usually steam powered but as the years went by electrical machines started to take their place. The first electrical shovels were actually electrified steam shovels but in 1925 the first real electric shovel was built and it used the Ward Leonard control system. Electrical control of the shovel made its use a lot easier because electrical motors could be used as a brake. Before the introduction of electrical systems shovels were equipped with difficult brake and clutch systems. It was also hard for shovel constructions to use those mechanical brakes. Actually the first time this motor braked system was demonstrated people were quite disappointed to it because it was slow compared to steam systems. Still, with time it became most common way to use these excavators. Even smaller shovels started to have Ward Leonard control in the early 1940´s. Still the road to common use was not easy for Ward Leonard control. Steam control was quite as good as electrical control at first but when there was some research done into using electrical machines electrical control started to take over.

Earlier Ward Leonard control systems were equipped with series motors but series motors need large contacts when turned from forward to reverse mode because there are large armature circuits that have to be opened when reversing the direction of rotation. Because of the difficulties with series motors, separately excited dc-motors offered excellent possibilities to make control of the shovel simpler and also improved the operating characteristics. When an article about these shovels appeared in 1948 the Ward Leonard control was still in common use and the writer supposed that there wouldn´t be a replacement for Ward Leonard control coming in the near future.

(P.S. Stevens, 1491-1497)

2.7 Digitalized Ward-Leonard Control System in the 1990´s

In the past a lot of factories have been built with Ward Leonard control system in South Africa. By the early 1990´s these factories had become be old fashioned and low in efficiency. Usually these factories were equipped with an old kind of Ward Leonard system where excitation of the DC generator and DC motor was made with a separate exciting generator which was connected to the same axle as the DC generator that supplies DC motor. The advantage of this scheme is that there is a lot of kinetic energy stored in rotating masses so it could drive quite heavy loads with relatively small motors. The disadvantage is that it´s hard to make quick changes in rotating speed because of this kinetic energy storage.

In the early 1990´s they started to think in South Africa about what they should do with their factories which starts to be old fashioned and low in efficiency. They thought that it would be too expensive to replace Ward Leonard controls with all new technology. So they decided to modernize those old Ward Leonard systems with digital control.

In these digitally controlled Ward Leonard systems the exciter generator is removed and it is replaced with thyristor bridges for exciting the DC generator and DC motor. Digital Ward Leonard speed control is operated with two PID-controllers: One for controlling the armature voltage of the DC motor by means of controlling the exciting current of the DC generator and the other one to control motor EMF via the motor excitation field.

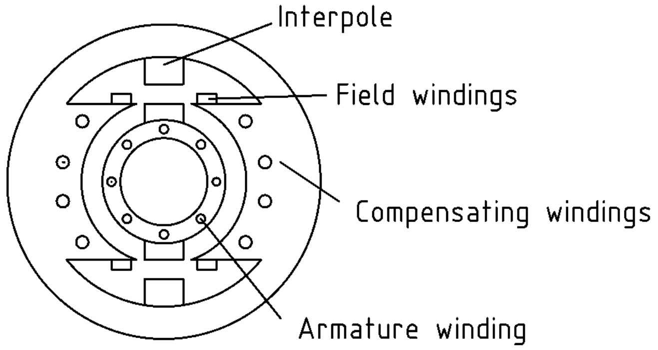
They found out in South Africa that with this digital Ward Leonard control factories could be modernized with low costs and be made competitive again. In the early 1990´s there were still a lot of Ward Leonard control driven factories which could have at least ten more years of effective working time. They also discovered that the overall performance of the factories can be substantially improved by the new reliable control system.
(F. Vaccaro, M. Janusz, K. Kühn 1992, 123-127)

3 DC-MACHINES

3.1 DC-machine types

DC-machines can operate either as a generator or a motor. A DC-motor is a DC-generator with the power flow reversed. Today, the use of DC-generator is limited because of the wide use of AC-power. The DC-machine is widely used as a motor in industry because its speed control is relatively easy over a broad range. Although it is easy to control, it has its drawbacks. The efficiency of DC-machines is a little lower than that of induction motors. DC-machines cannot stand very high speeds and need frequent maintenance. The commutators and coal brushes need to be replaced regularly and this gear is expensive. Even with these drawbacks it is still used in many places. But it is gradually being replaced by AC-machines.

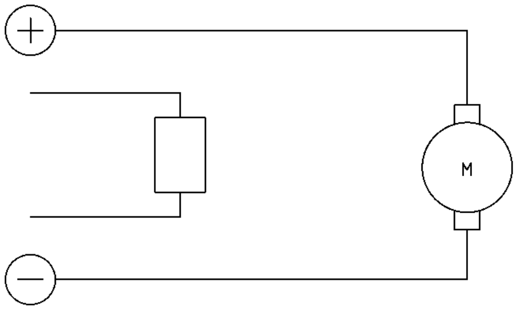
In DC-machines electrical energy is converted to mechanical rotation. In order to make the DC-machine work, the magnetic field of the stator must be created. The supply for this magnetic field is also called the *"excitation power".* This power can be supplied from two different sources: either from an external source or from the generator itself. These two different ways are called "Independent excitation" and "Self excitation". The armature windings are placed on the rotor and the field windings are placed on the stator. The stator poles are excited by one or more field windings.
(P.C. SEN 1997; Vincent Del Toro 1990; Ernst Hörnemann, Hübscher, Jagla, Larisch, Müller, Pauly 1988; Lappeenranta University Of Technology)



GRAPH 4. DC-machine

3.1.1 Independent excitation

In the independent excitation connection the anchor voltage and magnetizing current must be and can altered separately. Thus this type of DC-machine is the most widely spread type in industry. Because it´s easy to regulate.



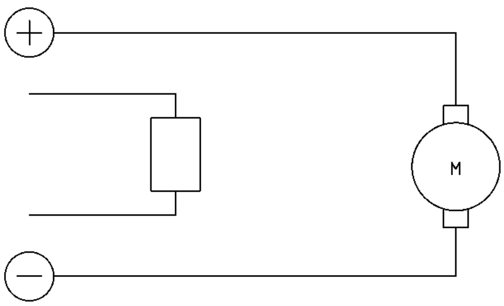
GRAPH 5, Independently excitated DC-motor

3.1.2 Self excitation

There are three types self excitation DC-machines according to the means by which they produce the magnetic field of the stator (the so called excitation): the shunt motor, the cumulatively compounded motor and the series motor.

3.1.2.1. Shunt machines

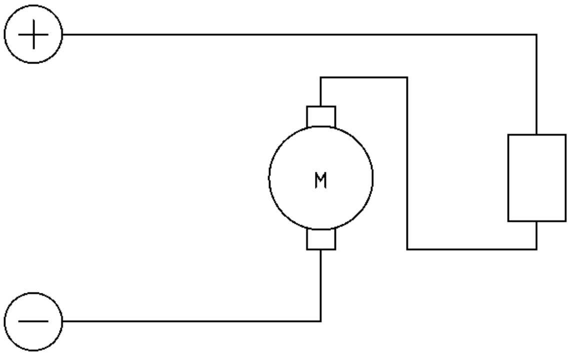
The shunt machine is of the self excited type. The field winding is connected in parallel with the armature winding. In this way the voltage that drives the current through the field winding is the full armature voltage. The current can be altered by using a series resistance in the field circuit if needed.
(Donald V. Richardson, Arthur J.Caisse Jr, 1987; Ernst Hörnemann, Hübscher, Jagla, Larisch, Müller, Pauly 1988)



GRAPH 6. Shunt machine

3.1.2.2 Series Wound machines

The field connection is connected in series with the armature circuit. The field current is controlled by the resistance of the connected load. There is no field excitation if there is no current flow to the load; also the voltage falls if the current is too high. (Donald V. Richardson, Arthur J.Caisse Jr, 1987)



GRAPH 7. Series wound machine

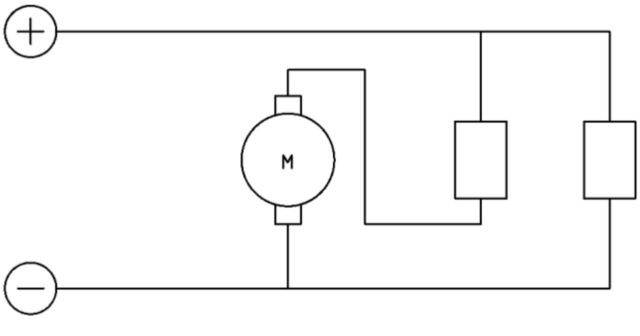
3.1.2.3 Compound machines

This type combines a shunt and a series field and is thus called *a compound machine.* This type combines the features of the two machines presented previously. There are two subdivisions of compound machines according to how they are connected. (Donald V. Richardson, Arthur J.Caisse Jr, 1987)

The two types are:

1) Short-shunt compound

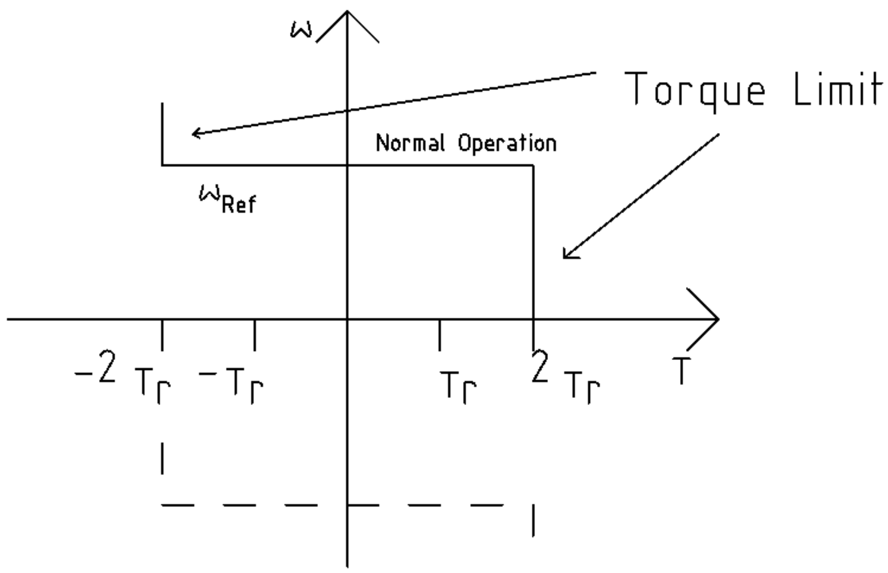
2) Long-shunt compound



GRAPH 8. Compound machine

3.2 DC-machine control

In this section we look more closely at the control of electrical machines.
In the DC-machine drives, feedback control is usually necessary to achieve the desired operating characteristics in the presence of supply and load disturbances. The reason why DC drives normally contain feedback loops is that the armature of a larger motor has a very small impedance which – when supplied with the rated voltage – would result a current of up to 10 times the rated value. While the machine is accelerating or braking there is always the danger of excessive current due to the fast changing of armature voltage or speed. The same thing occurs in a steady overload of the machine. Therefore it is important to provide a fast current or torque limit in order to protect the motor, the power supply and the load, and this is mostly done by feedback control.



GRAPH 9. Torque limit

In most situations the user of the controlled drive wants to select a reference speed which the motor should keep. If the motor is overloaded, the motor should produce maximum torque. Twice the normal torque is rated as a short time current limit. (W. Leonhard, 1985)

Once the DC-motor is running, the question of how fast it should be driven arises. There are four easy means of controlling a DC-motor's speed, and each means has a different applicable range of effectiveness:

1) *Field control*

2) *Armature resistance control or control of the available armature voltage by series resistance.*

3) *Series and parallel armature resistance control*

4) *Armature voltage control*

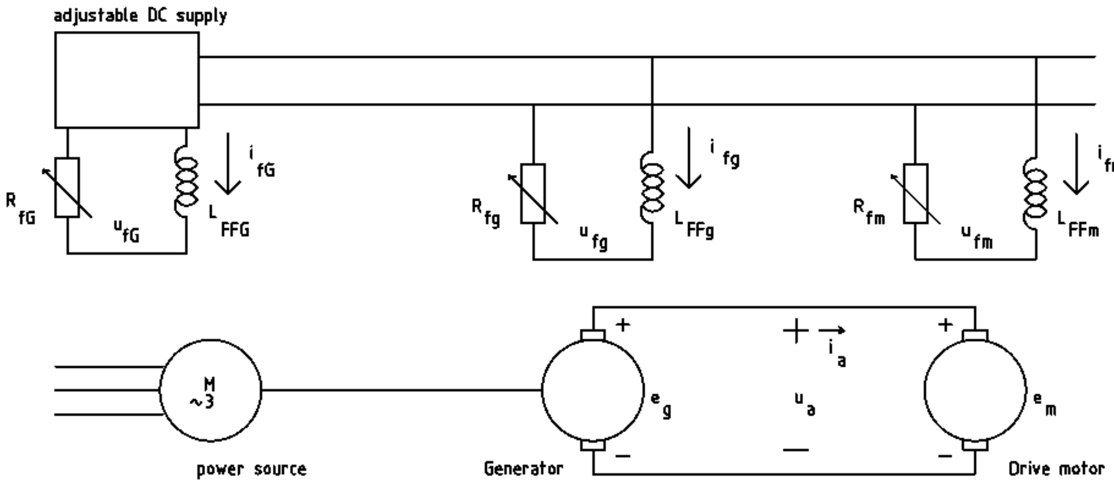
(Donald V. Richardson, Arthur J.Caisse Jr, 1987)

4 WARD LEONARD SYSTEM

It is assumed that any adjustable voltage source could be used as a power supply for the DC-motor armature. One classical way to achieve precise DC-machine control was developed by Ward Leonard in 1891. This system uses a power source (AC-machine, DC-machine, diesel engine, etc. running on a constant speed), DC-generator and a DC-motor which drives the load.

The only task of the power source is to rotate the DC-generator, usually connected by an axle. If the prime mover is not an electric motor it usually rotates also a second generator which produces the exciting power for the main generator and drive motor. The DC-generator (running at approximately constant speed) supplies current to a shunt motor. The DC-generator is separately excited and it´s field winding current is supplied from the main circuit or from a different exciting generator which is also connected to the prime mover axle. The current can be regulated by a resistance from the full value to nearly zero. By varying the exciting current, the generator's output voltage can be varied.

The drive motor is a separately excited DC-motor which drives the load. The armature of the drive motor is connected to the DC-generator to supply to variable voltage while the field current is supplied from the main line or from the exciting generator. With these arrangements the drive motor's speed can be varied from full speed to zero by simply adjusting the generator's field current.
In this system three full-sized machines (if exciting power needed to produced, four machines are needed) are required instead of one and this method is used when the precise control cannot be obtained by more economical means.



GRAPH 11. Ward Leonard connection

The prime mover or power source is usually an induction motor. In ships or vehicles a turbine or diesel engine is mostly used. In large applications the drive is often split up into several machines. Two motors can run separately from each other without any direct mechanical connection when needed. This can be used, for example, in rolling paper mill machines, rolling mills and big draglines in mines.

The disadvantage of the Ward Leonard system is that two machines of the same power rating are necessary even though they could be of different sizes. Because of the continuous rotation the machines require regular service, bearings, brushes, commutators, etc.

Because of these reasons static power converters have completely replaced rotating motor-generator sets in new installations.
(W. Leonhard 1985; Edwin P. Anderson 1975)

The voltage that the generator produces is given by the following equation:

$\left(\tau_{fg} + \tau_{FG}\right)\frac{dk_{vg}}{dt} = \frac{L_{AFg}}{L_{FFg}}\left(\tau_{fg} u_{fg} - \tau_{FG} u'_{fG}\right) - k_{cg}$ Formula 1: Generator voltage that is produced

(Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff 1995, 117-119)

4.1 Ward Leonard speed control

The most valuable features in Ward Leonard control system is it's smooth starting and very good speed control even at the slow speeds. The performance of the Ward Leonard drive is dominated by the electrical time constant of the generator shunt field and by the electromechanical time constant associated with the inertia of the motor shaft. This makes the Ward Leonard drive smooth to accelerate and decelerate. It is hard to make rheostatic armature controlled machines work as smoothly as the Ward Leonard drive.
(K.A. Yeomans 1968,144-148)

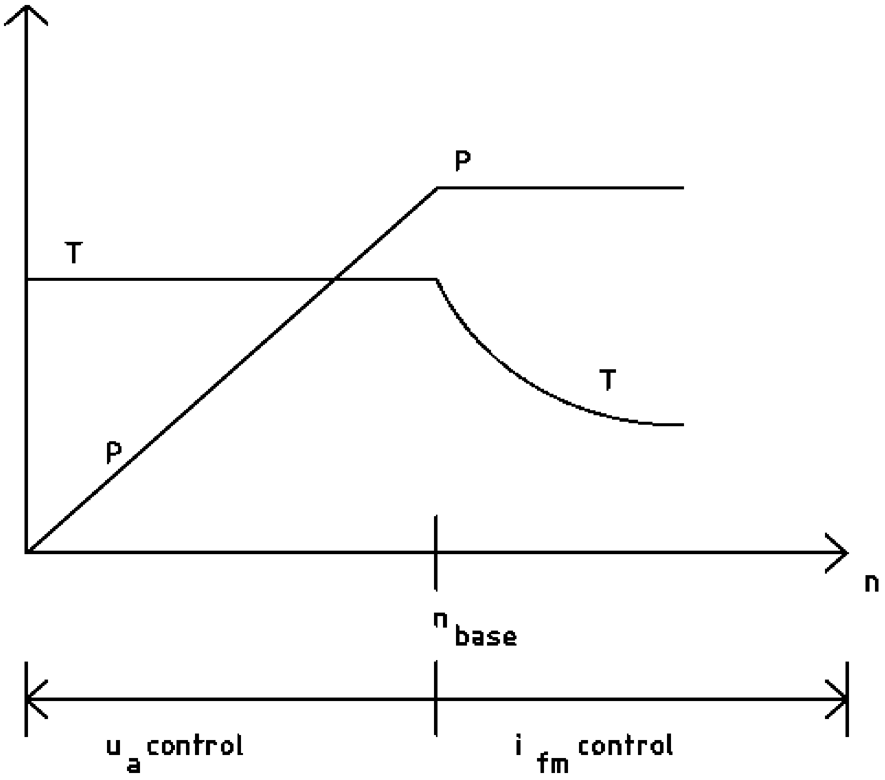
The Ward Leonard system can be controlled easily by two basic means. Varying the generator field current i_{fg} causes the the generator voltage u_a to change, which in turn that changes the DC motor speed. The Ward Leonard system can be driven in two different control modes:

4.1.1 Generator output voltage (u_a) control

In the voltage control mode, the drive motor current i_{fm} is kept constant. The generator field current i_{fg} value is changed so that u_a varies. By doing this the speed rises to the base speed. In this range of speed the torque can be maintained during constant operation.

4.1.2 Drive motor field current (i_{fm}) control

By weakening the field current of the drive motor, it is possible to obtain speeds greater that the base speed. This time u_a is kept constant and the drive motor i_{fm} field current is decreased. Armature current is kept in constant. Torque decreases as speed increases. (P.C. SEN 1997, 128-129)



GRAPH 12. Drive motor field current control

4.2 What replaced the Ward Leonard System

4.2.1 Electronics and rectifiers

Somewhere in the middle of the 20^{th} century the advent of electronics and controlled rectifiers brought remarkable improvements to speed control systems. Manual open-loop control was replaced by closed-loop feedback systems. This resulted in improved response and accuracy. These systems were developed as an alternative to Ward Leonard control.

At first low-power gas diodes and thyristors were used to control the exciting current of DC generator in Ward Leonard connections. High power silicon diodes and silicon-controlled rectifiers were developed in the 1960´s. With these devices ac current could be converted to dc current for the purpose of controlling of the drive motors. This increased the power range as well the range of speed control.

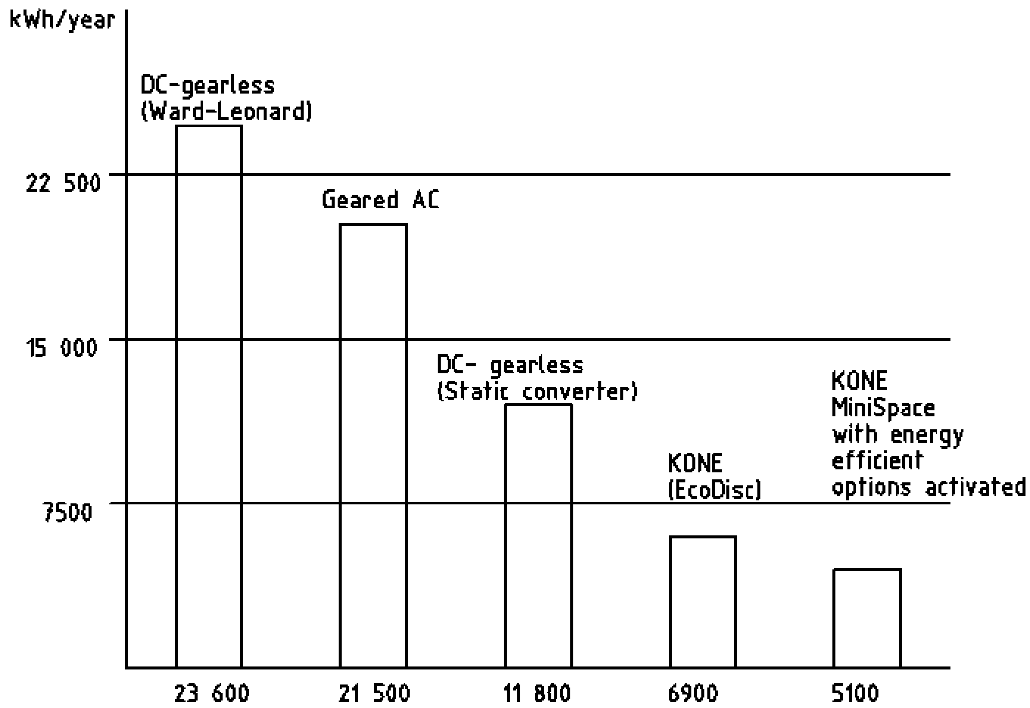
Controlled rectifiers are more efficient than Ward Leonard systems and they don’t need as much space as the motor-generator set does. On-load efficiency is better in controlled rectifiers and there is practically no loss under no-load conditions. They need less maintenance and there is no commutator to spark in the generator. On heavy drives it is also lighter than rotating machines so building costs are less than with rotating machines. By using controlled rectifiers rheostatic power losses can also be avoided.

Still, controlled rectifiers can´t achieve all the advantages that Ward Leonard control has. A phase-angle controlled-rectifiers scheme adjusts the mean voltage applied to DC-motor, but the rectifier current, and therefore the supply current, is the current supplied to the motor. High motor starting currents cannot be achieved with reduced line currents. Controlled rectifiers can be used to supply comparatively large capacity only if significant voltage fluctuations can be avoided. So, in case Ward Leonard´s demand for reduced power-station equipment is not met. Controlled rectifiers also need quite stiff supply because of their poor power factor and the harmonic disturbance they generate.

Nevertheless, controlled rectifiers are a better way of controlling DC-motors than Ward Leonard sets in many cases. The reduced space need and lower cost makes them more attractive to customers. Nowadays nearly all DC drives that are manufactured employ some sort of rectifier to supply adjustable terminal voltage, thereby eliminating the Ward Leonard generator-motor system. (K.A. Yeomans 1968; P.C Sen 1987)

4.2.2 Electrical power consumption

One of the main reasons for replacing the Ward-Leonard system is it´s power consumption. Since there are nowadays more efficient ways to implement a control system for DC-machines with less power consumption the Ward-Leonard has almost disappeared from use. (KONE 2011)



GRAPH 13. Annual energy consumption consumption of mid-sized elevators (KONE 2011)

4.3 The applications of the Ward Leonard system today

Thyristor controllers have replaced almost all of the small to medium sized Ward-Leonard systems but some very large ones with of thousands of kilowatts still remain in service. The field currents are a lot lower than the armature currents enabling moderate sized thyristors to control a much larger motor than they could control normally. For example, if one has an installation which has a 300 A thyristor unit to control the generator field, the generator output current would exceed 15 kA, which could be relatively expensive and inefficient to control by just using thyristors. (Lander, Cyril W 1993)

4.3.1 Finnish Icebreaker Ship Voima

GRAPH 14. Icebreaker Ship Voima (SMU 2011)

The Ward Leonard control system in this ship was taken into use in 1954. The differential was build up by Strömberg (today ABB) with six diesel engines which ran their own generators, so the total output was six times 1370 kilowatts. ABB has experience in supplying electrical propulsion systems in to vessiles which move in polar regions ever since 1939. When ABB delivered the first DC current functional Strömberg Ward-Leonard propulsion system to a Finnish icebraker ship. Later on in 1979 the diesel engines were replaced and the axial output was raised from 7723 kilowatts to 10200 kilowatts.

The icebreaker Voima is still in use today in the Finnish Gulf. This information gives us a hint that this system has been used also as a drive motor in marine technology, not only to operate gun turrets. We are quite sure that one can find similar systems in other ships also. (SMU 2011; ABB 2011)

4.3.2 Fast Breeder Test Reactor

Nowadays Ward Leonard control system is used also in modern nuclear power plants. In India, at the Indira Gandhi Centre for Atomic Research they have used Fast Breeder Test Reactor since 1985. In this kind of reactor there are two sodium circles before the generator steam circle. In this Indian reactor a Ward Leonard drive system is used to control the flow of the primary sodium. Primary sodium is straightly connected to nuclear fuel.

This Ward Leonard system is equipped with a large flywheel because in case of loss of electricity supply the pumps must rotate for a while in order that the safety system has enough time to act. This is so that the reactor won´t overheat and so that the power plant stays safe in case of failure. They use a Ward Leonard control system in this power plant because it has great features (excellent speed control behavior) in speed control. Variable control of the primary sodium pumps is very important in running a nuclear plant because one can´t run the power plant with different outputs if one can´t control the flow of the primary sodium. This is why Ward Leonard control is quite ideal for this power plant.
(G. Vaidyanathan, N. Kasinathan, K. Velusamy)

5 WARD LEONARD LABORATORY EXPERIMENTS

Once we had the theory part of this project done, we tried to apply the theory in practice. These experiments were done in cooperation with University of Applied Sciences Aachen, in the laboratory of electric drives in the Juelich campus.

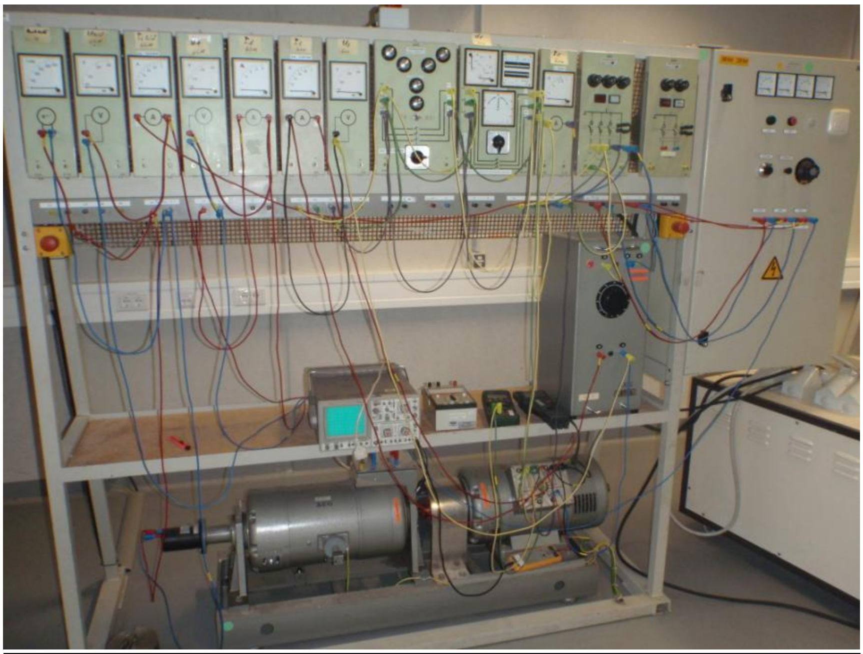
With the theory as our background we built the hardware machinery shown in attachments 1 and 2, which we used to do our laboratory experiments. When the hardware was ready we did some measurements. We tried to figure out that what parameters we could alter, while keeping the connection stable.

In the next three sub-sections we deal with building the hardware connection, the measurements are displayed and finally we give the conclusions that followed the experiments. We tried not to prove the Formula 1 that is mentioned in part 4 (Ward Leonard System), because we could not get access to all the parameters that are required to prove the functionality of this formula.

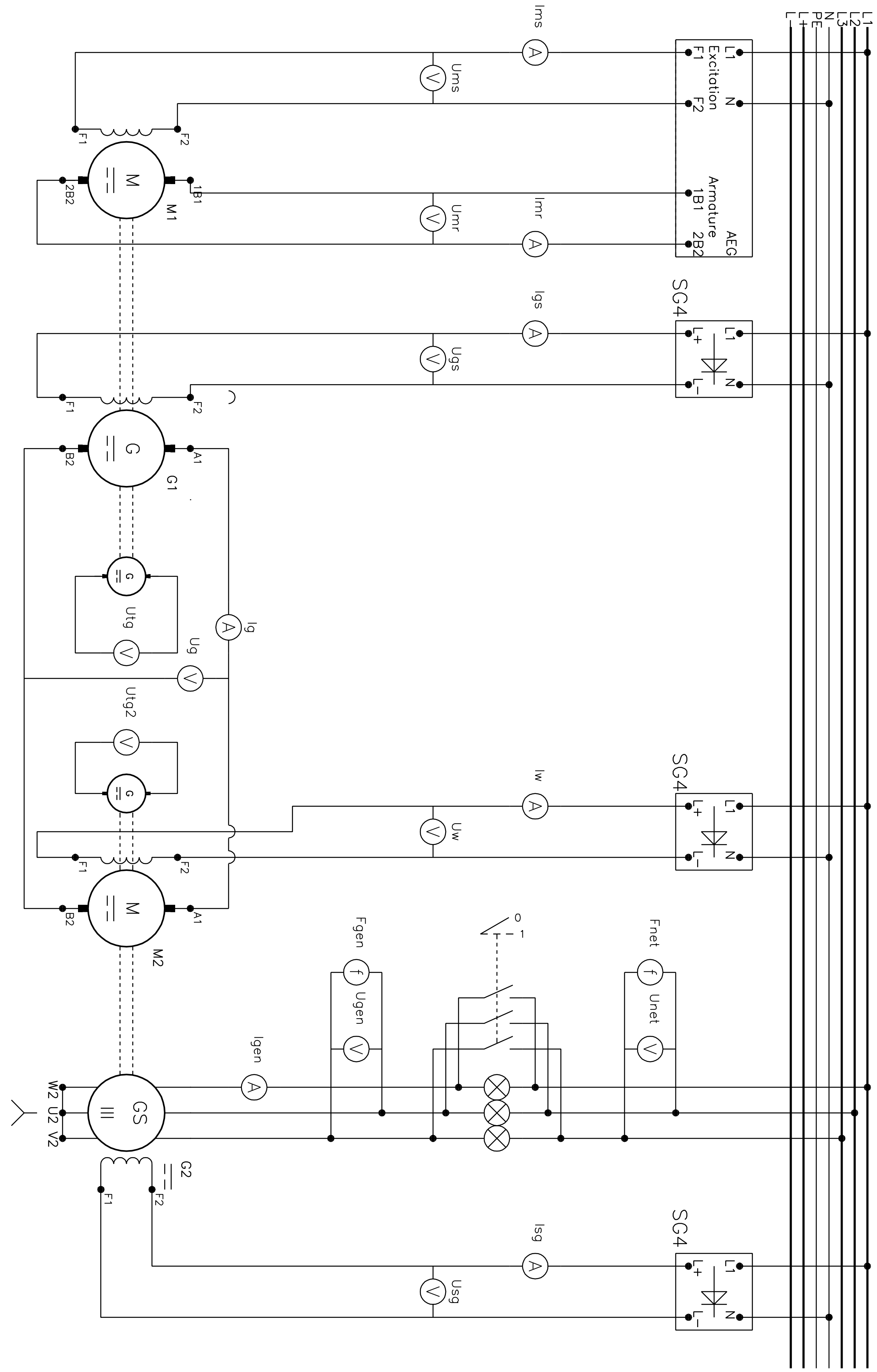
5.1 The Connection

Making the connection started by drawing a wiring diagram. After the diagram was drawn, it was checked by the laboratory engineer. The connection was built using the wiring diagram we had drawn and after wiring the connection we asked the laboratory engineer to check the connection. After the connection was checked we tested that the connection worked correctly and when the connection was found to be correct we made the measurements on our own. All the experiments were done using the connection diagram presented in GRAPH 17.The electric motors that were used in these experiments are laboratory specified motors (see APPENDIX 1). All the measurements were done under no-load conditions.

GRAPH 15. Generator G1, Motor M1;



GRAPH 16. Hardware machinery on the synchronous generator side with Motor M2, Generator G2



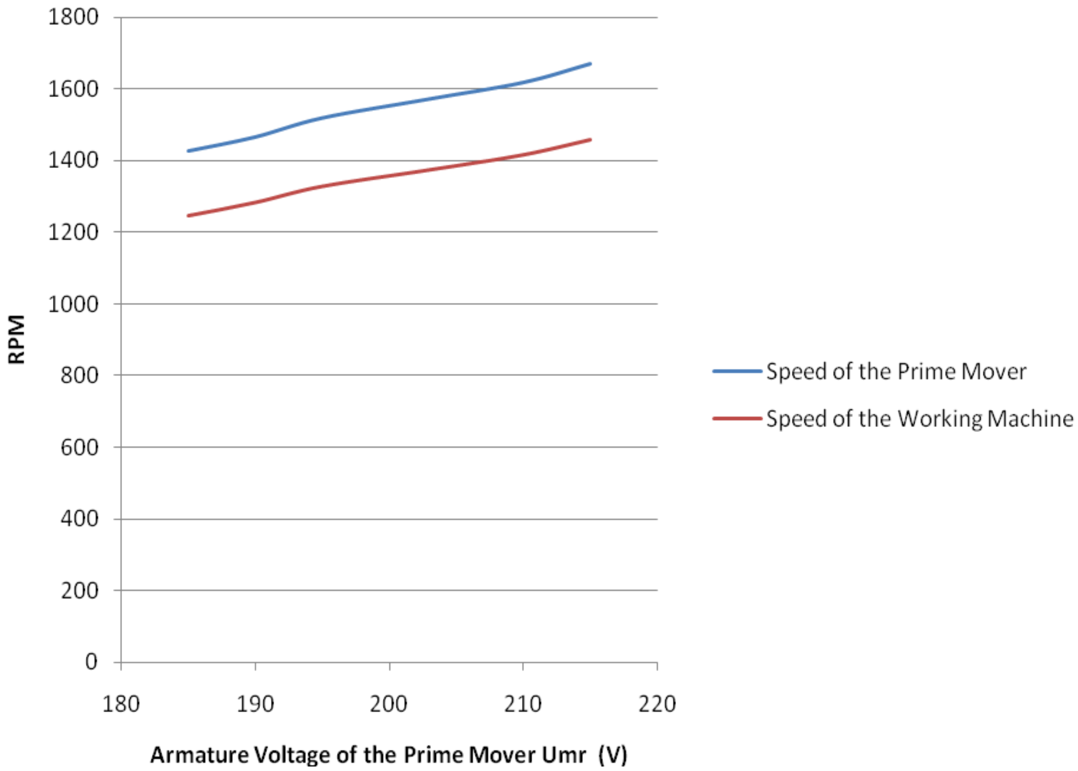
GRAPH 17. Connection made in the laboratory

5.2 Measurements

In this chapter, the laboratory measurements are displayed.

5.2.1 Measurement 1

The objective of this experiment was to alter the speed of the prime motor and to see how it changes the speed of the work motor. In this experiment all the other parameters were kept constant; only the rotation speed of the prime mover was altered by varying its armature voltage. The prime mover excitation was done by using an adjustable voltage supply. The measurement protocol can be seen in APPENDIX 2. In (GRAPH 18) one can see how the speed of the working machine varies when the speed of the prime mover is changed.

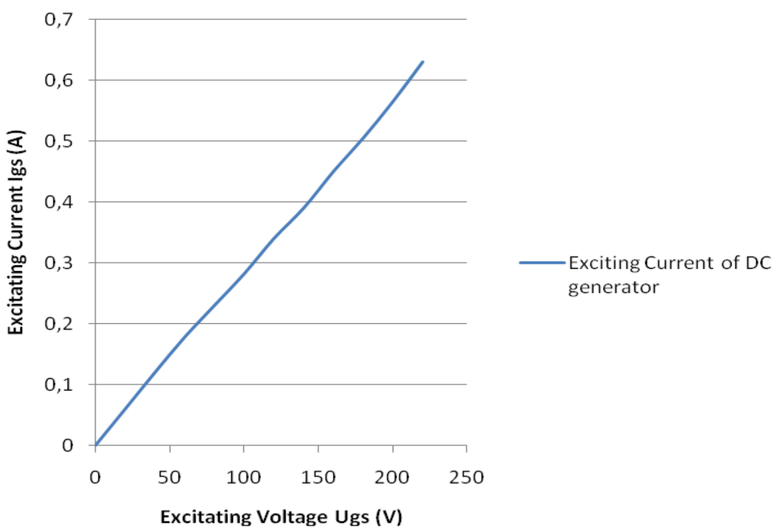


GRAPH 18.Relationship between RPM and Armature voltage of the Prime Mover

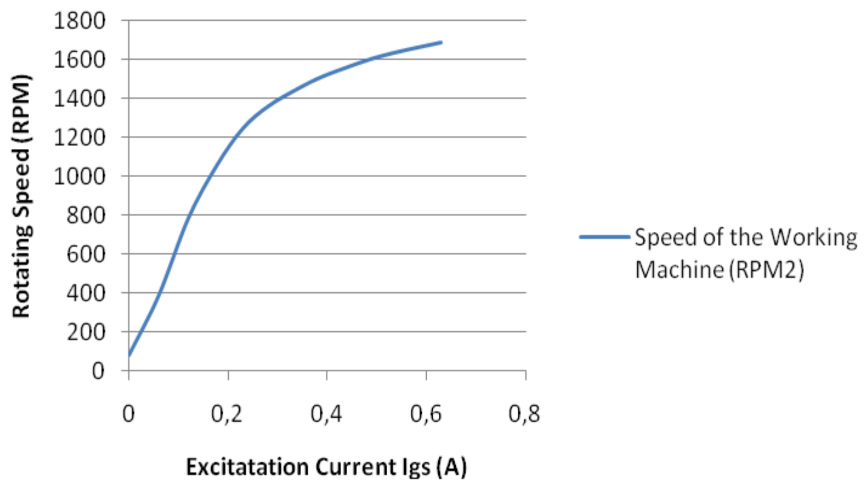
5.2.2 Measurement 2

The point of this experiment was to alter the speed of the work motor by altering the generator field current. We choose the voltage as the measured quantity in this measurement. We set the voltage to the maximum value allowed by the motors. We lowered the voltage by steps of 20 volts and each time we wrote down the measured values. The measurement protocol can be seen in APPENDIX 3.

In (GRAPH 19) one can see how the excitation voltage affects the excitation current. (GRAPH 20) shows how the excitation current affects the speed of the working machine.



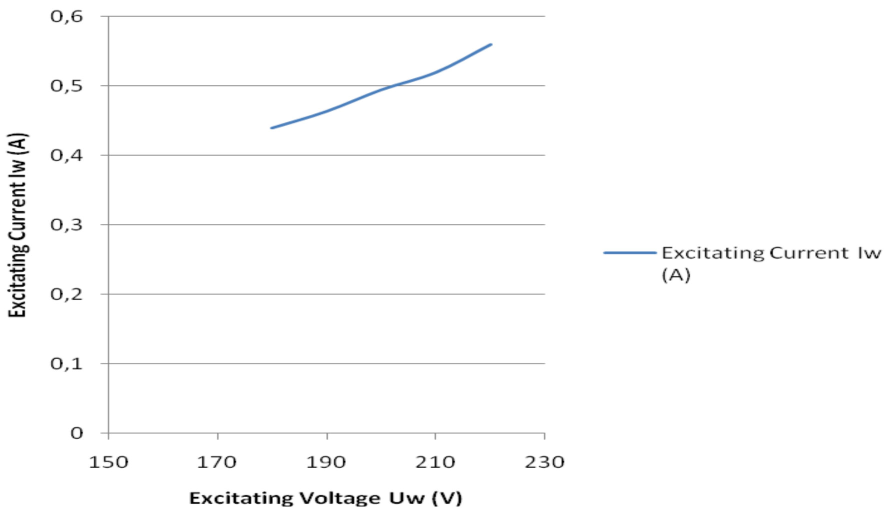
GRAPH 19. Relationship between exciting current and voltage



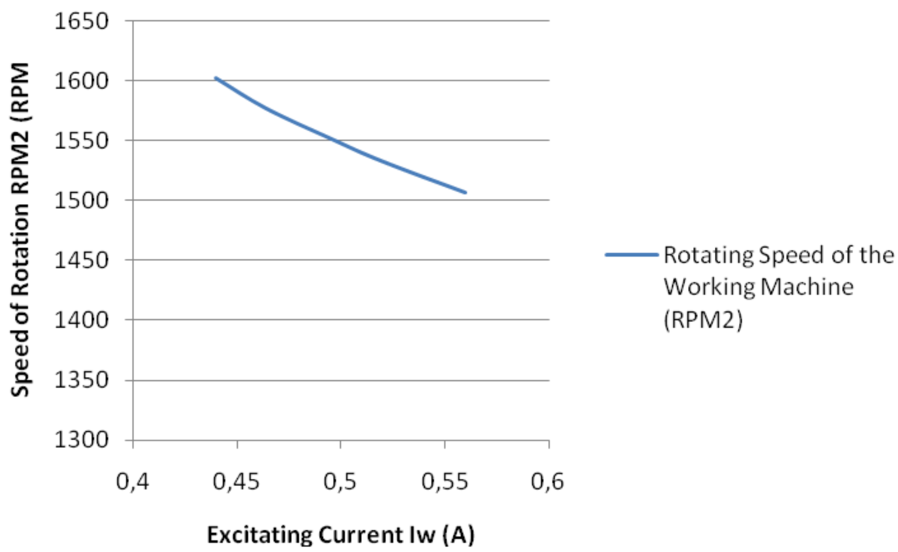
GRAPH 20. Relationship between RPM and excitation current

5.2.3 Measurement 3

The objective of the final measurement was to run the Ward Leonard set at higher speeds than the base speed by altering the working motor field current. We kept other values constant and altered only the excitation current of the work motor. First we regulated the work machine to run at 1500 rpm and after that started to lower the excitation power. During measurements we monitored how the work motor reacted to lower excitation power. The measurement protocol can be seen in APPENDIX 4. In (GRAPH 21), the relationship between voltage and current can be seen. (GRAPH 22) shows how weakening the excitation current changes the working motor speed.



GRAPH 21. Relationship between excitation voltage and current



GRAPH 22. Relationship between speed of rotation and excitation current

5.3 Conclusions

During the measurements we found out that there are three ways to control the speed of the working motor in Ward Leonard control. These ways are to control the speed of the prime mover, to control the excitation of the DC generator and the field weakening of DC motor. Usually the prime mover runs at constant speed but if its speed is varied, the change in the DC motor´s speed is almost same as the change in the prime mover's speed. When using excitation current control of the DC generator, the DC machine's speed can be varied from almost zero to base speed. The DC motor won´t stop completely because of magnetic field storage in motor´s coils. One can also make the DC motor run faster than its base speed by lowering the excitation current of the motor but the excitation power of the motor should never be reduced to zero because it will damage the generator side of the connection.

All these adjustments can be done at the same time or they can be done separately. Though altering the excitation power of the generator gives the best results in speed control from zero speed to base speed. Usually prime movers run on a constant, most efficient, speed and that's why it is not wise to alter the speed of the prime mover.

By lowering the excitation current of the DC motor one can raise the DC motor´s speed of rotation. Still by this means the power of the DC motor does not increase but in some cases one might find it convenient to get the motor run on higher speed than the base speed.

We found out that excitation power should be connected to DC motor before connecting the excitation to the DC generator. If excitation is connected to the generator before the motor it will do damage on the generator side of the connection. The measurements that we made were carried out in no load conditions but one could easily add load to the connection just by increasing the excitation of the synchronous generator connected to the DC motor's axle. The connection was also made in a way that the synchronous generator could feed power to the grid if one would like to do an experiment like that. While running these tests one should pay attention to the meters attached to this connection so that there won´t be high over-currents or over-voltages that could produce damage.

FORMULAS

Formula1. Generator voltage produced

$$\left(\tau_{fg} + \tau_{FG}\right)\frac{dk_{vg}}{dt} = \frac{L_{AFg}}{L_{FFg}}\left(\tau_{fg} u_{fg} - \tau_{FG} u'_{fG}\right) - k_{cg}$$

$$k_{vg} = L_{AFg}\left(i_{fg} + i'_{fG}\right)$$

L_{AFg} =Armature voltage in DC generator

i_{fg} =generator current

i'_{fG} = current in the adjustable dc supply for the drive motor

$$\tau_{fg} = \frac{L_{FFg}}{R_{fg}}$$

L_{FFg} =generator exciting winding

R_{fg} =adjustable field rheostat on the generator side

$$\tau_{FG} = \frac{L_{FFG}}{R_{fG}}$$

L_{FFG} = exciting winding in the adjustable dc supply

R_{fG} =adjustable field rheostat in the adjustable dc supply

$L_{AFg} = \dfrac{N_a N_f}{R}$ = Armature voltage in DC machine

u'_{fG} = field voltage on the adjustable dc supply

u_{fg} =generator field voltage

i_{fg} =generator field current

u_a =generator output voltage (varies due the changes of the u_{fg} & i_{fg})

i_{fm} = field current for the motor (constant)

Formula 2. Generator voltage produced

$$\left(\frac{L_{FFg}}{R_{fg}} + \frac{L_{FFG}}{R_{fG}}\right)\frac{d(L_{AFg}(i_{fg} + i_{fG}))}{dt} = \frac{L_{AFg}}{L_{FFg}}\left(\frac{L_{FFg}}{R_{fg}} v_{fg} - \frac{L_{FFG}}{R_{fG}} u'_{fG}\right) - L_{AFg}\left(i_{fg} + i'_{fG}\right)$$

(Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff 1995, 117-119)

REFERENCES

Donald V. Richardson, Arthur J.Caisse, Jr. 1987. ROTATING ELECTRIC MACHINERY AND TRANSFORMER TECHNOLOGY. Third Edition.

Edwin P. Anderson.1975. Electric Motors. Second Edition Sixth printing. AUDEL

Ernst Hörnemann, Hübscher, Jagla, Larisch, Müller, Pauly Electrical Power 1988. Engineering Proficiency Cource.

F. Vaccaro, M. Janusz, K. Kühn. 1992. Digital Control of a Ward Leonard Drive System AFRICON´92 Proceedings, 3rd AFRICON Conference

FrontRunner 9/07, ABB Marine
WWW-document.Available:
http://www02.abb.com/global/fiabb/fiabb250.nsf!OpenDatabase&db=/global/fiabb/fiabb254.nsf&v=1D4E&e=fi&url=/global/seitp/seitp202.nsf/0/ED14AAB47C106D5DC1257378002CE780!OpenDocument
Accessed 25march.2011

G. Vaidyanathan, N. Kasinathan, K. Velusamy
Dynamic Model of Fast Breeder Test Reactor
Annals of Nuclear Energy 37
PDF-document. Available:
http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V1R-4YDTS0F-2-39&_cdi=5681&_user=4816310&_pii=S0306454910000344&_origin=search&_coverDate=04/30/2010&_sk=999629995&view=c&wchp=dGLzVzb-zSkzV&md5=3e536a524795661d43a38e2df19798ce&ie=/sdarticle.pdf
Accessed 22 February 2011

Imre Jàkli. 1997.History of the Electric Locomotives in Hungary
WWW-document. Available: http://gigant.chem.elte.hu/mav/electric_story.html
Accessed 14 march 2011

K.A. Yeomans .1968.Electronics and Power, April 1968.Ward Leonard Drives – 75 Years of Development

Kone 2011
WWW-document. Available: http://www.kone.com/countries/en_CY/products/elevators/office/cseriesofficeelevators/Energyefficiency/Pages/default.aspx
Accessed 11march.2011

Lander, Cyril W. 1993. D.C. Machine Control. Power Electronics. Third Edition

Lappeenranta University Of Technology, DC motor, LUT.fi

WWW-document. Available:
http://www.lut.fi/fi/technology/lutenergy/electrical_engineering/articles/electrical_motor/Sivut/Default.aspx
Accessed 17 march 2011

Michael C. Duffy
Electric Railways 1880-1990
WWW-document. Available:
http://books.google.fi/books?id=cpFEm3aqz_MC&pg=PA47&lpg=PA47&dq=ward+leonard+applications&source=bl&ots=atpDICrN78&sig=9-tVGZ5w1AJsPYaxH9DO1wsftvY&hl=fi&ei=OFJ3Tb3wKImdOuO6_McB&sa=X&oi=book_result&ct=result&resnum=9&ved=0CFsQ6AEwCDgU#v=onepage&q=ward%20leonard%20applications&f=false
Accessed 11march.2011

Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff .1995. Analysis of Electrical Machinery. Second print.

P.C Sen. 1987. Power Electronics.

P.C. SEN. 1997. Principles of electric machines and power electronics.

P.S. Stevens. Evolution of Ward-Leonard Control for Shovels and Draglines
Transaction of the American Institute of Electrical Engineers: Vol. 67

The Heilmann Locomotives
WWW-document. Available:
http://www.aqpl43.dsl.pipex.com/MUSEUM/LOCOLOCO/heilmann/heilmann.html
Accessed 14march.2011

Theory of DC motor Speed control:
PDF-document. Available:
http://www.aseanexport.com/PDF/dc_motor_speed_controller.pdf
Accessed 11 march 2011

Vincent Del Toro. 1990. Basic Electric Machines.

W. Leonhard. 1985. Control of Electrical Drives

SMU: Picture of the Icebraker ship Voima
WWW-document. Available:
http://www.smu.fi/viestinta/nettijutut/arkisto/nettijutut_2009/jaanmurtaja_voima/
Accessed 25 march2011

APPENDIX 1

Nominal values of motors and generators

Motor 1

CETEL		
T1 DC – 3M		1C
220 V	17 A	3 kW
1500 rpm	IP 23	Ex 220 V
cl. F	MOT.CPD	
91 – 05 – 801 - 2007		

Generator 1

CETEL		
SERIE: T1CD – 11B		4DF
220 V	13,60 A	3 kW
1500 rpm	ŋ DYN FREIN	Ex 220 V
cl: F	IP 23	8935593
W= 0,025 X NEWX IR/M		

Motor 2

CETEL		
T1 DC – 11P		N 2
220 V	13,6 A	3 kW
1500 rpm		Ex 220 V
		872833
W= 0,025 X N X rpm		

Generator 2

CETEL		
T1 AC7G/P.T		N 2
230 / 400 V	7,6 / 4,35 A	3 kWA
Cos 0,8 / 1		50 hz
1500 rpm		Ex 220 V
87- 2832		

Measurement 1
Changing the speed of the drive motor

U_{mr} (V)	I_{mr} (A)	U_{ms} (V)	I_{ms} (A)	U_g (V)	I_g (A)	U_{gs} (V)	I_{gs} (A)	U_{tg} (V)	RPM_1
215	2,1	185	0,805	265	0,1	113	0,34	100,20	1670
210	2,0	185	0,805	258	0,1	113	0,34	97,1	1618
203	2	185	0,8	250	0,1	113	0,34	94,3	1572
195	2	185	0,8	240	0,1	113	0,34	91,15	1519
190	2	185	0,8	232	0,1	113	0,34	88,0	1466
185	2	185	0,8	225	0,1	113	0,34	85,6	1427

U_{tg} (V)	I_w (A)	U_w (V)	RPM_2
87,6	0,55	225	1460
85,1	0,55	225	1418
82,6	0,55	225	1376
79,8	0,55	225	1330
77,1	0,55	225	1285
74,9	0,55	225	1248

Measurement 2
Changing the generator magnetic field voltage

U_{mr} (V)	I_{mr} (A)	U_{ms} (V)	I_{ms} (A)	U_g (V)	I_g (A)	U_{gs} (V)	I_{gs} (A)	U_{tg} (V)	RPM_1
220	2,3	210	0,905	300	1	220	0,63	97,7	1628
220	2,3	210	0,9	295	1	200	0,565	98	1633
220	2,3	210	0,9	290	1	180	0,505	98	1633
220	2,3	210	0,9	282	1	160	0,45	98	1633
220	2,3	210	0,9	272	1	140	0,39	98,3	1638
220	2,3	210	0,9	260	1	120	0,34	98,3	1638
220	2,3	210	0,9	244	1	100	0,282	98,3	1638
220	2,3	210	0,9	220	1	80	0,23	98,8	1647
220	2,3	210	0,9	190	1	60	0,178	98,6	1647
220	2,3	210	0,9	140	0,9	40	0,12	98,7	1645
220	2,3	210	0,9	50	0,8	20	0,06	99	1650
220	2,3	210	0,9	0	0,8	0	0	99	1650

U_{tg} (V)	I_w (A)	U_w (V)	RPM_2
101,1	0,54	220	1685
99	0,54	220	1650
96,8	0,54	220	1613
94	0,54	220	1567
90,6	0,54	220	1510
86,8	0,54	220	1447
81,6	0,54	220	1360
74,7	0,54	220	1245
63,5	0,54	220	1058
47,7	0,54	220	785
25,3	0,54	220	388
5	0,54	220	83

Measurement 3
Changing the motor field current

U_{mr} (V)	I_{mr} (A)	U_{ms} (V)	I_{ms} (A)	U_g (V)	I_g (A)	U_{gs} (V)	I_{gs} (A)	U_{tg} (V)	RPM_1
220	2,2	210	0,92	270	1	150	0,44	97,6	1627
220	2,2	210	0,92	270	1	150	0,43	97,9	1632
220	2,2	210	0,92	273	1	150	0,43	98,2	1637
220	2,2	210	0,92	273	1	150	0,43	98,1	1635
220	2,2	210	0,92	273	1	150	0,43	98,1	1635

U_{tg} (V)	I_w (A)	U_w (V)	RPM_2
90,4	0,56	220	1507
92	0,52	210	1533
93,1	0,495	200	1552
94,6	0,464	190	1577
96,1	0,44	180	1602