LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology
Department of Energy- and Environmental Technology
MASTER'S THESIS

**COMPETITOR COMPARISON: VARIABLE SPEED DRIVES IN PUMPING APPLICATIONS**

The topic of the Master's thesis has been approved by the department head of the Department of Energy- and Environmental Technology on the 15th April 2008.

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**ABSTRACT**

Lappeenranta University of Technology
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**Competitor comparison: variable speed drives in pumping applications**

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100 pages, 57 pictures, 3 tables and 8 appendixes

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Keywords: Variable speed drive, pumping application, drive system, efficiency

As the world's energy demand is increasing, a durable solution to control it is to improve the energy efficiency of the processes. It has been estimated that pumping applications have a significant potential for energy savings trough equipment or control system changes. For many pumping applications the use of a variable speed drive as a process control element is the most energy efficient solution.

The main target of this study is to examine the energy efficiency of a drive system that moves the pump. In a larger scale the purpose of this study is to examine how the different manufacturers' variable speed drives are functioning as a control device of a pumping process. The idea is to compare the drives from a normal pump user's point of view. The things that are mattering for the pump user are the efficiency gained in the process and the easiness of the use of the VSD. So some thought is given also on valuating the user-friendliness of the VSDs. The VSDs are compared to each other also on the basis of their life cycle energy costs in different kind of pumping cases.

The comparison is made between ACS800 from ABB, VLT AQUA Drive from Danfoss, NX-drive from Vacon and Micromaster 430 from Siemens. The efficiencies are measured in power electronics laboratory in the Lappeenranta University of Technology with a system that consists of a variable speed drive, an induction motor with dc-machine, two power analyzers and a torque transducer.

The efficiencies are measured as a function of a load at different frequencies. According to measurement results the differences between the measured system efficiencies on the actual working area of pumping are on average few percent units. When examining efficiencies at the whole range of different loads and frequencies, the differences get bigger. At low frequencies and loads the differences between the most efficient and the least efficient systems are at the most about ten percent units. At the most of the tested points ABB's drive seem to have slightly better efficiencies than the other drives.

**TIIVISTELMÄ**

Lappeenrannan teknillinen yliopisto
Energia- ja ympäristötekniikan osasto

Niina Aranto

**Kilpailijavertailu: Taajuusmuuttajien pumppusovellukset**

Diplomityö

2008

100 sivua, 57 kuvaa, 3 taulukkoa ja 8 liitettä

Tarkastajat: Professori TkT Esa Marttila
TkL Simo Hammo

Hakusanat: Taajuusmuuttaja, pumppusovellus, energiatehokkuus

Energian kulutus ympäri maailmaa kasvaa jatkuvasti. Kestävä keino hillitä kasvua on parantaa prosessien energiatehokkuutta. On osoitettu, että oikeanlaisella prosessinohjauksella ja laitteistolla pumppusovelluksien tehokkuutta voidaan parantaa merkittävästi. Monissa tapauksissa on taloudellisinta ohjata pumppausprosessia taajuusmuuttajan avulla.

Tämän tutkimuksen päätavoite on tutkia pumppua pyörittävän taajuusmuuttaja-ohjatun moottorin tehokkuutta. Työssä vertaillaan toisiinsa eri laitevalmistajien taajuusmuuttajia ja niiden soveltumista pumppausprosessiin. Ideana on vertailla taajuusmuuttajia normaalin pumppukäyttäjän näkökulmasta, jolloin tärkeimpiä vertailukohteita ovat prosessissa saavutettava tehokkuus sekä taajuusmuuttajan käytön vaivattomuus. Lisäksi työssä vertaillaan taajuusmuuttajia erilaisten pumppausprosessien elinkaarten aikaisten energiakustannusten perusteella.

Vertailussa mukana olevat taajuusmuuttajat ovat ACS800 ABB:lta, VLT AQUA Drive Danfossilta, NX-Drive Vaconilta sekä Micromaster 430 Siemensiltä. Taajuusmuuttajien ja moottorin hyötysuhteet mitataan Lappeenrannan Teknillisen Yliopiston tehoelektroniikan laboratoriossa. Mittauslaitteisto koostuu taajuusmuuttajasta, moottorista ja kuormakoneesta, kahdesta tehoanalysaattorista sekä vääntömomenttianturista.

Hyötysuhteet mitataan kuorman funktiona eri taajuuksilla. Mittauksista saatujen tulosten mukaan erot systeemien hyötysuhteissa pumpun käyttöalueella ovat korkeintaan muutamia prosenttiyksiköitä. Tutkittaessa hyötysuhteita laajemmalla alueella eri taajuuksilla ja kuormilla erot kasvavat laitteiden välillä. Erot ovat suurimmillaan pienillä taajuuksilla ja suurilla kuormilla, jolloin ero maksimissaan on noin 10 prosenttiyksikköä. Testattavista laitteista ABB:n taajuusmuuttajalla ohjatulla moottorilla oli suurimmassa osassa mittapisteitä hieman muita parempi hyötysuhde.

**PREFACE**

At the end of April 2008 this interesting and challenging period of writing my master's thesis is ending. This project has given me a great opportunity to learn more about pumping systems not to mention the practical view that I got of the energy efficiency of the motors and variable speed drives.

This study was a part of ABB Oy Drives' investigations. The supervisor of my study from ABB was M.Sc. Jukka Tolvanen. To him I want to give my great thanks for his guidance and dedication. I also want to thank my examiners at Lappeenranta University of Technology, Professor Esa Marttila and Lic.Sc. Simo Hammo for their advices. To Juha Viholainen I'm grateful for his help along the way and especially with the practical part of my study. My thanks also to Markku Niemelä, Erkki Nikku and Martti Lindh for their assistance during the laboratory measurements.

Foremost I want to thank my family for their support during my studies. Heartfelt thanks also to my friends, especially to Ville for his encouragement on the way.

Lappeenranta 28.4.2008

Niina Aranto

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# SYMBOLS

## Greek letters

| | | |
|---|---|---|
| $\eta$ | efficiency | [%] |
| $\rho$ | density of the liquid | [$kg/m^3$] |
| $\lambda$ | power factor | |

## Roman letters

| | | |
|---|---|---|
| $D$ | impeller diameter | [m] |
| $E$ | energy | [kWh] |
| $f$ | frequency | [Hz] |
| $g$ | acceleration of gravity | [$m/s^2$] |
| $I$ | current | [A] |
| $H$ | head | [m] |
| $N$ | rotation speed | [rpm] |
| $P$ | power | [kW] |
| $Q$ | flow rate | [l/s], [$m^3/s$] |
| $T$ | torque | [Nm] |
| $U$ | voltage | [V] |
| $v$ | velocity | [m/s] |

## Subscripts

| | |
|---|---|
| a | axis |
| add. | additional |
| cu | copper |
| d | demand |
| D | dissipation |
| d.s. | drive system |
| dyn. | dynamic |

| | |
|---|---|
| f | first harmonic |
| fe | ferro |
| geod. | geodetic |
| in | input |
| m | motor |
| mech. | mechanical |
| out | output |
| p | pump |
| r | rotor |
| s | stator |
| sys. | system |
| VSD | variable speed drive |

# 1 INTRODUCTION

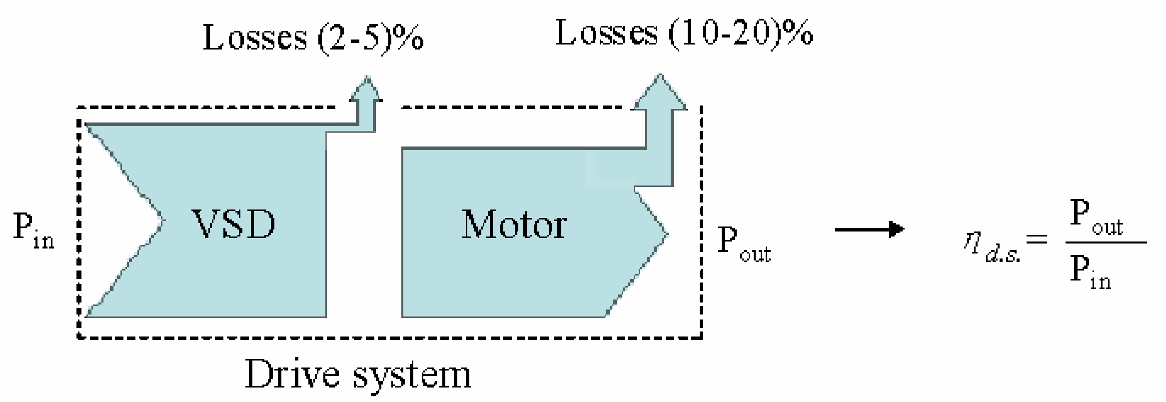
## 1.1 Background of the study

As the energy demand all over the world increases and climate change accelerates, must ways to save energy be invented. Energy-efficiency, getting more use out of the electricity we already generate, is a durable solution to meet the need of increasing energy demand. Technological solutions to improve energy efficiency not only decrease the environmental burden but also produce cost savings. To achieve energy savings new energy efficient equipment need to be developed, but there also lays a great potential to accomplish energy savings in old existing processes. Among others processes, pumping systems have a great technical and economic potential for energy saving. After motors, pumps are the second most widely used machine in the world. So by increasing the efficiency of pumping systems would a great amount of energy be saved.

All pumping systems comprise a pump, a driver, piping and operating controls. The efficiency of a given pump is one small factor affecting the efficiency of a pumping system. Pumping applications represents a significant potential to save energy by using a variable speed drive technology to control the process. The use of a variable speed drive in a pumping process will in many cases save a remarkable amount of energy. Even more energy will be saved, if the drive system is as efficient as possible. In this study, the attention is paid in the efficiency of the drive system, which consists of a variable speed drive and a motor. A special attention is given to the comparison of different manufacturer's variable speed drives. This study is a part of an investigation of ABB Oy Drives.

Efficiency of the drive system is an important factor because in the long run high efficiency means economic savings for the user, not to mention the benefits for environment. The efficiency of the drive system consists of the efficiency of the motor and the efficiency of the device that controls the motor. The main objective of this study is to examine how the different manufacturers variable speed drives are functioning as a part of a pumping system, and what kind of an effect they have on the efficiency of the drive system in comparison to each other.

In picture (1) there is illustrated how the efficiency of the drive system forms. The losses of the variable speed drive and the motor define the efficiency of the drive system. The efficiency of the drive system ($\eta_{d.s.}$) is equal to the ratio of the input power to the variable speed drive and the output power of the motor. Typically the losses of a variable speed drive controlled motor (11 kW or smaller) are (10-20)% at the nominal speed and load. The losses of a variable speed drive are typically (2-5)%. The focus of this study is to compare the efficiencies of drive systems with different manufacturers' drives.




**Picture 1.** The formation of the drive systems efficiency at nominal speed and load. Sizes of the arrows depict energy flows: the input and output energies and the losses. (The amount of losses in the picture is typical for a variable speed drive controlled motor size of 11kW or smaller).

## 1.2 Competitor comparison

The main objective of this study is to compare variable speed drives from different manufacturers functioning as a control device of a pumping process. The comparison is made between ACS800 from ABB, VLT AQUA Drive from Danfoss, NX-drive from Vacon and Micromaster 430 from Siemens.

The comparison is made from the perspective of a normal pump user. From the person's point of view, who is using a variable speed drive in a pumping process, the mattering things in the first instance are the efficiency of the process and the user-friendliness of the control device of the process. Also the environmental impact of the process concerns the pump user. When it comes to electrical devices, the biggest environmental impact of the device is caused by the use of the device.

So the normal pump user's perspective being the starting point of this study, the main comparing categories are the efficiency of the drive system (VSD + motor) and the user-friendliness of the variable speed drive. The environmental aspect is taken into account trough energy-efficiency.

The efficiency of the system is measured in power electronics laboratory in the Lappeenranta University of Technology with a system that consists of a variable speed drive and an induction motor with DC-machine. The input powers to the variable speed drive an to the motor are measured with two power analyzers, one located before the variable speed drive and the other located between the VSD and the motor. The mechanical power on the motors shaft is measured with a torque transducer. The efficiency of the variable speed drive itself is examined as well as the efficiency of the drive system.

The target of the efficiency measurements is not to give exact and absolute efficiency results of the different drive systems, but to compare the variable speed drives of different manufacturers functioning as a control device of a pumping process. The idea is to examine and compare what kind of efficiencies the pump user manages to achieve with different variable speed drives. So too much attention should not be paid in individual efficiencies; the main point of the measurements is to compare the efficiencies of different drive systems to each other. The measured efficiencies are commensurable to each other in the light of the fact that the measuring equipment and circumstances are the same in all efficiency measurements. The measuring accuracy is the same in all cases.

Besides the efficiency the user-friendliness is an aspect of the comparison. The definition of the user-friendliness varies depending on the user, so it is impossible to give a comprehensive valuation about the user-friendliness of a device. Because of the user oriented nature of this point of comparison, the valuation of the user-friendliness is based on empiric experiences of the user and the installer of the drive.

The valuation of the user-friendliness is given by the measurer who can be compared to a person who uses the variable speed drive in a pumping application. When evaluating the user-friendliness, the attention is paid in the easiness of the implementation, easiness of the start-up and the use, logicalness of the control panel and readability of the manuals.

The opinions of user-friendliness are formed on the basis of how the measurement situation succeeded with the drive. Because an opinion is more or less a matter of judgment, the evaluation of user-friendliness should be thought more as an depiction of the problems and successes with different VSD's in the measurement situation.

## 1.3 Objectives and the scope of the study

The main objective of this study is to examine different variable speed drives functioning as a part of a pumping process. The main attention is paid in the efficiency of the drive system that runs the pump. The idea is to examine what kind of an effect different manufacturers' variable speed drives have on the efficiency of the drive system. The comparison is made between variable speed drives from ABB, Vacon, Danfoss and Siemens. The efficiencies of the drive systems are measured in power electronics laboratory in the Lappeenranta University of Technology with a system that consists of a variable speed drive and an induction motor with DC-machine. The measurements consists of two test runs: in the first test run the efficiencies are measured without any energy optimization and on the second test run the efficiencies are measured with the optimization on. The efficiencies are measured for the VSD itself and for the drive system, which consists of a variable speed drive and an induction motor.

On the grounds of the measured efficiencies are calculated life cycle energy costs of three imaginary pumping cases. The idea of the calculations is to examine how the different manufacturers' drives function as a part of different kinds of pumping cases, and what kind of an effect they have on the energy consumption of the processes. As a result of the calculations are gained the life cycle energy costs of different pumping cases with different drives.

Another objective of this study is to compare the easiness of the use of the drives from a pump user's point of view. The purpose is to find out what kind of differences there are in the use of the different variable speed drives, and what things might cause problems for the user and what things go well with the drives. The approach of consideration when valuating the user-friendliness of the variable speed drives is pretty practical.

## 1.4 Structure of the study

As this study concerns variable speed drives used in pumping applications, at fist there is presented basic theory about pumps and pumping (Chapter 2). After that is presented theory about variable speed drive technology and the use of it in pumping applications (Chapter 3). The main focus of this study is the efficiency of the drive system, so in chapter four there is theory about induction motor controlled with a variable speed drive. The attention in that chapter is paid in the losses and the efficiency of VSD-controlled motor.

In the last five chapters is presented the experimental part of this study. Before going into results of the comparison it is clarifying to have a general view of the aspects of the comparison. The aspects and the focus of the competitor comparison are introduced in the chapter five. In chapter five there is also described the method of the life cycle energy calculations and shortly introduced the course of the efficiency measurements.

The efficiency comparison is the main focus of this study, and chapter six is devoted to the description of the measurements. In chapter six there are also presented the measured efficiencies of different drives systems.

The actual results of the different aspects of the comparison are presented in chapter seven. The measured efficiencies are presented already in the chapter six, but in chapter seven there are presented the efficiencies of the drives compared to each others. The results of the life cycle cost analysis are also presented in this chapter as well as the valuations of the user-friendliness of the VSDs.

In chapters eight and nine there are conclusions and a summary of this study.

# 2 PUMPS

This chapter presents theory about pumps. At first are introduced some applications where pumps are used and the energy saving potential in pumping processes. The pumping system hydraulic characteristics and the methods of flow control are introduced as well.

## 2.1 Pumping applications

After motors, pumps are the second most widely used machine in the world. Practically all manufacturing plants, commercial buildings and municipalities rely on pumping systems for their daily operation. In the commercial sector, pumps are primarily used in heating, ventilation and air conditioning systems to provide water for heat transfer. Municipalities use pumps for water and wastewater transfer and treatment and for land drainage. Pumps are used in many kinds of applications: they provide domestic services, commercial and agricultural services, municipal water/wastewater services, and industrial services for food processing, chemical, petrochemical, pharmaceutical, and mechanical industries. (Asdal 2006, 44.)

Pumping systems account for nearly 20% of the world’s electrical energy demand and can account for anywhere from 25–50% of the energy usage in certain industrial plant operations. The situation is, at least in the US and in Europa, that 70% of all energy production is used to drive electric motors, and 70% of those motors drive pumps, compressors and fans. (Nolte 2004, 27.)

Energy costs can exceed a pump’s purchase price by four to 20 times, depending on the application and the running time. In fact, in most cases, energy is the single largest component of a pumps’ life cycle cost (LCC). That is the reason, why special attention should be paid in energy consumption and the efficiency of the pumping system. (Nolte 2004, 27.)

## 2.2 Energy saving potential in pumping applications

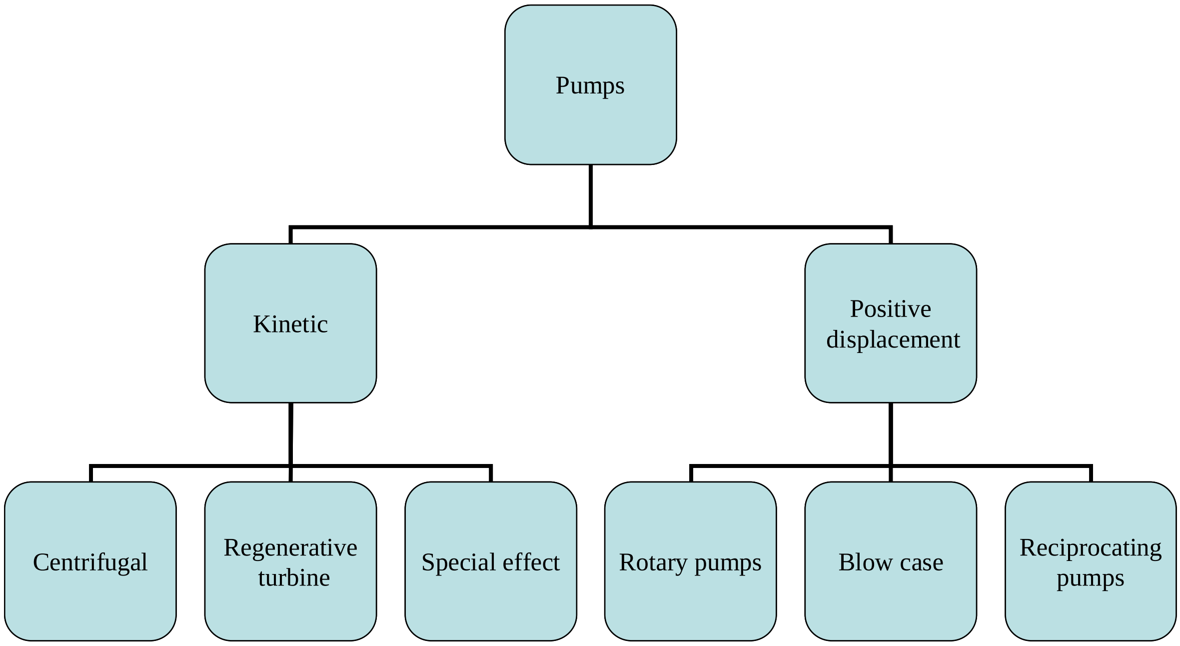
Opportunities to improve pump system energy efficiency fall into two distinct categories: existing and new systems. Existing systems provide a greater opportunity for savings than do new systems for two reasons. First, there are at least 20 times as many pumping systems in the installed base as are built each year; and, second, many of the existing systems have pumps or controls that are not optimized since the pumping tasks change over time. (Asdal et. al. 2006, 45.) Some studies have shown that 30% to 50% of the energy consumed by pumping systems could be saved through equipment or control system changes (Europump and Hydraulic Institute 2004, 3).

Opportunities in new system design must not be ignored, though. For a given new system, the potential savings in energy and life cycle costs are far greater than in a given existing system of similar size and application. One reason for this is the opportunity to optimize the piping system design. Other aspects of the pump system can also be better customized to the system requirements in the design of new systems. (Asdal et. al. 2006, 45.)

## 2.3 Pump basics

Pump is a machine used to move liquid trough a piping system and to raise the pressure of the liquid. A pump moves liquids from lower pressure to higher pressure, and overcomes this difference in pressure by adding energy to the system. The energy input into the pump is typically the energy source used to power the driver. The input energy is converted in the driver output shaft, operating at a certain speed and transmitting a certain torque. (Volk 2005, 1-5.)

Pumps can be classified several ways: according to their function, their conditions of service, materials of construction etc. At the first level pumps can be categorised to kinetic pumps and positive displacement pumps according to the principle by which energy is added to the liquid (Picture 2). (Volk 2005, 1-5.)




**Picture2.** Classification of pumps. (Volk 2005, 6.)

### 2.3.1 Centrifugal pumps

A centrifugal pump is a commonly used pump type. This study concentrates on the centrifugal pump applications, so the following theory concerns centrifugal pumps.

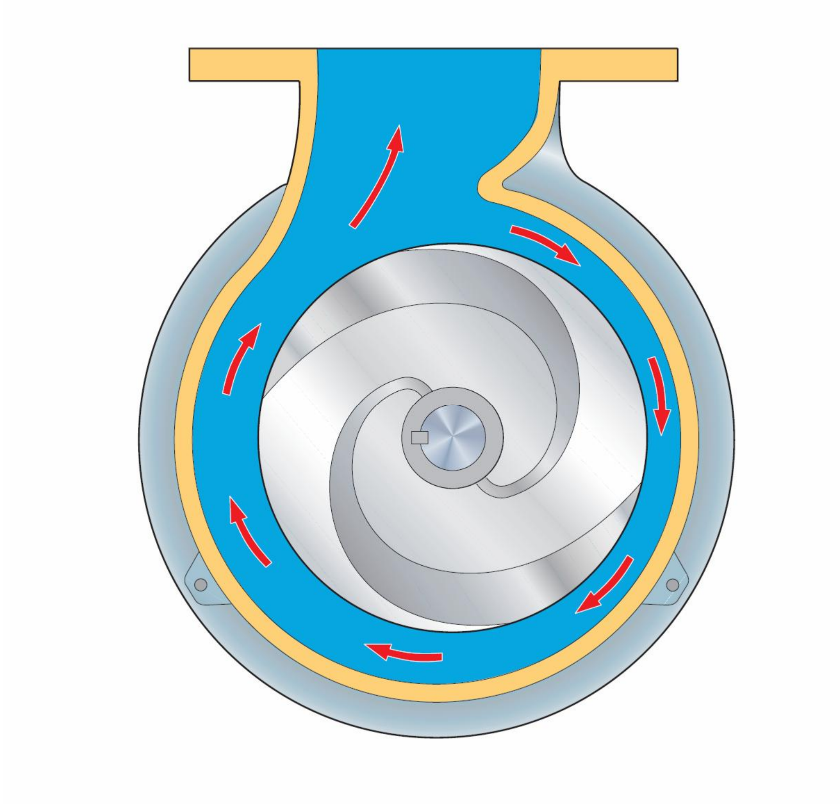
A centrifugal pump belongs in the category of kinetic pumps. In a kinetic pump, energy is continuously added to the liquid to increase its velocity. When the liquid velocity is subsequently reduced, this produces a pressure increase. Although there are several special types of pumps that fall into this classification, for the most part this classification consists of centrifugal pumps. (Volk 2005, 1-5.)

A purpose of a centrifugal pump is to convert energy of a prime mover (for example an electric motor) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy. (Sahdev, 2.)

#### 2.3.1.1 Function of a centrifugal pump

A centrifugal pump consists of an impeller attached to and rotating with the shaft and a volute casing that encloses the impeller. In a centrifugal pump, liquid is forced into the inlet side of the pump casing by atmospheric pressure or some upstream pressure. As the impeller rotates, liquid moves toward the discharge side of the pump. This creates a void or reduced pressure area at the impeller inlet. The pressure at the pump casing inlet, which is higher than this reduced pressure at the impeller inlet, forces additional liquid into the impeller to fill the void. (Volk 2005, 1-5.)

The movement of the liquid is illustrated in the picture (3), which depicts a side cross section of a centrifugal pump.



**Picture 3.** Cross section of a centrifugal pump.

## 2.4 Pumping system hydraulic characteristics

This chapter introduces the basics of pump hydraulics, particularly as they apply to centrifugal pumps. A pump's behaviour is described with characteristic curves, which are introduced in this chapter. In addition to the head, efficiency and power curves this chapter introduces the operating point of the pump and system, losses of the pump and the affinity laws. By using the affinity laws the change in pump's performance can be figured out if the speed or the impeller diameter of the pump is modified. A short review is given also about a pump problem called cavitation and the characteristic curve related to it, the net positive suction head.

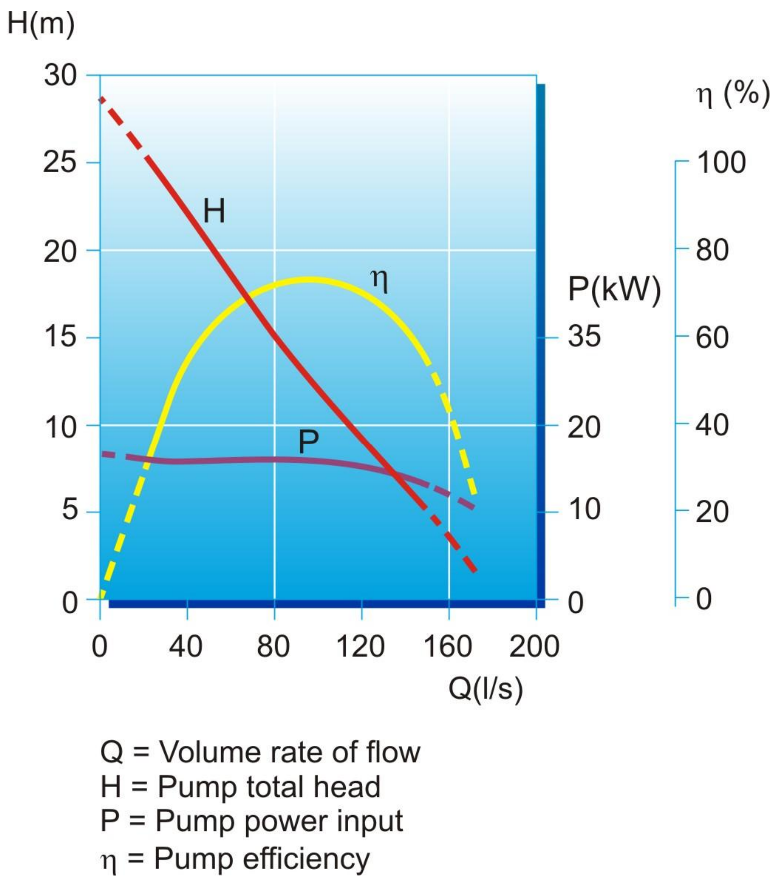
### 2.4.1 Characteristic curves

Characteristic curves of centrifugal pumps are used to illustrate operating behaviour and are used as the basis for assessing hydraulic capability. Pump performance is usually described graphically with curves (Picture 4) and it is published in pump manufacturer's literature. One graph often contains virtually the entire pump operating data and can be confusing unless properly understood and interpreted. (Spitzer 1987, 19.)

Pump curves are valid for either specific constant speed or a constant impeller diameter. Centrifugal pump performance can be represented by multiple curves indicating either: various impeller diameters at a constant speed, or various speeds with a constant impeller diameter. (Karassik 1998, 428.)

There are many characteristics of the pump function which can be illustrated as curves (Picture 4). Usually the performance of the pump, efficiency and power are expressed graphically against the flow rate.

Example of typical performance curves for submersible pump is presented below. A closer view to curves in the picture is presented in the next chapters.




**Picture 4.** Typical performance curves for a submersible pump, where Q is volume rate of flow, H is pump total head, P is pump power input and η is pump efficiency.

### 2.4.2 Head

The head curve illustrates the performance of the pump. In brief, the head means the net work done on a unit of water by the pump impeller. From the graph in picture (4), the pump head can be determined at each flow rate. It should be noted that the head of a centrifugal pump is typically at its maximum when the pump is under no flow conditions and decreases with increasing flow. (Spitzer 1987, 20.)

The head term is used to measure the kinetic energy created by the pump. In other words, head is a measurement of the height of a liquid column that the pump could create from the kinetic energy imparted to the liquid.

As head being the energy added to the liquid in the system, it can have forms of static, velocity, friction or elevation. The four separate components summed up compose the total system head.

Static head is the total elevation change that the liquid must undergo. In most cases, static head is normally measured from the surface of the liquid in the supply vessel to the surface of the liquid in the vessel where the liquid is being delivered. The total static head is measured from supply vessel surface to delivery vessel surface, regardless of whether the pump is located above the liquid level in the suction vessel, or below the liquid level in the suction vessel. (Volk 2005, 56.)

Friction head is the head required to overcome the resistance to flow in the pipe and fittings. It is dependent upon the size, condition and type of pipe, number and type of pipe fittings, flow rate, and nature of the liquid. (Volk 2005, 58.)

Pressure head must be considered when a pumping system either begins or terminates in a tank which is under some pressure other than atmospheric. The pressure in such a tank must first be converted to meters of liquid. Denoted as pressure head, pressure head refers to absolute pressure on the surface of the liquid reservoir supplying the pump suction, converted to feet of head. If the system is open, pressure head equals atmospheric pressure head. (Volk 2005, 66.)

Velocity head refers to the energy of a liquid as a result of its motion at some velocity '$v$'. It is the equivalent head in meters through which the water would have to fall to acquire the same velocity, or in other words, the head necessary to accelerate the water. The velocity head is usually insignificant and can be ignored in most high head systems. However, it can be a large factor and must be considered in low head systems. (Volk 2005, 70.)

When determining the required size of centrifugal pump for a particular application, all the components of the system head for the system in which the pump is to operate must be added up to determine the pump total head.

### 2.4.3 Power

The Pump power is also usually illustrated as a function of the flow rate. In picture (4) power curve P shows how the pump power varies as the flow rate increases. Power is usually expressed in kilowatts.

The power curve indicates the amount of rotational energy required by the pump at its shaft under given operating conditions. The required rotational energy on the pump's shaft can be determined at each flow rate.  Picture (4) illustrates, that as flow is increasing, rotational energy increases due the increased pump loading.

The required power on the pumps axis can be expressed as follows (Wirzenius 1978, 47):

$$P_a = \frac{Q.\rho \cdot g \cdot H}{\eta_P}, \tag{1}$$

| | | |
|---|---|---|
| where | $P_a$ | = Required power on the pumps axis [kW] |
| | $Q$ | =  Flow rate [$m^3$/s]] |
| | $\rho$ | = Density of the pumped liquid |
| | $g$ | = Acceleration of gravity [m/$s^2$] |
| | $H$ | =  Total head [m] |
| | $\eta_P$ | = Efficiency of the pump |

### 2.4.4 Efficiency

Pump efficiency is expressed as a function of the flow rate as well. As shown in picture (4), the efficiency can be determined at any flow rate. It can be noticed that the efficiency is zero at no flow conditions, and it increases as flow increases before peaking, and decreases with increased flow.

The pump efficiency is expressed as decimal number less than one, for example 0,75 for 75% efficiency. The relative importance of the losses (Chapter 2.4.5) varies from one pump type to another. Actual efficiencies for various types of centrifugal pumps can vary widely, over a range from less than 30% to over 90%.

The losses define the efficiency of the pump. The pump efficiency ($\eta$) is equal to the ratio of the output power ($P_{out,p}$) and the input power ($P_{in,p}$) of the pump:

$$\eta_{pump} = \frac{P_{out,p}}{P_{in,p}} \tag{2}$$

### 2.4.5 Losses

The input power is grater than output power because of the fact that a pump is not a perfectly efficient machine. There are four factors that cause a centrifugal pump to be less than perfectly efficient, which are hydraulic losses, volumetric losses, mechanical losses and disk friction losses. (Volk 2005, 80-83.)

The term ‘hydraulic losses’ is a summary of internal losses in the impeller and volute (or diffuser) due to friction in the walls of the liquid passageways and the continual change of direction of the liquid as it moves trough the pump. (Volk 2005, 82.)

Volumetric losses refer to the leakage of a usually small amount of liquid from the discharge side of a centrifugal pump to the suction side. Volumetric losses increase as internal clearances are opened up to due to wear and erosion in the pump. This causes the pump to run less efficiently. (Volk 2005, 82.)

Mechanical losses are the frictional losses that occur in the moving parts of pumps which are in contact (bearings and packing or seals). (Volk 2005, 83.)

Disk friction losses are caused because of frictional resistance between pump impeller and the casing. If the pump impeller is thought of as a rotating disk, rotating in very close proximity to a fixed disk (the casing), there is a frictional resistance to this rotation known as disk friction. (Volk 2005, 83.)

### 2.4.6 Net positive suction head

In addition to the head, power and efficiency manufacturer can also express other characteristics as graphs, for example the required net positive suction head (NPSH).

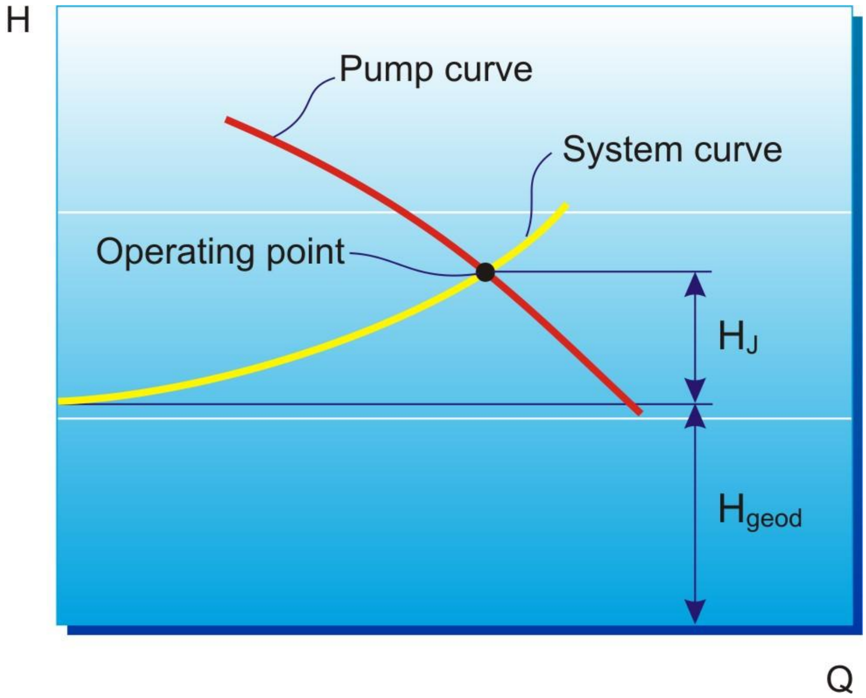
Net positive suction head (NPSH) is one of the least-understood principles of pump hydraulics and is the cause for many pump problems. It is also often mistakenly blamed for other unrelated pumps problems that nevertheless have similar symptoms. (Volk 2005, 89.)

As the liquid velocity increases trough the pump, there may be locations within the pump where the local pressure is below the suction pressure. Should the pressure fall below the vapour pressure of the liquid before rising to the discharge pressure, cavitation, the formation and subsequent implosion of bubbles, can occur and cause pump and/or piping damage. Signs of cavitation include pump/piping vibration, a sound as if rocks or ping-pong balls were inside the pump, and an eventual loss of pump output caused progressive pump damage.

The required NPSH is the amount of suction head expressed in meters required to keep the liquid from cavitating. NPSH requirements for each impeller are typically presented in graphic form. The available NPSH is the sum of barometric pressure, gage pressure at pump suction corrected to pump centreline, and the velocity head in the suction pipe, less the vapour pressure of the liquid at operating conditions, where all pressures are expressed in meters of water column. (Spitzer 1987, 22-23.)

### 2.4.7 Operating point

A pumping system operates where the pump curve and the system curve intersect (Picture 5).




**Picture 5.** An operating point.

First is explained the system curve. The system curve depicts the losses of the pipe system. The system curve is a characteristic curve of the pipeline, and it is formed of the static head ($H_{st}$) and the dynamic head ($H_{dyn}$) of the pipeline (In the picture 5 static head is $H_{geod}$ and dynamic head is $H_J$). The system curve can be represented graphically in a manner similar to the pump performance curves (Picture 5). The upward shift in the curve from the origin at no flow is due to static system head, while the curved shape of the system curve is due to the quadratic relationship between flow and the differential pressure attributable to the piping system. Pipe losses $H$ (friction and other losses) are plotted against flow rate $Q$ and added to the static head. (Spitzer 1987, 26-29.)

The intersection of the system curve and the pump curve defines the operating point of both pump and process. Static pressure and dynamic pressure drops can affect where the pump operates on its curve. The operating point of the system will slide up and down the pump curve in response to changes in the dynamic pressure drop. A static pressure drop is introduced by the elevation changes that the liquid must overcome so that flowing conditions can occur. Dynamic pressure drops are caused by pipe friction losses, pressure drops across equipment that vary with flow, and that like. (Spitzer 1987, 26-29.)

In a nutshell, by plotting the system head curve and pump curve together, can be determined, where the pump will operate on its curve, and what changes will occur if the system head curve or the pump performance curve changes. (Sahdev, 26.)

### 2.4.8 Affinity laws

The relationship between important pump parameters can be expressed mathematically for centrifugal pumps using affinity laws. By using affinity laws can changes in pump capacity, head, and power be defined, when a change is made in pump speed or impeller diameter. If the rotation speed or the impeller diameter is changed, the pumps characteristic curves will shift. The new characteristic of the pumps performance at the changed circumstances can be calculated according to affinity laws. The affinity laws are valid only under conditions of constant efficiency.

According to affinity laws:

Capacity, $Q$ changes in direct proportion to impeller diameter $D$ ratio,

$$Q_2 = Q_1 \cdot \frac{D_2}{D_1} \tag{3}$$

or to speed $N$ ratio:

$$Q_2 = Q_1 \cdot \frac{N_2}{N_1} \tag{4}$$

Head $H$ changes in direct proportion to the square of impeller diameter $D$ ratio,

$$H_2 = H_1 \cdot \left( \frac{D_2}{D_1} \right)^2 \tag{5}$$

or the square of speed $N$ ratio:

$$H_2 = H_1 \cdot \left( \frac{N_2}{N_1} \right)^2 \tag{6}$$

Power changes in direct proportion to the cube of impeller diameter ratio:

$$P_2 = P_1 \cdot \left( \frac{D_2}{D_1} \right)^3 \tag{7}$$

or the cube of speed ratio:

$$P_2 = P_1 \cdot \left( \frac{N_2}{N_1} \right)^3, \tag{8}$$

where the subscript: 1 refers to initial condition, 2 refer to new condition.

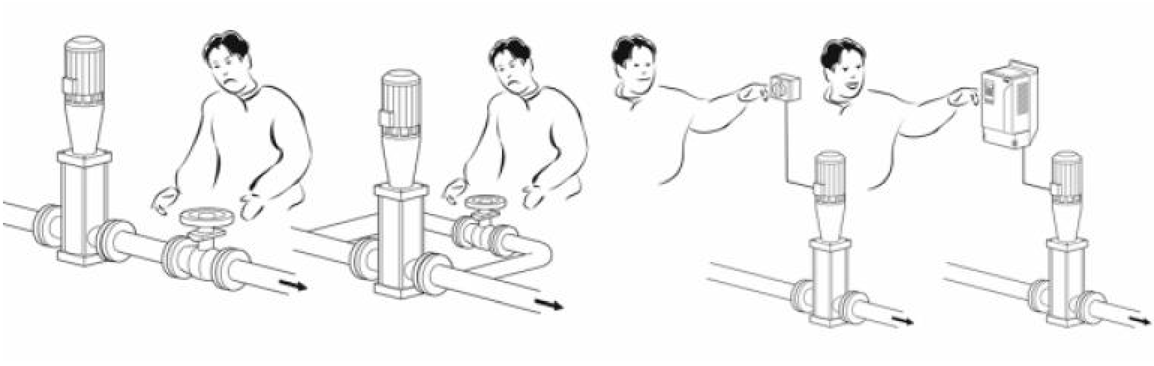
When the pump performance is known at one operating point, the applicable equation can be used to determine pump performance at another operating point. It should be noted that the efficiency remains virtually constant for changes in speed and small impeller diameter changes. Quoting Spitzer (Spitzer 1987, 25): “For example, if a given pump is operated at 90 percent of its nominal operating speed, its capacity, head, and power requirements will be 0,9 or 90 percent, $(0,9)^2$ or 81 percent, and $(0,9)^3$ or 72,9 percent. Thus 10 percent speed reduction results in a 27,1 percent reduction of power”.

## 2.5 Methods of flow control

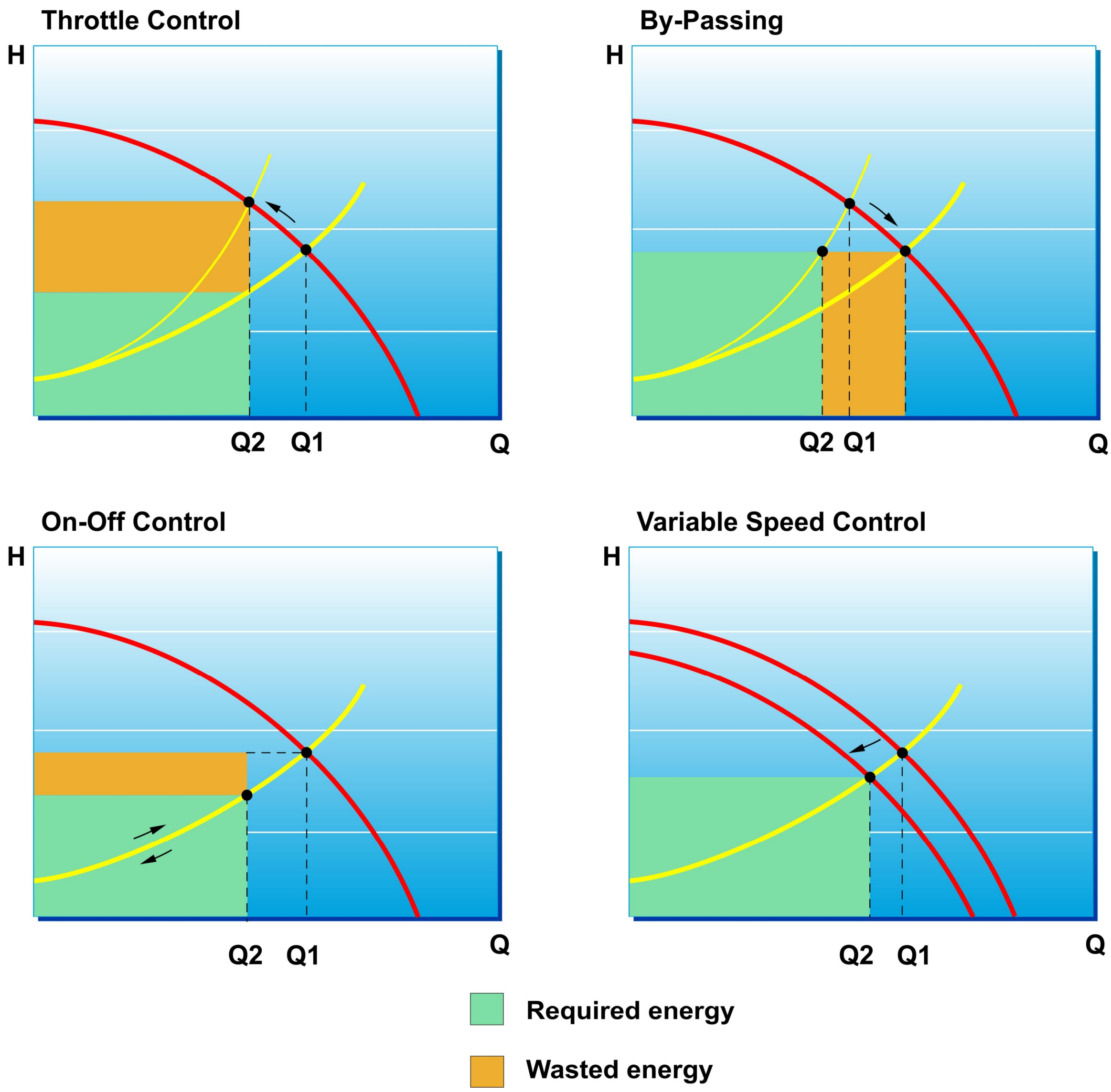
Many pumping systems require a variation of flow or pressure. It is common that the pump capacity is selected according to maximum flow, and the average pumping capacity is much smaller than that. If the pump is not functioning with the same flow rate all the time, some kind of a pump control is needed.. Because the operating point of the pump and system is at the intersection of the system curve and the pump curve, either the curves must be changed to get a different operating point. (Europump and Hydraulic Institute 2004a, 21.)

There are several different methods to match the flow to the system requirements. The most common flow control methods of pumps are varying speed, throttling, bypassing and on-off control (Picture 6). A used method to meet the demand is also to switch pumps in series or in parallel. To make an effective evaluation of which control method to use, all of the operating duty points, and their associated run times and energy consumptions, have to be identified so that the total costs can be calculated and alternative methods compared. In many cases varying the speed with a variable speed drive is the most economic solutions. (Europump and Hydraulic Institute 2004a, 22-28.)

In picture (7) is illustrated the power consumption of the most common control methods compared to each others. As can be seen from the picture, in the other control methods of throttling and by-passing the system curve shifts to meet the new demand. With the on-off control the system curve stays at the place but there is still wasted energy in the process. In the case of VSD-control the pump curve shifts to meet the new demand, and there is no wasted energy.  The methods of flow control are introduced in next chapters. The method of the variable speed control of the pump is introduced more detailed in chapter 3. “Variable speed pumping”.



**Picture 6.** Left to right: throttling, bypassing, on-off control and VSD control.




**Picture 7.** Power consumptions of different process control methods.

### 2.5.1 Throttling

With throttling the pump runs continuously and valve in the pump discharge line is opened or closed to adjust the flow to the required value (Picture 6). From the picture (7) can be seen the change in the system curve when controlling the process with valve. When the valve is closed, the pressure increases and the system curve shifts up meeting the new operating point. When the valve is in the half open position it introduces an additional friction loss in the system. (Europump and Hydraulic Institute 2004a, 27.)

There is some reduction in pump power absorbed at the lower flow rate, but the flow multiplied by the head drop across the valve is wasted energy.

### 2.5.2 By-passing

With by-pass control the pump runs continuously at the maximum process demand duty, with a permanent by-pass line attached to the outlet (Picture 6). The flow output to the system is reduced by bypassing part of the pump discharge flow to the pump suction. This means that the total flow increases but the head decreases (Picture 7). By-passing is even less energy efficient than a control valve because there is no reduction in power consumption with reduced process demand. (Europump and Hydraulic Institute 2004a, 28.)

### 2.5.3 On-off control

In this method of control, the flow is varied by switching the pump on or off. It is necessary to have a storage capacity in the system, as a wet well, an elevated tank or an accumulator type pressure vessel. The storage can provide a steady flow to the system with an intermittently operating pump.

On-off control is often used where stepless control is not necessary, such as keeping the pressure in a tank between preset limits. The pump is either running or stopped. When it is running, it runs at the chosen duty point and when it is off, it does not consume any energy. The on-off operation causes additional loads on the power transmission components and increased heating in the motor. (Europump and Hydraulic Institute 2004a, 26-27.)

### 2.5.4 VSD control

A variable speed drive is an electrical device used to control AC motor speed and torque. It provides a continuous range of process speeds compared to a discrete speed control device such as multiple-speed motors or gearboxes.

As the operation point always falls at the intersection of the pump curve and the system curve, must one of the two curves change to meet the new operation point. When controlling a pumping process with a variable speed drive, the pump curve is the one that moves.

With low static head systems, the optimal efficiency of the pump follows the system curve. With VSD control, the duty point of the pump follows the unchanged system curve. Changing the speed of the pump moves the pump curves in accordance with the affinity laws (Picture 7). If the pump impeller speed is reduced, the pump curve moves downwards. If the speed is increased, it moves upwards. This means that the pumping capacity is matched to the process requirements and there will be no wasted energy. (Europump and Hydraulic Institute 2004a, 22-24.)

In chapter three (3) there will be a closer overview about VSD control.

# 3 VARIABLE SPEED PUMPING

There are numerous methods to enable a pumping system to operate at variable speed. These methods use the application of either mechanical or electrical equipment components specifically designed for such results.

One reasonable electrical method of achieving variable speed in a pumping system is through the use of variable speed electrical drive, or shortly VSD (VSD, Variable Speed Drive). The use of VSDs allows the speed of the motor to be varied by controlling the voltage and frequency. As pump speed changes, the pump curve shifts, creating a new intersection with the system head curve. (Stolberg 2003, 29.)

Variable speed drive technology can be applied on old systems as well on new projects. There are compound benefits through implementation. These include energy and maintenance savings, pump and process reliability improvements, better process control and less fugitive emissions. Also, on new projects, VSD application can reduce overall capital cost by eliminating valves and starters plus the associated wiring and pneumatic lines. In many cases, smaller pumps with lower horsepower motors can be used. (Pemberton 2005, 22.)

## 3.1 Variable speed pumping applications

The all applications were variable speed drives are commonly used can be divided into two groups: applications associated to energy saving and the different kind of applications of materials handling. The volumes of the both applications are about the same, and the volumes are increasing all the time. The applications where the use of the variable speed drive is associated to energy saving are applications of pumps or fans. Commonly the applications of pumps and fans are from their size bigger than 2,2 kW, except some small pumping applications like applications with chemical pumps. (Erkinheimo et al. 1997, 57.)

The applications that take advantage of the variable speed technology are used for example in processing industry, in municipalities for water supply and in sewage treatment plants. In water pumping plants variable speed drives are controlling different kind of pumps. A typical and commonly used application for VSD is to control the pressure of pipeline network. In addition to benefits of energy saving achieved by the use of VSD it also eliminates water hammer in the piping caused by the starts and stops of the motor. Also momentary undervoltages in the supply net are avoided. Undervoltages of the supply net can be a big problem especially at booster stations in sparsely populated areas, where the electrical network is not stiff enough. (Erkinheimo et al. 1997, 58.)

## 3.2 Variable speed technology

Pumping applications represents a significant opportunity for applying variable speed drive technology in new as well as retrofit applications.

In a typical level control loop, the level in a vessel is controlled by throttling a control valve at the pump discharge. In many applications, the flow through the pump will be between 25 and 75 percents of capacity the major of the time. While this loop is conceptually straight-forward, a significant percentage of the hydraulic energy generated by the pump is dissipated across the control valve to regulate the pressure downstream of the control valve to produce the desired flow. The pump must be sized to accommodate the pressure drop associated with the control valve at maximum flow.

Application of variable speed drive as the final control element in the loop will control the pump so as to generate only the hydraulic energy required to discharge the desired amount of liquid. This approach reduces electric costs while reducing pump maintenance requirements. The net result is a system that that reduces operating and maintenance costs by eliminating the need for a control valve, bypass piping and the associated energy losses. (Spitzer 1987, 110.)

Variable frequency drive technology employs solid-state electronic techniques to vary motor speed, thereby varying the operating speed of piece of equipment. These drives have no moving parts and hence require minimal maintenance when compared to other non-electronic alternative final control elements. (Spitzer 1987, 110.)

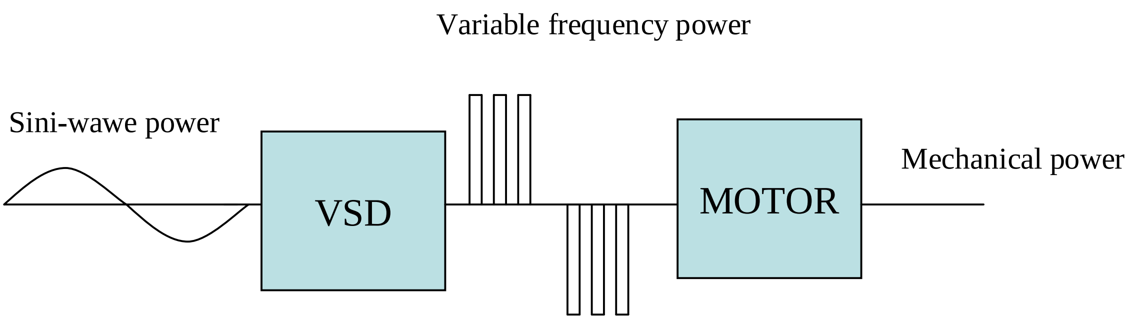
### 3.2.2. Variable speed drive

Variable speed drives have improved much since the first VSDs came to the market in the end of 60´s. (Erkinheimo et al. 1997, 11). While all of the alternate final control elements have their place, recent technical developments and cost reductions, primarily in the field of semiconductor technology, have resulted in an increased application of electronic variable speed drive technology. (Spitzer 1987, 109.)

The overall drive control strategy is to produce a waveform that is compatible with the motor, which in most cases tends to approximate the sine wave that the motor was designed to accept. (Spitzer 1987, 110.)

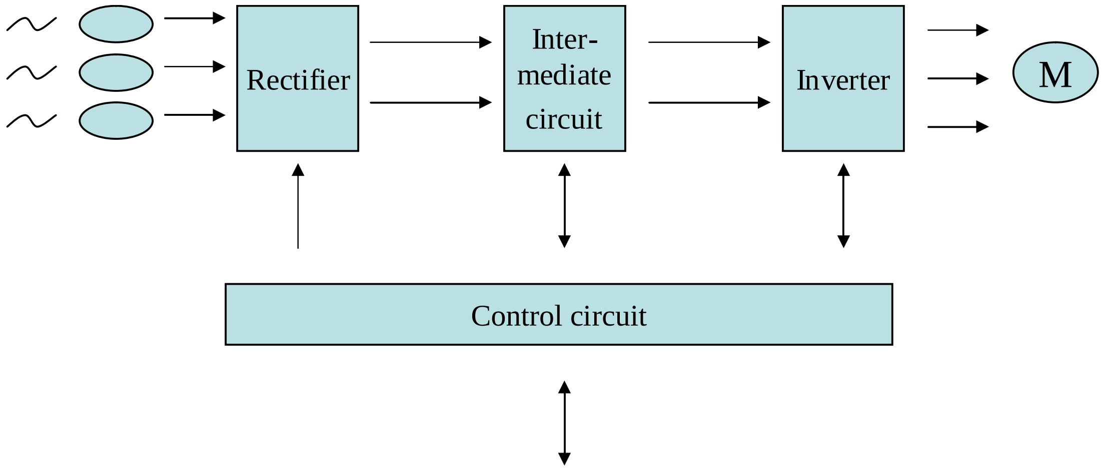
#### 3.2.2.1.Construction and operational principle of VSD

Variable speed drive converts the sini-wave power from the power supply into the variable frequency power, which is sent to the motor. Motor converts variable frequency power into the mechanical power, which rotates the pump. (Picture 8.)




**Picture 8.** Power transformation.

The usual design of a variable speed drive consists of four main parts (Picture 9).




**Picture 9.** Skeleton diagram of variable speed drive (Erkinheimo et al. 1997, 11).

A variable speed drive as described in picture above (9) first converts three-phase alternating-current voltage to pulsating direct-current voltage using rectifier. (Erkinheimo et al. 1997, 58.)

The intermediate circuit can be thought as a store, where from the motor gets its energy through the inverter. There are three types of intermediate circuits. One type converts the voltage coming from rectifier into direct current. Another type stabilizes the pulsating dc-voltage and sends it to the inverter. Third type of intermediate circuits converts rectifier's constant direct-current voltage into alternative voltage. (Erkinheimo et al. 1997, 16.)

Inverter is the final module of the variable speed drive before the motor. Inverter controls the frequency of motor voltage and it takes care, that the supply to the motor is always alternating current. Intermediate circuit is the last module which adapts the output voltage to be appropriate to the load. (Erkinheimo et al. 1997, 18.)

Electronics of the control circuit sends information to rectifier, intermediate circuit and inverter. Control circuit has two missions: it controls the semiconductors of the VSD and it also receives information from the devices around the VSD as well as it sends information to them. This information can be given by the end user through the control panel or higher level PLC-controlling. (PLC, Programmable Logic Circuit) (Erkinheimo et al. 1997, 31.)

### 3.2.3. Induction motor

The most commonly used adjustable motor drive in industry is an induction motor controlled with the variable speed drive. The task of an electric motor is to convert the electric power from power supply into mechanical power to the motor shaft. The losses in motor reduce the efficiency of power conversion.

The functioning of induction motor is premised on the basis of mutual reactions between magnetic field and current-carrying conductor in it.

Earlier it was more complicated to accommodate variable speed drive with motor, because the effects of starting voltage, starting compensation and slip compensation were hard to construe. Nowadays variable speed drive fixes these magnitudes automatically in accordance with motors nominal effect, frequency, voltage and current. (Erkinheimo et al. 1997, 59.)

### 3.2.4. Benefits of using variable speed drive

Several benefits of using variable speed drive in a pumping application can be summed up in three categories: energy savings, improved process control and improved system reliability. (Europump and Hydraulic Institute 2004b, 12.)

Energy savings of 30-50% have been achieved in many rotodynamic pump installations by installing VSDs (Europump and Hydraulic Institute 2004b, 12). Energy savings are possible with VSD control due to the affinity laws that govern the operation of centrifugal pumps. Compared with throttling valves and bypass systems, speed reduction provides significant energy savings at partial load. (Pemberton 2005, 23.)

By matching pump output flow or pressure directly to the process requirements, small variations can be corrected more rapidly by a VSD than by other control forms, which improves process performance. There is less probability of flow or pressure surges when the control device provides rates of change, which are virtually infinitely variable. (Europump and Hydraulic Institute 2004b, 12.)

Use of VSD also improves system reliability. When reducing speed by using a VSD, the wearing of pump reduces, particularly in bearings and seals. (Europump and Hydraulic Institute 2004b, 12.) Variable speed pump systems can also minimize the occurrence of line surges and the resultant water hammer in the upstream piping, which will lengthen the mechanical life of the pump and valve equipment. (Stolberg 2003, 31.) Need for maintenance will reduce and breakdowns will compute. Use of VSD smoothes out the process flow from point to point.

As been estimated, there are many benefits through implementation of VSD in old as well as in new pumping application. These include energy and maintenance savings, pump and process reliability improvements, better process control and less fugitive emissions. On new projects, VSD application can reduce overall capital cost by eliminating valves and starters plus the associated wiring and pneumatic lines. In many cases, smaller pumps with smaller motors can be used. In terms of piping, smaller diameters often suffice and by-pass lines can be eliminated. (Pemberton 2005, 23.)

A variable speed drive as a final control element has many advantages compared with the other final control elements, such as throttling or by-passing. Yet it should be noted that variable speed drive technology is not universally applicable, and that other technologies may be better suited for a given application. (Spitzer 1987, 109.)

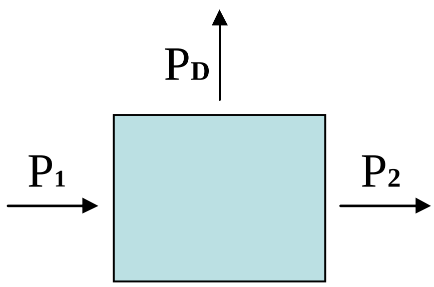
# 4. EFFICIENCY OF THE DRIVE SYSTEM

The efficiency of a given pump is one small factor affecting the efficiency of a pumping system. Another affecting factor is the efficiency of the drive system (motor and VSD), which is introduced in this chapter.

The VDE 0160-standard defines the efficiency of a device ($\eta$) as equal to the ratio of

$$\eta = \frac{P_2}{P_1}, \tag{9}$$

where $P_1$ is the input power to the device and $P_2$ is the output power. Remainder of $P_1$ and $P_2$ is the dissipation power $P_D$, which dissipates in a form of heat (Picture 10).




**Picture 10.** Input, output and dissipation powers of a device. (Erkinheimo et al. 1997, 75).

Efficiency can be calculated just for the VSD, just for the motor, or both of them together (= efficiency of the drive system).

Efficiency of VSD is equal to the ratio of input and output power:

$$\eta_{VSD} = \frac{P_2}{P_1}, \tag{10}$$

where $P_1$ is input power and $P_2$ is output power.

Efficiency of motor is also equal to the ratio of input and output power:

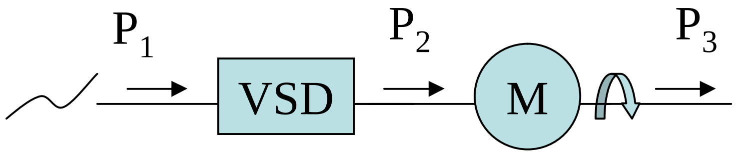
$$\eta_{Motor} = \frac{P_3}{P_2}, \tag{11}$$

where $P_2$ is input power and $P_3$ is output power.

In consequence efficiency of the drive system is

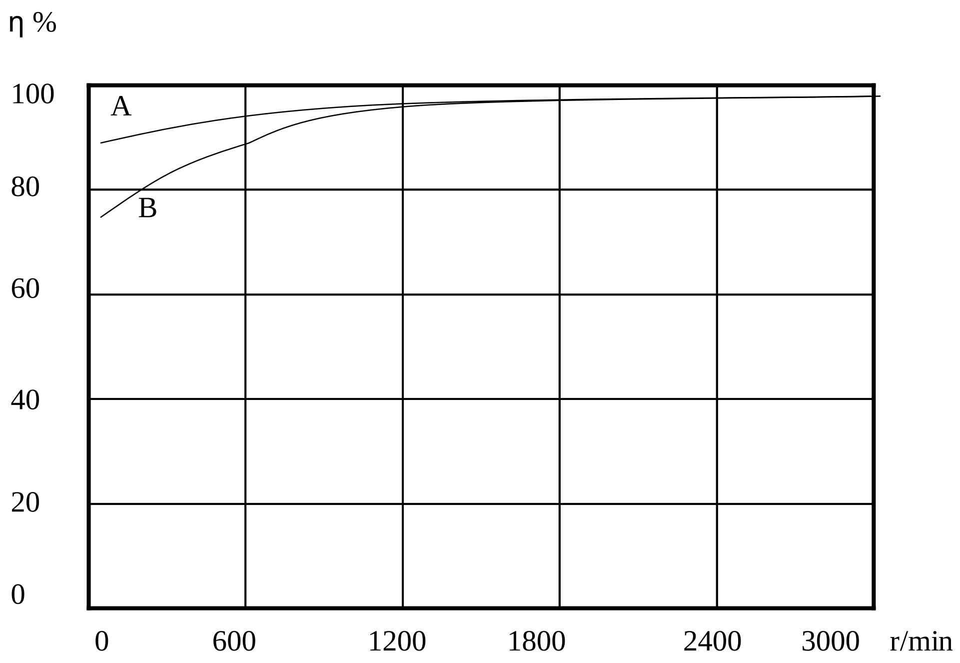
$$\eta_{sys.} = \frac{P_3}{P_1}, \tag{12}$$

where $P_1$ is input power to the VSD and $P_3$ is output power of the motor (Picture 11).



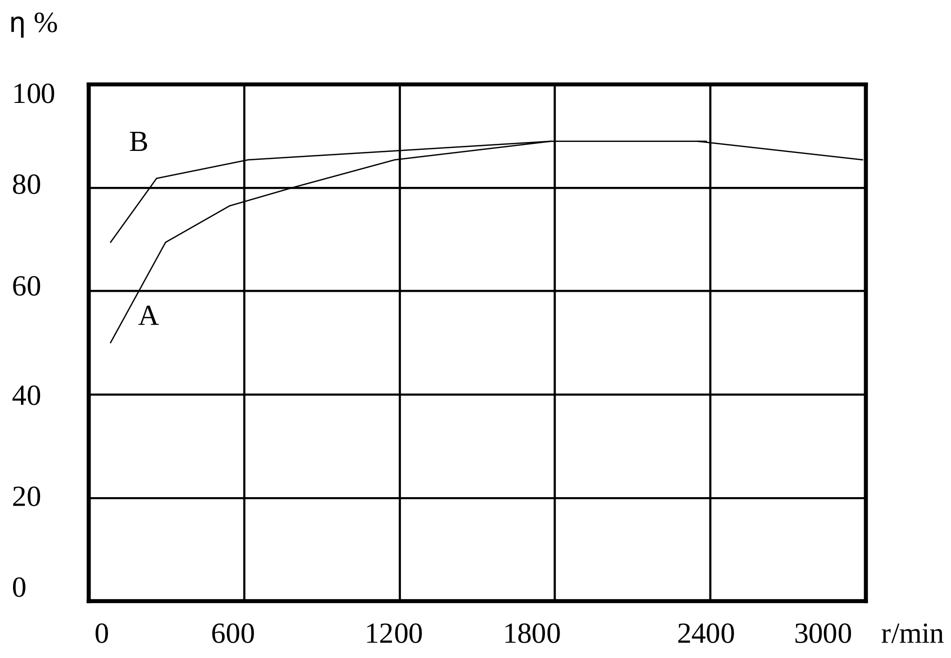

**Picture 11.** Input and output powers of the drive system (Erkinheimo et al. 1997, 75).

The picture (12) below illustrates that the efficiency of VSD is good in the whole control range, with high load as well as with low load.



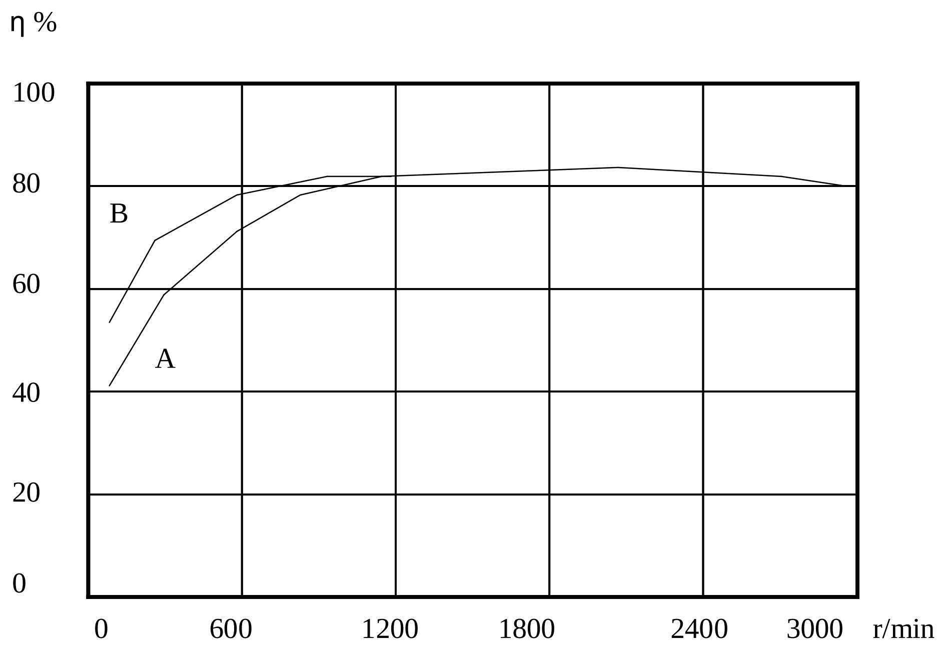

**Picture 12.** Efficiency curves for a variable speed drive, when the load is 100% (A) and 25% (B) (Erkinheimo et al. 1997, 75).

Picture (13) shows efficiency curves for a typical motor with full load and low load.




**Picture 13**. Efficiency curves for a typical motor, when the load is 100% (A) and 25% (B) (Erkinheimo et al. 1997, 75).

The picture (14) below illustrates the efficiency of the drive system (VSD and motor) with full load and low load.




**Picture 14.** Efficiency curves for a drive system (VSD and motor), when the load is 100% (A) and 25% (B) (Erkinheimo et al. 1997, 75).

The efficiency curves in pictures above demonstrate that the efficiency of the motor has a bigger effect on the total efficiency of the drive system. The efficiency of the VSD is high in the whole control range.

The graphs also show that the efficiency is lowest when the running speed is lowest. Yet it does not mean that the absolute power dissipation is biggest when running speed is low.

The better the efficiency of VSD is, the less power will dissipate as a form of heat. The less there develops heat in the semi-conductors and coils, the longer is their length of life.

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## 4.1 Losses of the VSD-controlled motor

The losses of an induction motor can be roughly categorized on the basis where the losses are physically developed. On the basis of this principle the losses can be divided into following categories (Malinen 2005, 10):

- Resistance losses of rotor and stator
- Iron losses of rotor and stator
- Ventilation- and friction losses of rotor

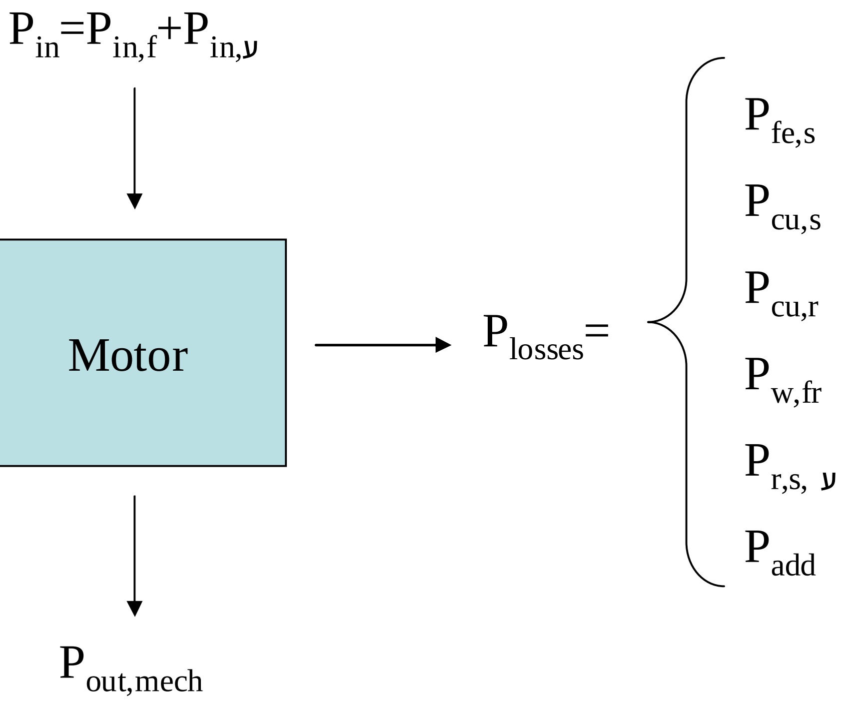
The efficiency of a typical double-, four- or six pole induction motor in the industrial field in a 50Hz net is 90-96%. The efficiency of smaller motors (1,1-11 kW) is lower, 80-90%.

The efficiency of the motor is lower when it is controlled with a variable speed drive. That is because the VSD generates an un-sinusoidal input to the motor. The efficiency of the whole drive system (motor and VSD) is composed of the efficiency of the motor and the efficiency of the variable speed drive. When the motor is controlled with VSD, the efficiency of the motor is lower because of the additional losses developed in the motor, which are caused by the harmonics in the VSD´s voltage. (Malinen 2005, 26-27.)

The VSD controls the running speed of the motor, so the mutual dependence between the running speed of the motor and the losses of the motor should be noticed. As motor is functioning above it's nominal running speed, the ventilation- and friction losses increase. When the motor operates below the nominal speed, the mechanical losses decrease. As the speed gets lower the cooling capacity decreases. (Malinen 2005, 20-26.)

The input power supplied to the motor can be divided into harmonic components. The first harmonic generates the torque. All the other harmonics except the first harmonic are disadvantageous for the sake of the motor. The harmonics cause heating in the motor, premature ageing of the windings, bearing damage and other damages. Only the power of the first harmonic can produce mechanical power while the power of the other harmonics is causing losses and not generating any shaft power. (Malinen 2005, 20-26.)

As been said, it can be presented that the motors input power $P_{in}$ consists of the power of the first harmonic $P_{in,f}$ and the power of the harmonics $P_{\text{in,ע}}$. The losses which are caused by the harmonics can be depicted as additional losses, and they are developed in the rotor and the stator. Other losses of the motor are resistance- and iron losses in rotor and stator, friction losses and other additional losses caused by the first harmonic or other harmonics. (Picture 15).




**Picture 15.** Losses of VSD controlled induction motor.

In picture (X) above, the input power $P_{in}$ is a sum of power of first harmonic $P_{in,f}$ and power of harmonics $P_{\text{in,ע}}$.

The losses consist of :

$P_{fe,s}$= iron loss in stator,

$P_{cu,s}$= resistance loss in stator,

$P_{cu,r}$= resistance loss in rotor,

$P_{w,fr}$= mechanical friction loss,

$P_{\text{r,s,ע}}$= additional losses caused by harmonics and

$P_{add}$= other additional losses.

## 4.2 Drive losses

Efficiency of the variable speed drive is high on the whole control range. On nominal power the efficiency of VSD is typically 96-98%.

The losses of a variable speed drive consist of four main sources:

- Lost volts in power semiconductor when conducting
- Coupling losses in semiconductors (coupling losses occur when state of the semiconductor is being changed.)
- Junction-, conductor- and choke losses
- Losses of control circuit.

(Piiroinen, Lecture material 1998)

# 5 COMPETITOR COMPARISON

Earlier in this study is presented some theory about pumping and variable speed technology used in pumping applications. At this point of the work the understanding of the theory explained earlier helps to understand the aspects of the main point of this study: the competitor comparison of different manufacturer's variable speed drives.

In this chapter the criteria of the comparison is introduced as well as the variable speed drives under comparison. The purpose of this chapter is to explain the perspective and the aspects of the comparison. The results of the comparison are introduced later in chapter (7) "Comparison results". The efficiency comparison has the main role in this study. The results and depiction of the efficiency measurements are introduced in chapter (6) "Measurements".

The variable speed drives are compared from the perspective of a normal pumper. From the pumpers point of view the mattering things concerning the VSD are the efficiency of the process and the user-friendliness of the VSD. The efficiency has advantages in economic sense as well as in environmental sense: energy efficient pumping system costs less money and causes less environmental burden in the long run. In this study the economic and environmental aspects are taken into account by calculating the life cycle energy costs of different drive systems. Within the limits of the study, the life cycle cost analysis considers only the costs based on energy consumption. The comparison aspects of efficiency, life cycle energy costs and user-friendliness are introduced closer in this chapter.

## 5.1 Competing variable speed drives

In this study the comparison is made between the variable speed drives of four different manufacturers. The observation involves VSDs manufactured by ABB, Vacon, Danfoss and Siemens. The observed drives are sized for a pumping process, where the pump is run with a motor of 7,5 kW. In picture (16) are introduced the competing variable speed drives.

| **ABB: ABB industrial drive, ACS800** | **Danfoss: AQUA Drive FC 202 Advanced** |
|---|---|
|   |   |
| **Vacon: NXS 00165A2H1 + water treatment –application** | **Siemens: Micromaster 430** |
|   |   |

**Picture 16.** The Variable speed drives under comparison.

More detailed specifications of the variable speed drives and the other measuring equipment in appendix I.

## 5.2 Focus and perspective of the comparison

Comparison is made from the perspective of a normal pump user. The most essential matters from the pump user's point of view are the efficiency of the process and the comfort and the easiness of the VSD's use. Also the environmental impact of the process concerns the pump user. When it comes to electrical devices, the biggest environmental impact of the device is caused by the energy use.

So the normal pump user's perspective being the starting point of this study, the main comparing categories are efficiency of the system (VSD + motor) and user-friendliness of the variable speed drive. The environmental aspect is taken into account in energy-efficiency.

Next chapters introduce more closely the aspects of the comparison.

## 5.3 Efficiency

The biggest environmental effect caused by an electrical device is usually a consequence of the use of the device. The variable speed drive, the motor, and the pump compose a pumping system which provides electric power to work. Depending on the method of the electricity production, atmospheric emissions are released when producing the electricity that the system needs. Of the greenhouse gases produced by humans the carbon dioxide has the biggest effect in contributing the generation of the greenhouse effect. A durable solution to control the accelerating energy demand and to reduce emissions is to increase the energy-efficiency of the processes.

Energy-efficiency, getting the maximum use out of the electricity that is consumed, is usually in first place thought as an economical advantage. But the importance of the climatic angle of view keeps on emphasizing by the side of the traditional economic perspective.

Energy-efficiency of a device or a system is a significant character whether it was thought from the economical perspective or the climatic perspective. The efficiency of a pumping system consists of the efficiencies of the motor, the VSD and the pump taking into consideration also other undefined losses. This study concentrates to measure the efficiency of the drive system, which consists of the motor and the variable speed drive. The other factors that effect on the systems efficiency are not taken into consideration, because the pump is thought to be exactly similar with every variable speed drive-cases, and so the pump losses are the same as well and therefore irrelevant for the sake of the comparison.

The efficiency of the system is measured in power electronics laboratory in the Lappeenranta University of Technology with a system that consists of a variable speed drive and an induction motor with dc-machine. The input powers to the variable speed drive and to the motor are measured with two power analyzers, one located before the variable speed drive and the other located between the VSD and the motor. The mechanical power on the motors shaft is measured with a torque transducer. The efficiency of the variable speed drive itself is examined as well as the efficiency of the drive system. The efficiency of the VSD ($\eta_{\mathrm{VSD}}$) is the ratio of input power to the motor and input power to the variable speed drive ($P_{\mathrm{m}}/P_{\mathrm{VSD}}$). The efficiency of the drive system ($\eta_{\mathrm{sys.}}$) is the ratio of input power to the variable speed drive and the mechanical power on the motors shaft ($P_{\mathrm{VSD}}/P_{\mathrm{mech.}}$).

The attention is paid in the comparison of the measured efficiencies, not in individual efficiencies. The efficiencies are measured with different combinations of rotation speed of the motor and the load of the motor. The frequency is kept constant and the loads are changed between (10, 20, 30,… ,100)% of the full load. The efficiencies are measured in these test points at frequency (10, 20,..,50)Hz.

All of the tested variable speed drives have some kind of a flux optimisation- or energy-saving mode. Efficiencies are measured also with this mode on.

## 5.4 Life cycle cost analysis

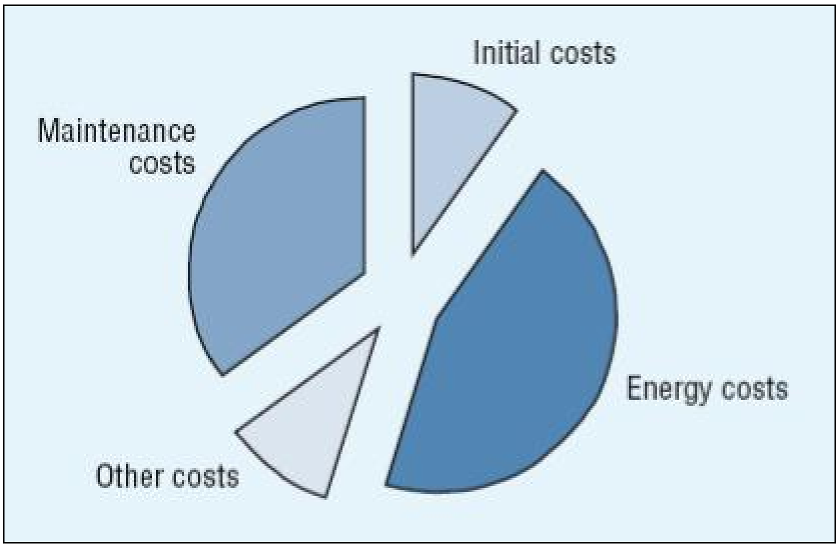
The life cycle cost analysis (LCCA) is a useful tool when comparing possible alternatives to indentify the most financially attractive one. The LCC process is a way to predict the most cost-effective solution; it does not guarantee a particular result, but helps to make a reasonable comparison between alternate solutions within the limits of the available data. In addition to the economic reasons for using LCC, many organizations can use it when considering energy efficiency as one way to reduce emissions and preserve natural resources. (Europump and Hydraulic Institute 2001, 1-2)

At this study the LCC analysis is limited to concern only the energy costs of a pump’s life time. At first in the next chapter LCC is introduced more closely as a comparison tool for possible alternatives. After that is introduced how the life cycles energy costs are calculated in this study for the competing drive systems.

### 5.4.1 Life cycle costs

With a greater understanding of the components that make up the total cost of the pumping system it is possible to dramatically reduce energy, operational, and maintenance costs. Reducing energy consumption and waste also has important environmental benefits. Life cycle cost (LCC) analysis is a management tool that helps minimizing waste and maximizing energy efficiency for many types of systems. (Europump and Hydraulic Institute 2001, 1)

The initial cost of a pump is typically a small part of the total cost to operate the pumping system over its life, which is average 15 to 20 years, depending upon its application and operating environment. Energy, maintenance and other operating costs will far outweigh the initial costs. (Europump and Hydraulic Institute 2001, 2) In picture (17) are presented typical life cycle costs for a medium sized industrial pump (Europump and Hydraulic Institute 2001, 1-6).




**Kuva 17.** Typical life cycle costs for a medium sized industrial pump.

The components of a life cycle cost analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, down time costs, environmental costs, and decommissioning and disposal costs.

### 5.4.2 Comparison of life cycle energy costs

As the main target of this study is to compare the efficiencies of different manufacturer’s variable speed drives, only the energy consumption of the drive system (VSD and the motor) is taken into account when analysing the life cycle energy costs of a pumping process. The energy costs of a pump’s life time are calculated for three imaginary pumping cases, and the results are compared to each others. The idea is to find out the energy demand of the pump in different pumping cases with different drive systems (= with different VSDs) The target is to examine how big differences there are in the pumps life cycle energy costs with different VSDs controlling the process. In this calculation the measured system efficiencies of the tested variable speed drives are used when calculating the annual energy consumption of the different pumping cases.

It must be noted that because the consideration takes into account only the efficiencies of the drive system, the energy costs got as a result are smaller than they would be in reality, because the losses of the pump are ignored. The efficiencies of just the drive system are naturally better than the efficiencies of the whole pumping system.

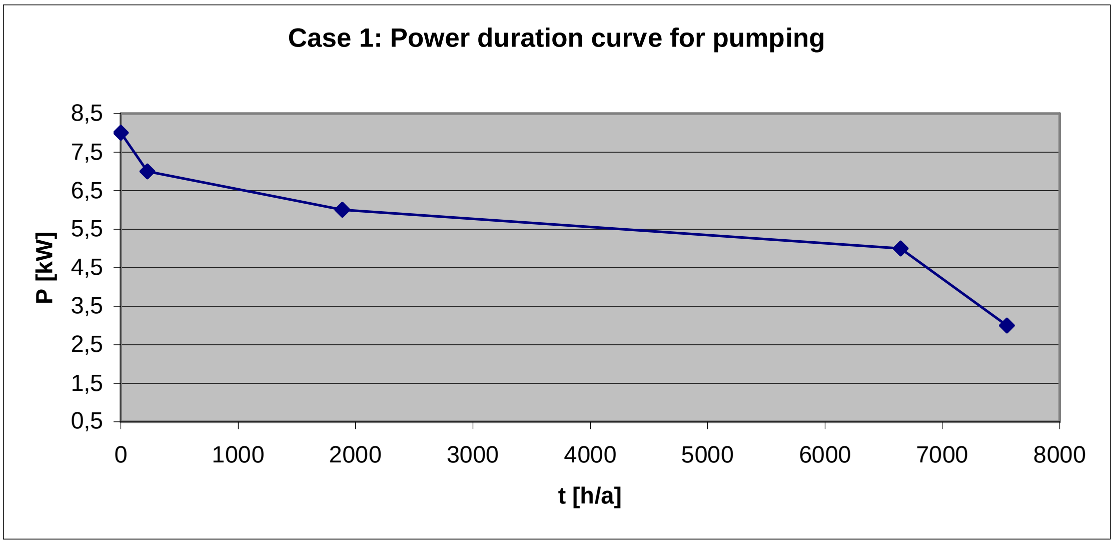
The method of the life cycle energy calculation used in this study is described in a nutshell as follows:

1. First the three pumping cases under consideration are picked: They are chosen so that they represent different kinds of pumping applications.
2. From the duration curves of the pumping cases (which illustrates the annual pumping volume) are calculated the pumping times at different powers
3. With the measured efficiencies are calculated the annual energy consumptions of the pumping cases to all of the drive systems. (Some of the efficiencies must to be interpolated, the method of that is descriped in the appendix II.)
4. The annual energy costs are discounted to the present value using 5% as a rate of interest and the using time is being ten years.
5. The present values of the life cycle energy costs of the different VSD's are compared to each other.

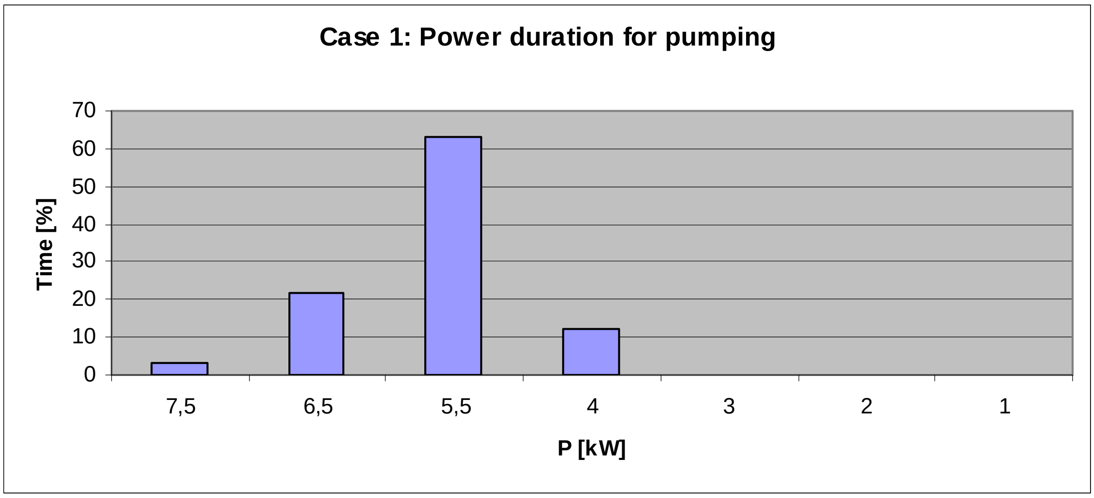
#### 5.4.2.1 Calculation method of the energy costs

The method of the calculation is explained here more detailed. The first pumping case under consideration is being an example in this description of the calculation method. The results of the calculations are presented in the chapter “Comparison results”.

The first pumping case represents a pretty typical pumping case where the pump operates at the bigger powers most of the time. In the picture (18) there is illustrated the power duration curve of the pumping case number one. In picture (19) there is roughly simplified the curve of the picture (18), so that the annual energy consumption can be calculated.




**Picture 18.**. Case 1: The power duration curve for pumping.




**Picture 19.** Case 1: The annual power duration for pumping.

The annual energy demand of the pumping process is calculated as a product of the operating time and the power.

$$E_d = t_o \cdot P \,, \tag{13}$$

where $E_d$ = Annual energy demand (without considering losses) [kWh/a]

$t_0$ = Annual operating time [h] and

P = Power [kW]

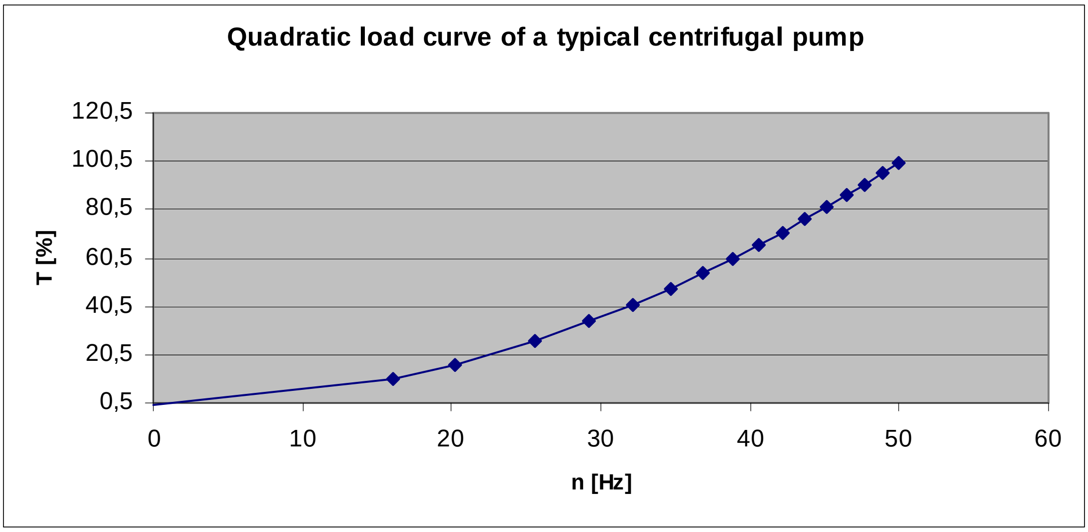
After that the losses of the drive system are taken into account. The real energy demand of the drive system is calculated as a ratio of the energy demand without the losses and the efficiency of the point. The total energy demand is a sum of the energy demands at the different powers.

$$E = \sum_{i=1}^{n} \left( \frac{E_d}{\eta} \right)_i , \tag{14}$$

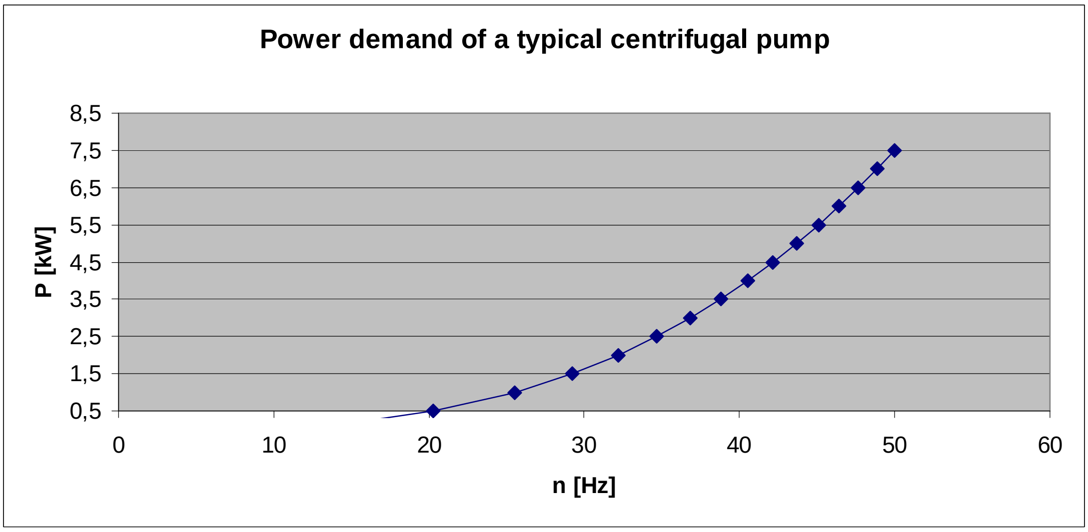
where E = Annual energy demand

$\eta$ = Measured efficiency at the point

To determine the efficiencies at the different pumping powers, must be known the correlation of the efficiency, rotation speed and the load. The correlation can be calculated according to affinity laws, and by marking the calculated points into coordinates the pumps load (torque) curve is created (Picture 20). The load curve of a typical centrifugal pump is quadratic. With the affinity laws can also be established a pumps power demand curve (Picture 21). By knowing the correlation of the power, rotation speed and the torque can the right efficiencies at the different pumping powers be established. Some of the efficiencies needed in the calculations are not measured, so they must be interpolated (More information in the appendix II).




**Picture 20.** A quadratic load curve of a typical centrifugal pump of a size 7,5 kW.




**Picture 21.** A power demand curve of a typical centrifugal pump of a size 7,5 kW.

With equations (13) and (14) are calculated the annual energy demands for all the tested variable speed drives. After that the annual energy costs are calculated. The price of the electricity is being 0,1 €/kWh.

Then the all annual energy costs are discounted to the present. The present value factor is calculated as equal to:

$$d_n = \frac{1}{(1+r)^n}, \tag{15}$$

where $d_n$ = Present value factor

$r$ = 5%, (rate of interest)

$n$ = Time of use, 10 years

The results of the life cycle energy costs are presented in the chapter of "Comparison results".

The pumping cases under consideration are presented in the context with the calculation result at the chapter of "Comparison results". More about the energy calculations in the appendix (II).

## 5.5 User-friendliness

The usability and user-friendliness of a variable speed drive used as a control device of a process is an essential matter from the pump user's point of view. When evaluating the user-friendliness, the attention is paid in the easiness of the implementation, easiness of the start-up and the use, logicalness of the control panel and readability of the manuals. The evaluation is based on empirical opinions of the user and the engineer who installs the variable speed drives.

The opinions about user-friendliness are formed on the basis of how the measurement situations succeeded with the different drives. Because an opinion is more or less a matter of judgment, the chapter of user-friendliness should be thought more as an depiction of the problems and successes with different VSD's in the measurement situation.

### 5.5.1 Installation

The variable speed drives were fastened with screws on a timber panel. The installation work was done by the experienced installers and employees of the laboratory. The easiness of the installation is evaluated by the installer.

### 5.5.2 Start up and use

When measuring the efficiencies every variable speed drive was in use for one or two days. The evaluation of the user-friendliness of the VSD is based on the user's empiric experience mostly of the start-up. This is because in such a short using time the start-up was the situation when the user got the best picture of how the variable speed drive operates and how easy it is to use. Besides the depiction of the success of the start-up a depiction is given of how easy-going the measurement situation was with every different VSD.

The user's experience of the success of the start-up and the use is based on:

- How easy it is to insert the start-up data to the VSD,
- How easy it is to perform the motor identification,
- How much time did the whole start-up-process take to get the system ready to operate
- Were there any un-predictable problems or other kind of confusion in the measurement situation

The instructions in manual play a great role in starting-up. The intelligible of the instructions to non-experts is one criterion when evaluating the user-friendliness of the VSD's. When starting-up the logic of the control panel is as well a factor that influences how easily the starting goes. These two factors are introduced closely in the next chapters.

### 5.5.3 Manuals

The easiness of the use of a device is a sum of several things. Among others the two important factors are the readability of the manuals and logicalness of the control panel.

The opinion of the manuals is mainly formed accordingly how the starting up succeed with the help of the manual. The help of the manual was also needed when changing the settings for the flux optimisation -measurements. The manual’s instructions of how to control the drive play a great role in how quickly the logic of the control panel is understood. So the user’s opinion of the manual is formed on the basis of how trouble-free it was starting the system up and change settings of the variable speed drive with the help of the manual.

### 5.5.4 Control panel

There can be great differences in the control panels of the VSDs’. Some of them have small displays and fewer rows in it while some of them have large displays. Some control panels have just few buttons meanwhile others over dozen buttons. The logics and navigations vary as well between different variable speed drives. If the logic of the control panel is user-friendly, the co-operation between buttons and menus is quickly understood.

The evaluation of the control panel is given on the basis of how easy it is to understand the logic of it and how easy it is to use the device trough the control panel. The manual’s instructions of how to control the drive play a great role in how quickly the logic of the control panel is understood.

In the efficiency measurements the user got the best touch of the control panel’s logic when starting up and when changing the settings for the energy optimisation –test run. Also opinion of the easiness of changing the frequency is given, because in that matter there seems to be much variation.

# 6 MEASUREMENTS

The efficiency measurements were performed 21.1.-28.1. 2008 at the power electronics laboratory of the Lappeenranta University of Technology with a system that consists of a variable speed drive, an induction motor and a dc-machine. The input powers to the variable speed drive and to the motor are measured with two power analyzers, one located before the variable speed drive and the other located between the VSD and the motor. The mechanical power on the motors shaft is measured with a torque transducer.

The efficiency of the variable speed drive itself is examined as well as the efficiency of the drive system (= motor + VSD). For the sake of the total energy consumption of the process the efficiency of the system is more significant than the efficiency of the VSD. Still it is interesting to compare the efficiencies of the variable speed drives them selves.

All of the variable speed drives under testing incorporate an “energy optimizing” of “flux optimizing” feature, which saves energy by reducing the motor magnetizing current at low mechanical loads. The measurements consist of two different test runs. First efficiencies are measured without energy optimization. The second test run is performed with flux optimization on. The similar test runs are done with all four variable speed drives.

In next chapters are introduced the measuring equipment, the course of the measurements and the two test runs and the results of the measurements. The comparison and deeper analysis of the results are presented in chapter (7) “Comparison results”.

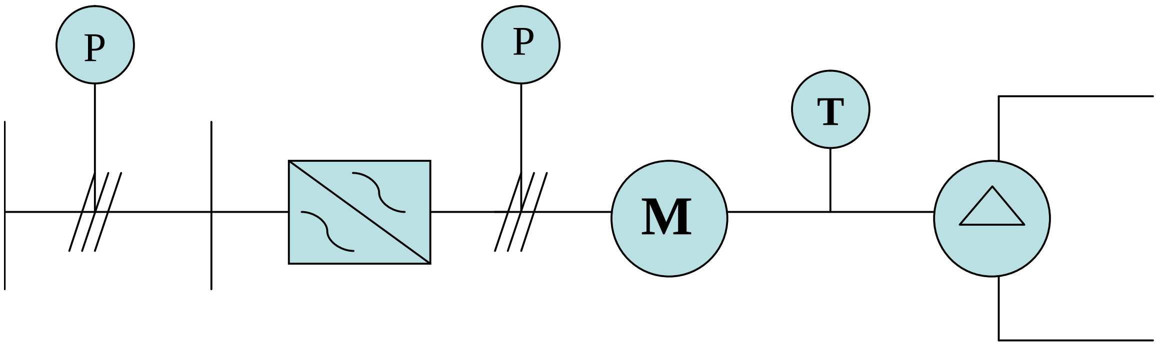
## 6.1 Measuring equipment

The measurement equipment consists of:

- Two power analyzers
- Variable speed drive
- Cage induction motor with DC-machine
- Torque transducer

- Current probes (3 pieces)

The measurements are performed with equipment described below (Picture 22).




**Picture 22.** Skeleton diagram of the measurement equipment. (P=power analyzer, M=motor, T=torque transducer, Δ=DC-machine)

In picture (22) (P) stands for a power analyzer. Between the two power analyzers there is a variable speed drive. After second power analyzer there is an induction motor (M). (T) stands for a torque transducer and after that there is a dc-machine (Δ). More detailed specifications of the measuring equipment are given in appendix (I).

The input power to the system ($P_{\mathrm{in}}$) is measured with the first power analyzer. The input power to the motor ($P_{\mathrm{m}}$) is measured with the second power analyzer. With the torque transducer is measured the mechanical power on the motors shaft, which is practically same as the pumps shaft power ($P_{\mathrm{out,mech}}$) (but these measurements are made without a pump).

## 6.2 Course of the measurement

The measurements consist of two different test runs.

Before starting to measure the efficiencies the motor was run for an hour to heat up. The first variable speed drive under testing was the ACS800 from ABB. The motor used in measurements was a brand-new, so it was run for the first time then. As the motor was warm enough, the measurement were started at frequency of 50 Hz.

The measurements were done by two measurers. Other measurer collected the data from the measuring devices and other measurer changed the motors load from the DC-machine and the frequency when needed. To minimize the systematic error, there was the same division of duties between the measurers in all measurements.

### 6.2.1 First test run: Efficiencies without flux optimisation

At the first test run the VSDs are run on default settings (only the needed start-up data is entered to the VSD), so efficiencies are measured without any flux optimization or corresponding energy saving –mode. The efficiencies are measured at a certain frequency as a function of the load. The test runs are performed at the frequencies (10, 20, 30, 40 and 50) Hz. The frequency is kept constant and the load is varied ten times between (10-100)% of the full load (full load is 50 Nm). So there are 50 test points at the first test run, ten test points (10, 20, …, 100% of the full load) per tested frequency.

### 6.2.2 Second test run: Efficiencies with flux optimisation

The second test run is performed with flux optimization on, or corresponding energy saving –mode. The test points are presented below at table (1).

**Table 1.** Flux optimisation -test points.

| **Torque, T** | **Running speed, N** | |
|---|---|---|
| **[%]** | **[Hz]** | **[rpm]** |
| 10 | 10 | 300 |
| 20 | 20 | 600 |
| 30 | 30 | 900 |
| 50 | 40 | 1200 |

| | | |
|---|---|---|
| 70 | 45 | 1350 |
| 100 | 50 | 1500 |

All of the four variable speed drives have some kind of an energy-optimization-function. In table (2) are introduced the changes in settings when measuring the efficiencies with energy optimization. In the first test run only the motor information and other necessary data was entered to the VSDs, but other wise the VSDs were run on default settings.

**Table 2.** Settings of the variable speed drives

| **VSD** | **Settings in first test run** | **Settings in second test run (energy-optimization)** |
|---|---|---|
| ABB | Default settings, Application macro: Hand/Auto | Parameter 26.01: Flux-optimization ON |
| Danfoss | Default setting: automatic energy optimization (AEO) is on when frequency is 10 Hz or more. | No changes made.<br>When measuring the efficiencies without the energy optimization, the min. freq. was set to be 40 Hz. (Parameter 14,42) |
| Vacon | Default settings, Basic application | Standard application, (P2.6.3 -> 3) Linear U/f -control + flux optimization |
| Siemens | Default settings: U/f with parabolic charac. | Linear U/f -control with flux current control |

As can be seen from the table (2) the variable speed drives of ABB, Vacon and Siemens have quite a similar flux-optimization –function. The variable speed drive of Danfoss has a difference in this matter comparing to others: an energy optimization is automatically on when the frequency is 10 Hz or more.

So that the effect of the energy optimization -function could be seen, first were measured the test points without the energy optimization on. Then the settings were changed and the similar test points were measured with energy optimization on.

### 6.2.3 Collected measuring information

The information collected from the measuring devices is presented in table (3).

**Table 3.** The information collected from the measuring devices.

| **1. Power analyzer** | **2. Power analyzer** | **Torque transducer** |
|---|---|---|
| - Current I [A]<br>- Voltage U [V]<br>- Power P [kW] | - Current I [A]<br>- Voltage U [V]<br>- Power P [kW] | -Running speed n [rpm]<br>- Torque T [Nm]<br>- Mechanical power P [kW] |

The voltage, the current and the power are measured with the two power analyzers. The running speed of the motor, the torque and the mechanical power on the motors shaft are measured with the power transducer.

With the measured quantities the efficiency of the variable speed drive can be calculated:

$$\eta_{VSD} = \frac{P_m}{P_{in}}, \tag{16}$$

as well as the efficiency of the system (which consists of the VSD and the motor):

$$\eta_{sys.} = \frac{P_{out,mech.}}{P_{in}}. \tag{17}$$

After the measurements were done for a day the off-set errors were noted from the torque transducer. The offsets of each measuring day with different VSDs are tabled in the appendix (III). In appendix (III) there are also harmonics of each VSD-case from the power analyzer 2 (power to the motor). The harmonics were measured at the frequency of

(50 and 40) Hz. The switching frequencies of the VSDs are presented as well in the appendix (III). The switching frequency of Siemens VSD was not found from the manuals so it is missing from the table.

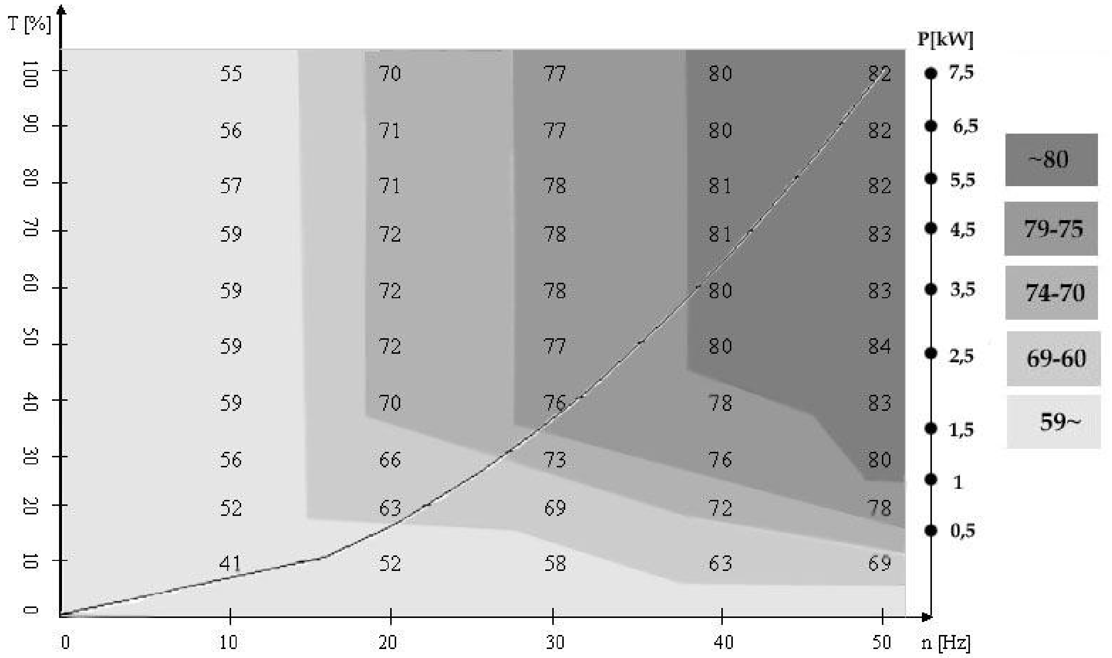
## 6.3 Measurement results

In next chapters the measured efficiencies are illustrated with pictures. More detailed measurement data (voltages and currents) are presented in appendixes (IV-VIII). The comparison results of the efficiencies are introduced later in chapter “Comparison results”.

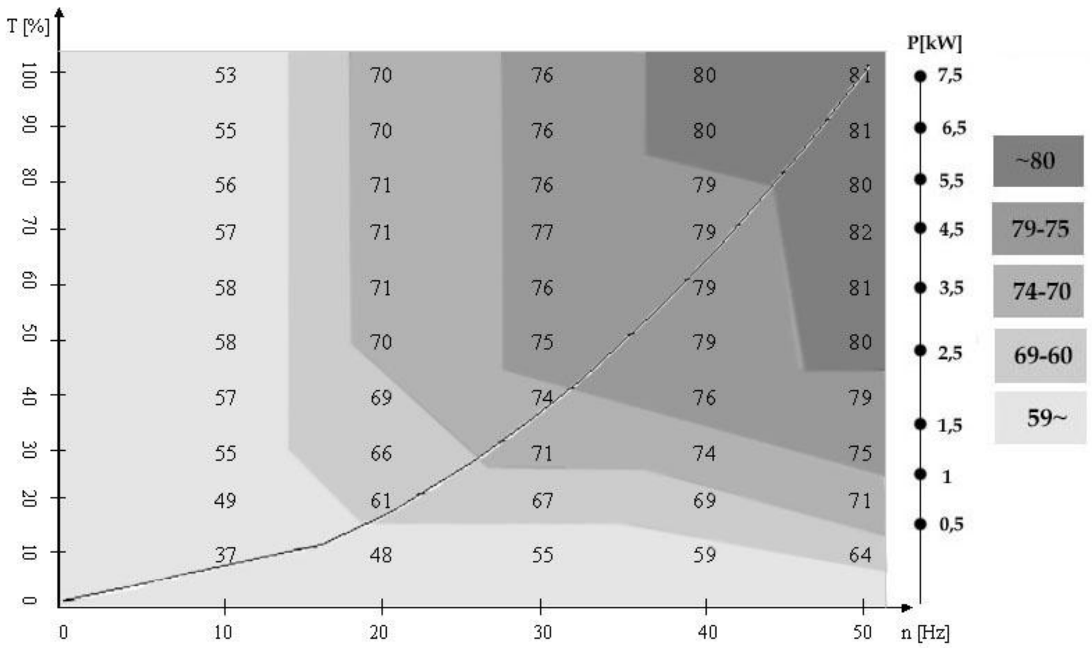
### 6.3.1 Efficiencies without flux-optimisation

The measured efficiencies [%] at different frequencies and loads are put together in pictures (23-26) (More detailed measurement results in appendixes IV-VII). The efficiencies are divided into ranges so that it is easier to compare the variable speed drives of different manufacturers with each other. The best efficiency range covers efficiencies better than 80%. The second best area covers efficiencies between (79-75)%. The efficiency ranges are introduced in the pictures (23-26).

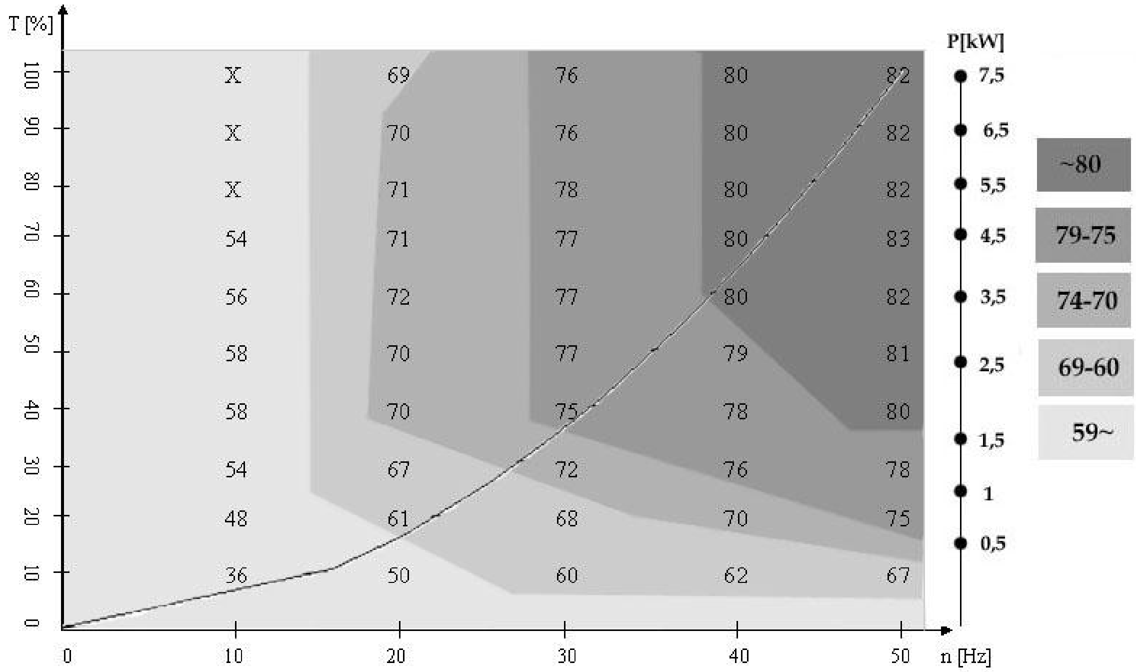
The curve in the pictures is a quadratic moment diagram, which is typical for a centrifugal pump. The curve depicts the performance of the pump: it describes how the change of the torque correlates with the change of the frequency. In the pictures there is a power scale [kW] at right, which tells the power at different points at the curve (to be clear, the power scale is valid only on the curve, not in other points in the picture). The correlations between moment, frequency and power are calculated according to affinity laws. The curve is valid for a pump of size 7,5 kW.



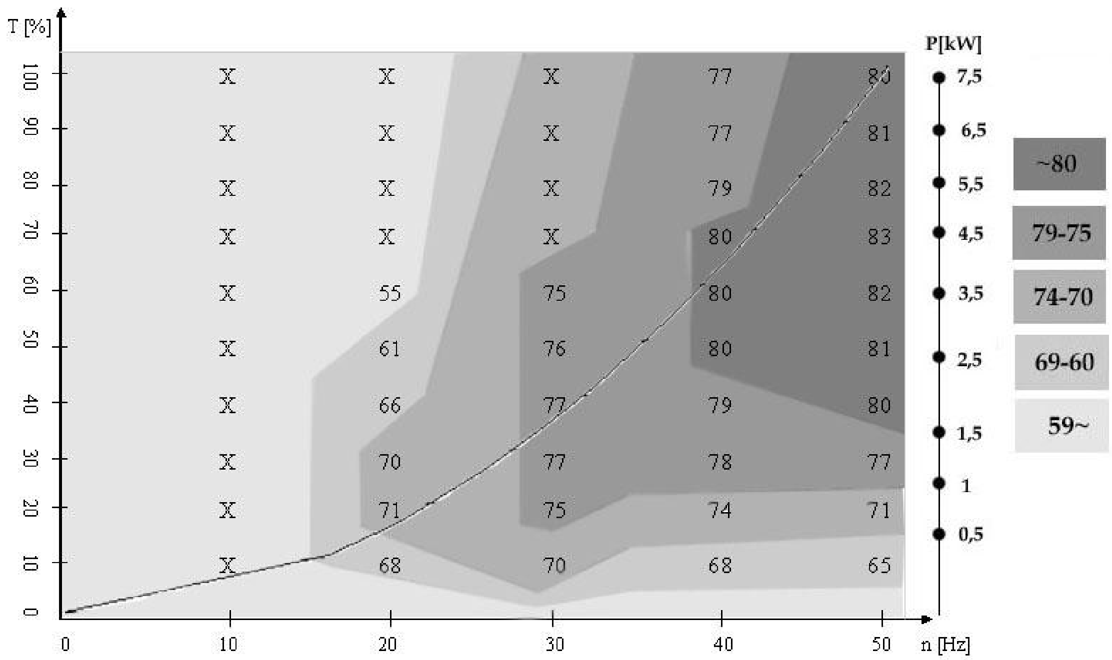

**Picture 23.** The efficiencies [%] of the drive system with the variable speed drive of *ABB*. The power scale at right in the picture is valid only on the curve region. Accuracy of the efficiencies is ±1,5 percentage units (Niemelä, Interview 11.3.2008).




**Picture 24.** The efficiencies [%] of the drive system with the variable speed drive of *Danfoss*. The power scale at right in the picture is valid only on the curve region. Accuracy of the efficiencies is ±1,5 percentage units (Niemelä, Interview 11.3.2008).




**Picture 25.** The efficiencies [%] of the drive system with the variable speed drive of *Vacon*. The power scale at right in the picture is valid only on the curve region. (The X-letters in the picture are points were motor stopped running and efficiencies could not be measured.) Accuracy of the efficiencies is ±1,5 percentage units (Niemelä, Interview 11.3.2008).




**Picture 26.** The efficiencies [%] of the drive system with the variable speed drive of *Siemens*. The power scale at right in the picture is valid only on the curve region. (The X-letters in the picture are points were motor stopped running and efficiencies could not be measured.) Accuracy of the efficiencies is ±1,5 percentage units (Niemelä, Interview 11.3.2008).

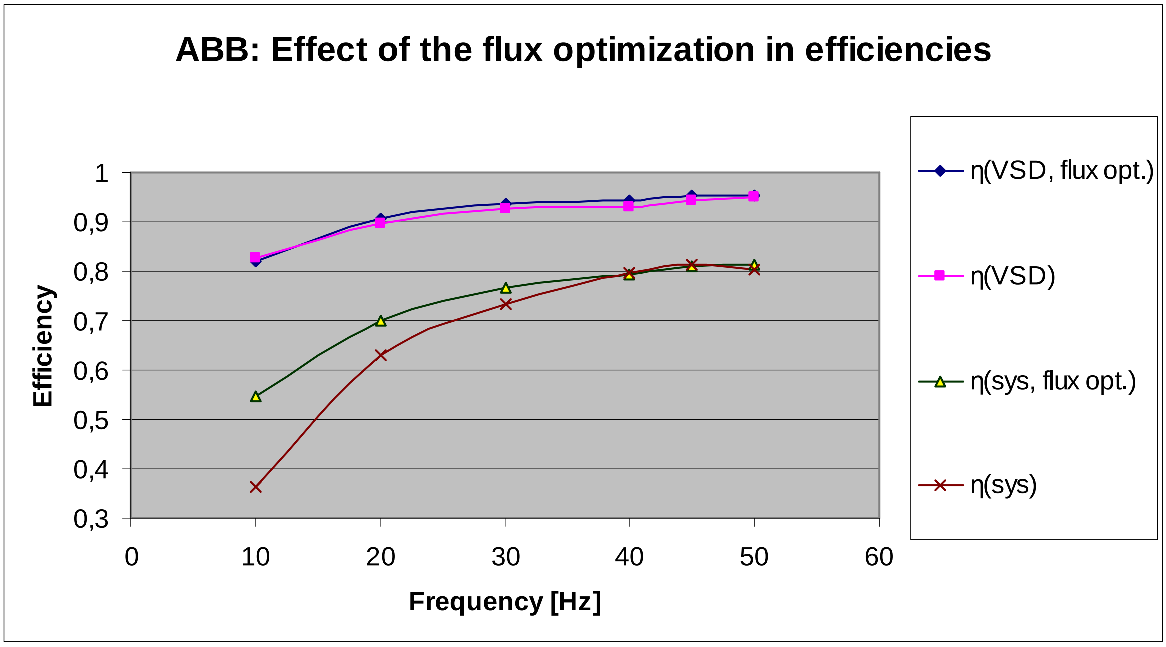
As a summary of the pictures it can be said that differences in the efficiencies are small but some difference on the dimensions of the efficiency ranges can be noticed. Most of the 7,5 kW-sized pumps are usually run at the powers between (6,5-7,5) kW. So the efficiencies on the curve at this power area are the ones that count most. According to the pictures this area can be run with the best efficiencies with all of the tested variable speed drives. The pump is working shorter times on the other areas of the curve too. So in the pictures the attention should be paid in the region of the curve and the efficiency areas on it.

### 6.3.2 Efficiencies with energy optimization on

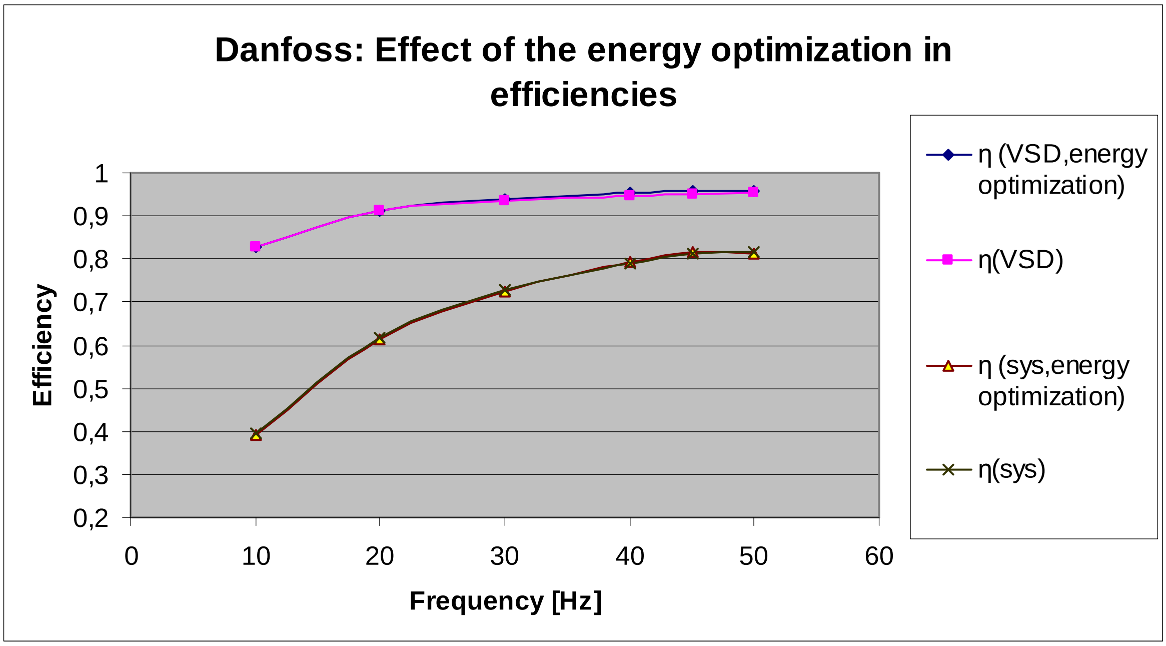
The measured efficiencies are illustrated in pictures (27-30). More detailed measurement results are presented in appendix (VIII). The comparison results are introduced later in chapter “Comparison results”.

The pictures (27-30) illustrate the measured efficiencies of the VSDs and of the systems (VSD + motor) with the flux (or energy) optimisation on, and without the optimisation. The pictures depict the effect of the flux optimisation in the cases of each VSD.

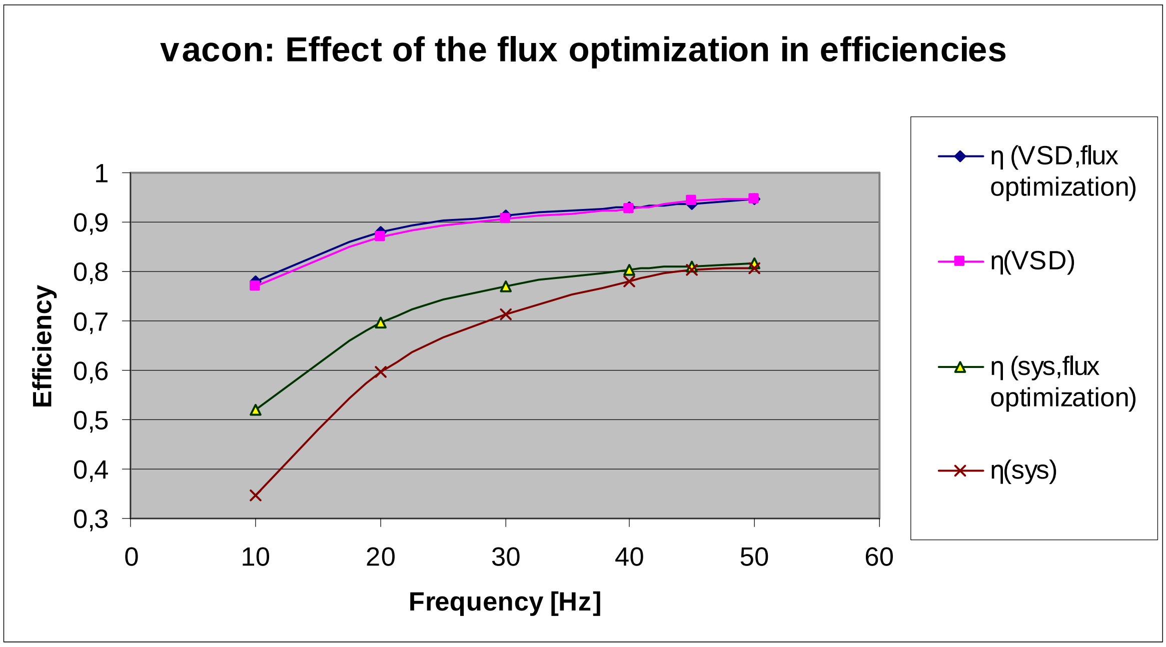
From the pictures of ABB and Vacon can be seen that the flux optimization has a positive effect on the efficiencies, especially on small frequencies. The efficiencies with the Danfoss’ device have meanwhile stayed the same. Explanation to that may be the different kind of energy optimization –function from the other devices. The effect of the flux optimization in the case of the Siemens’s device is negative: the efficiencies drop. That might be explained with a wrong kind of optimization settings for the application.



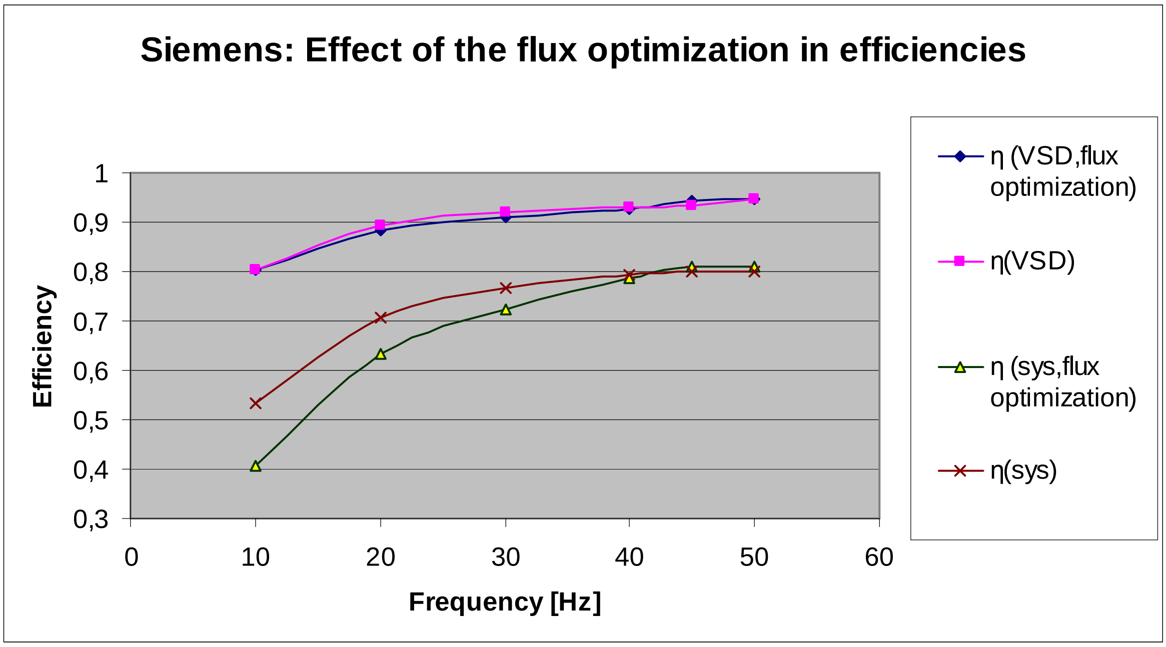

**Picture 27.** The change in efficiencies of the variable speed drive and the system when flux optimization on (*ABB*). Accuracy of the measurements: system efficiencies ±1,5 and efficiency of VSD ±2 percentage units (Niemelä, Interview 11.3.2008).




**Picture 28.** The change in efficiencies of the variable speed drive and the system when energy optimization on (*Danfoss*). Accuracy of the measurements: system efficiencies ±1,5 and efficiency of VSD ±2 percentage units (Niemelä, Interview 11.3.2008).




**Picture 29.** The change in efficiencies of the variable speed drive and the system when flux optimization on (*Vacon*). Accuracy of the measurements: system efficiencies ±1,5 and efficiency of VSD ±2 percentage units (Niemelä, Interview 11.3.2008).




**Picture 30.** The change in efficiencies of the variable speed drive and the system when flux optimization on (*Siemens*). Accuracy of the measurements: system efficiencies ±1,5 and efficiency of VSD ±2 percentage units (Niemelä, Interview 11.3.2008).

## 6.4 Accuracy of measurement

The error in the measurement results is a sum of systematic errors and measuring equipments errors. The systematic error is minimized by having the similar measuring equipment, the same measurers and the same circumstances and environment in all measurements.

The measuring equipments cause also errors in results. The efficiency of variable speed drive it self is calculated as a ratio of the power to the motor and the input power to the system ($\eta_{VSD} = P_m/P_{in}$). The input power to the system and the power to the motor are measured with power analyzers. The total error in the measured efficiencies of the VSD is estimated to be ±2 percentage units, which includes the measuring equipments error and the systematic error. (Niemelä, Interview 11.3.2008.)

The efficiency of the system is calculated as a ratio of mechanical power on the motors shaft and the input power of the motor. The mechanical power on motors shaft is measured with a torque transducer. The accuracy of the torque transducer is better than the accuracy of the power analyzer, which is used to measure the input power to the system. Therefore the error in the system efficiency is smaller than the error of the efficiency of the VSD. The total error in the measured efficiency of the system is estimated to be ±1,5 percentage units. (Niemelä, Interview 11.3.2008.)

In the sense of comparison this kind of measuring system is reasonable. The error in the efficiencies is the same in all measurements, and the margin of error does not change the mutual order of the efficiency curves. The error moves the whole set of curves up or down in the scale of efficiency. If the absolut efficiencies are needed to be established, a calorimetric measuring system would be more appropriate.

# 7 COMPARISON RESULTS

In this chapter the results of the different categories are presented.

## 7.1 Efficiency

In next chapters are introduced the comparison results of the measured efficiencies presented earlier.

### 7.1.1 Efficiencies without flux optimization

The pictures (31-40) introduce the efficiencies compared to each other. In the pictures are illustrated the efficiencies of the variable speed drives and the systems at different frequencies as a function of the load. The random deviations from the curve in some of the pictures are probably measuring errors, so they can be ignored.

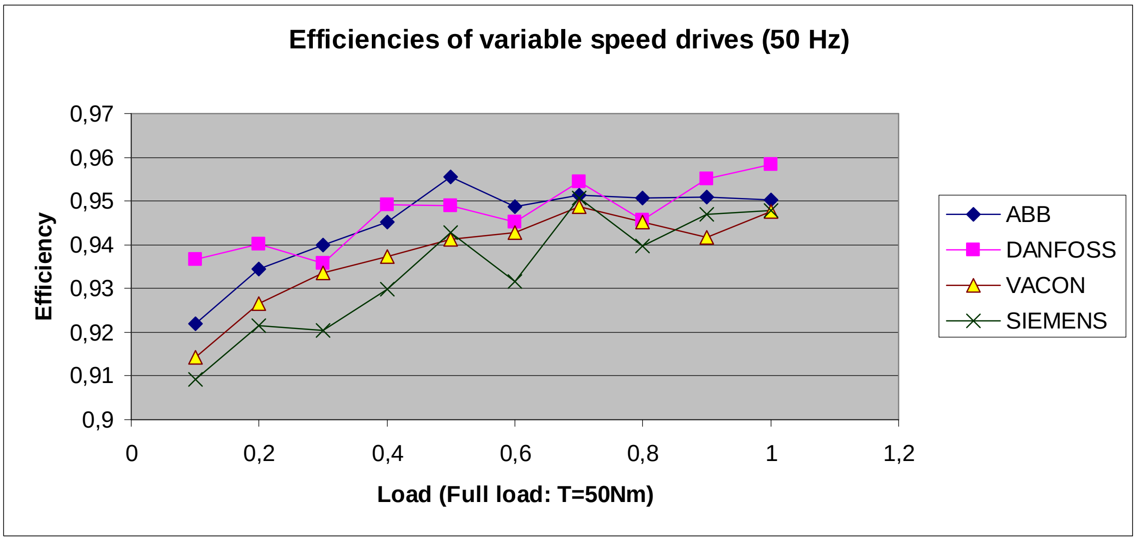
When paying attention into efficiencies of the VSDs', it can be seen from the pictures (31, 33, 35, 37 and 39) that Danfoss has the best VSD's efficiencies at all of the tested frequencies. The second best efficiencies are with ABB. At the frequency of 10 Hz ABB and Danfoss have almost equally good efficiencies. Siemens and Vacon are alternating with the third and the fourth position in the order. The differences with the efficiencies of the VSDs' are clearer at the smaller frequencies. At frequencies of 50 and 40 hertzs the biggest difference in efficiencies is not more than a few per cents. As the frequency gets lower the differences between the efficiencies grow. At the most the difference between the most efficient VSD ant the least efficient VSD is about seven per cents (that is at the frequency of 10 Hz between the VSDs from ABB and Vacon to ABB's advantage).

When considering the system efficiencies, it can be noticed from the pictures that ABB has the best system efficiencies at the all tested frequencies. The efficiencies seem mainly be the best at the all range of loads. The second best system efficiencies are with the Vacon. The system efficiency curves of Danfoss seem to follow also the same curve shape with the ABB and Vacon, but the efficiencies are slightly lower.

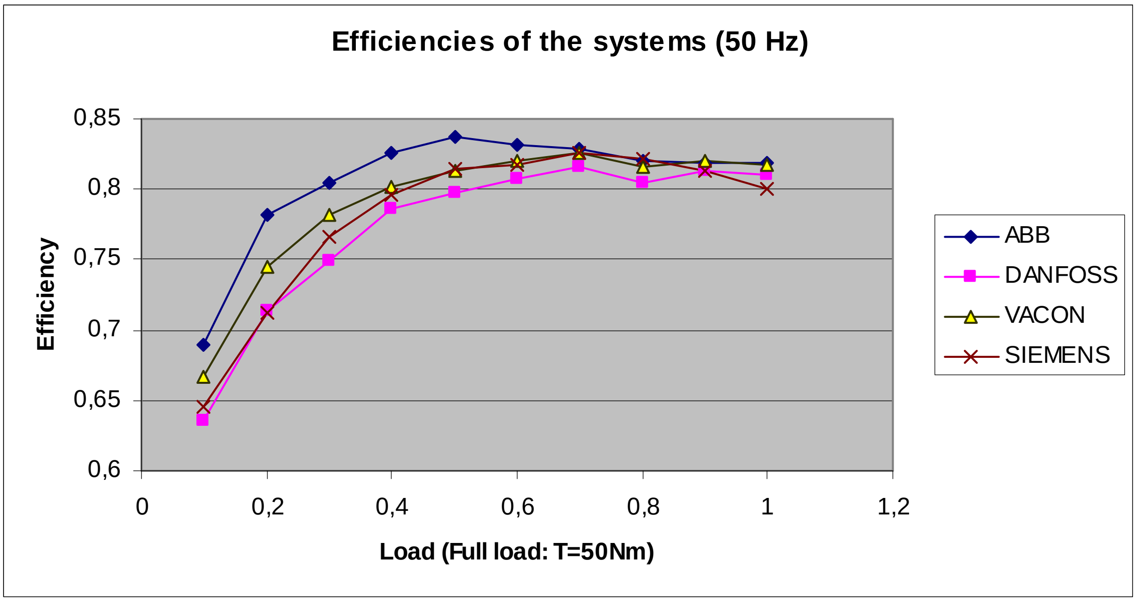
The shape of the Siemens system efficiency curve is different from the others, especially at the smaller frequencies (pictures 36, 38, 40). It can be noticed from the pictures, that with small loads at the frequency of 40 Hz or less, the VSD of Siemens has outstandingly better system efficiency results compared to others. Correspondingly the efficiencies of the system with Siemens's VSD are clearly lower with big loads at the small frequencies, or at the worst, they could not even be measured because the motor stopped. According to the pictures it seems obvious that Siemens is functioning better compared to each other at the small frequencies with small loads and worse with the big loads.

The differences in the system efficiencies seem to be at the big frequencies (40 and 50 Hz) smaller than at the smaller frequencies. At the bigger frequencies the differences in the system efficiencies seem to be less than six percent. At the frequency of 40 Hz or less the VSD of Siemens sticks out from the crowd with the differently shaped system efficiency curve. The system efficiencies of the other VSDs' still remain quite the same the difference being just few percents.

### Frequency 50 Hz

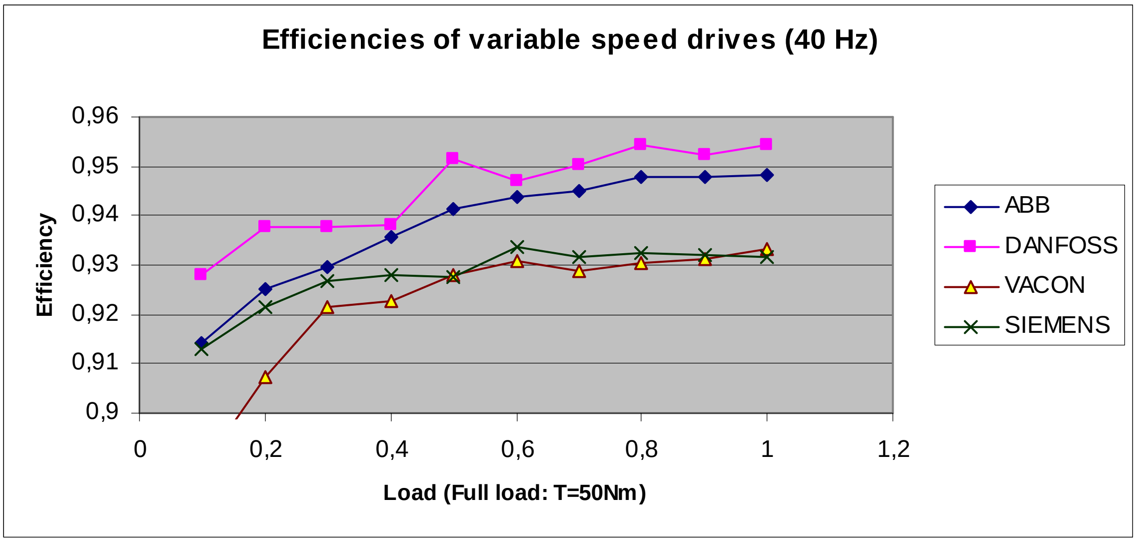



**Picture 31.** Efficiencies of the variable speed drives at frequency of 50 Hz as a function of the load. Accuracy ±2 percentage units (Niemelä, Interview 11.3.2008).

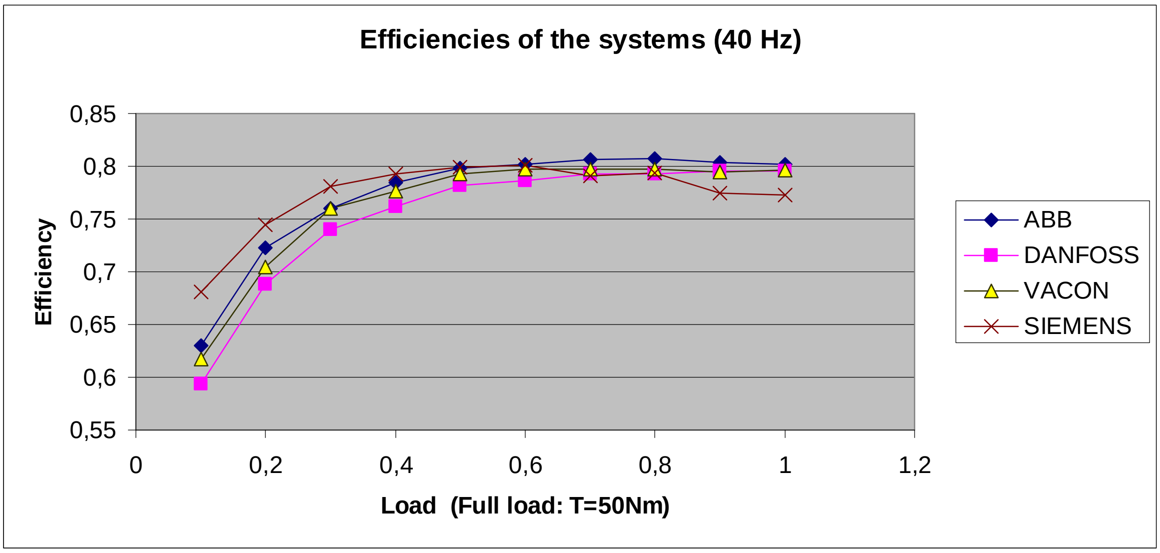



**Picture 32.** Efficiencies of the drive systems (Motor+VSD) as a function of the load at frequency of 50 Hz. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

## Frequency 40 Hz

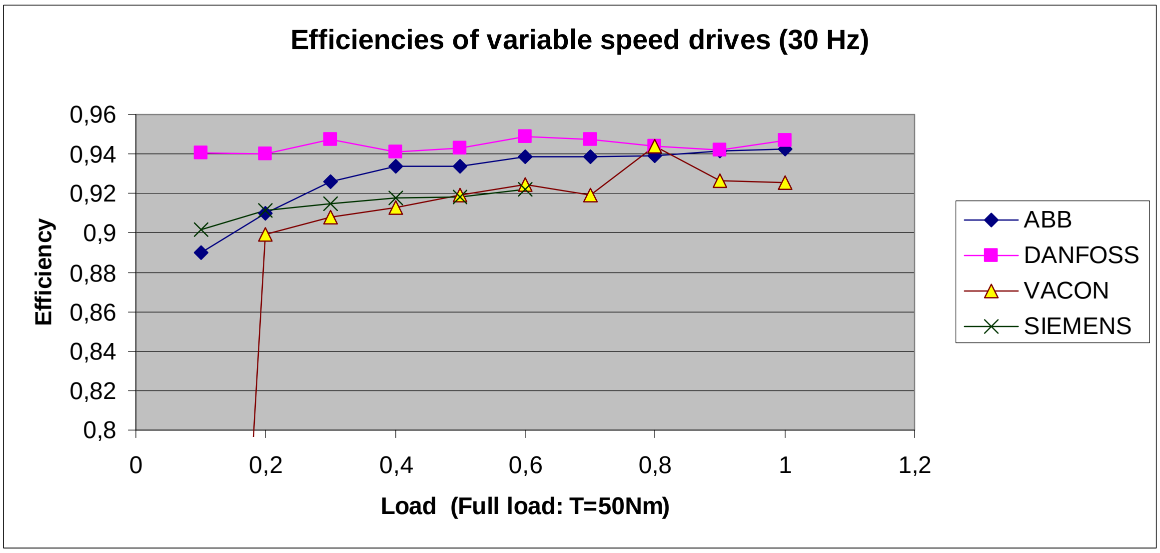



**Picture 33.** Efficiencies of the variable speed drives at frequency of 40 Hz as a function of the load. Accuracy ±2 percentage units (Niemelä, Interview 11.3.2008).

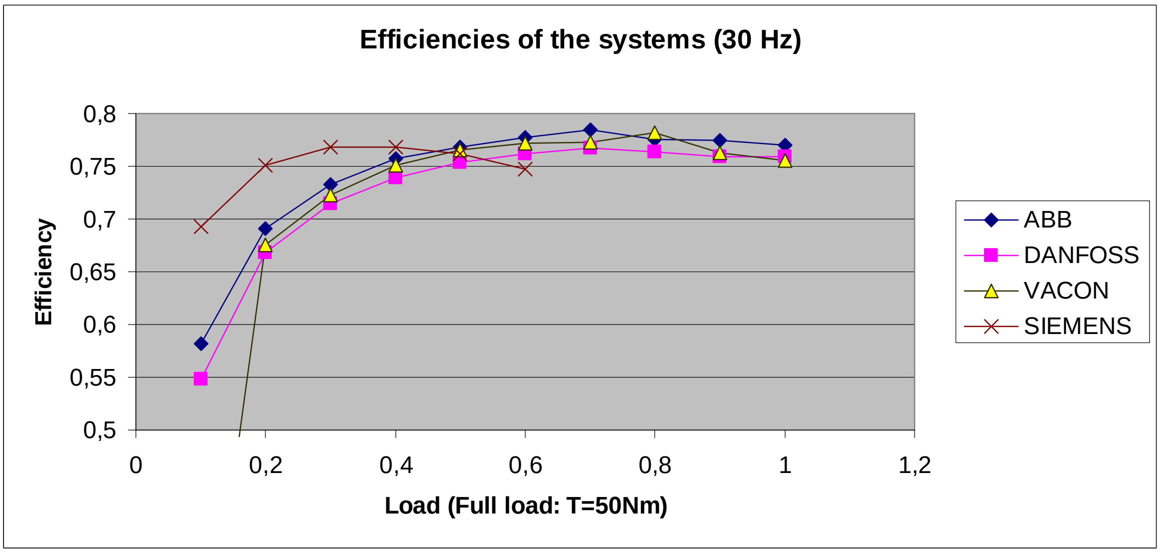



**Picture 34.** Efficiencies of the drive systems (Motor+VSD) as a function of the load at frequency of 40 Hz. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

## Frequency 30 Hz

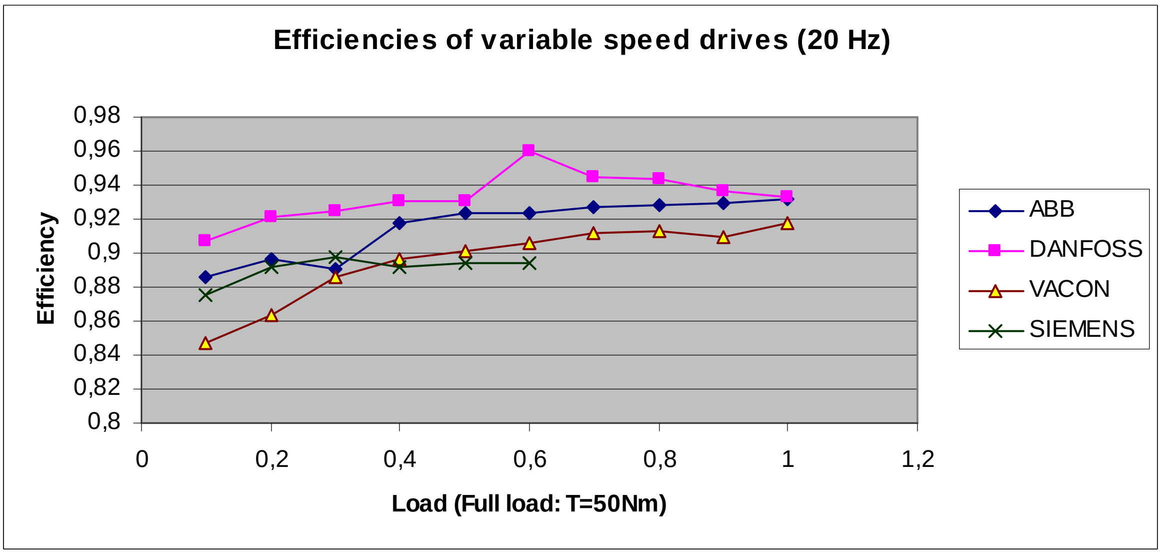



**Picture 35.** Efficiencies of the variable speed drives at frequency of 30 Hz as a function of the load. The efficiencies of Siemens's VSD could be measured only with the load of 60% or less. Accuracy ±2 percentage units (Niemelä, Interview 11.3.2008).

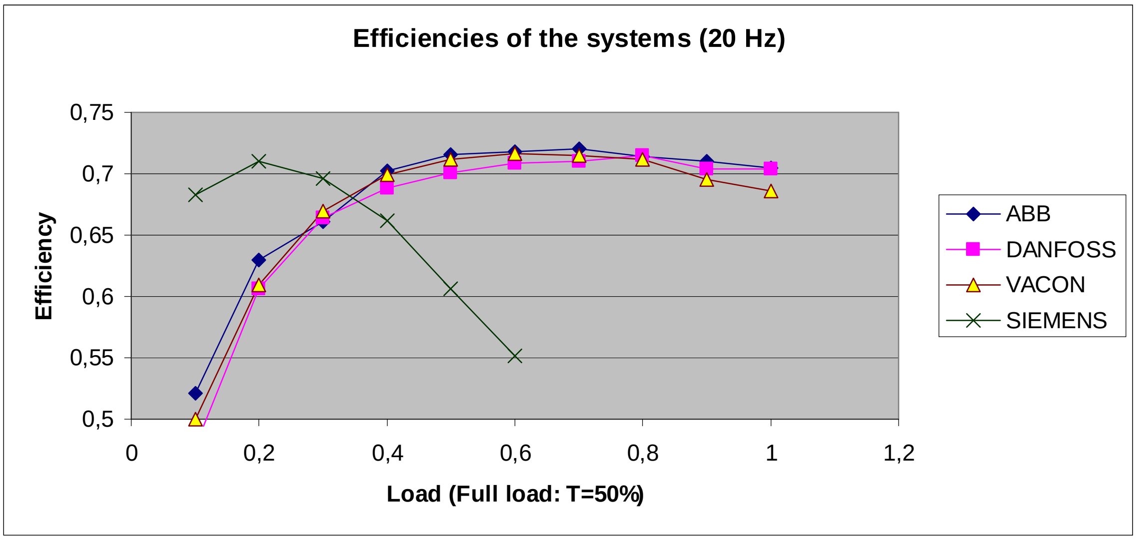



**Picture 36.** Efficiencies of the drive systems (Motor+VSD) as a function of the load at frequency of 30 Hz. The efficiencies of Siemens's VSD could be measured only with the load of 60% or less. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

### Frequency 20 Hz

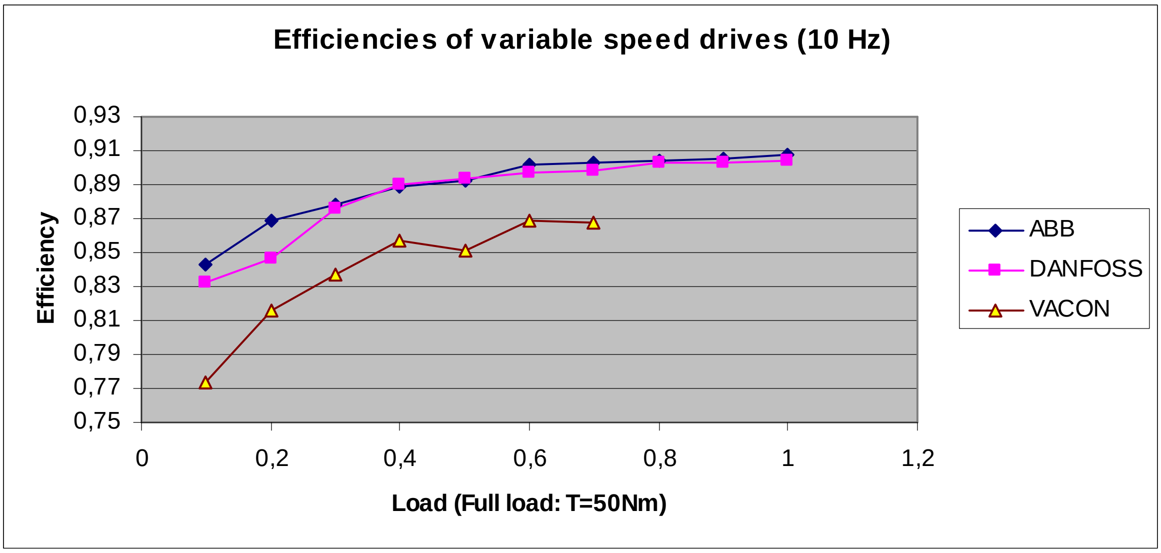



**Picture 37.** Efficiencies of the variable speed drives at frequency of 20 Hz as a function of the load. The efficiencies of Siemens's VSD could be measured only with the load of 60% or less. Accuracy ±2 percentage units (Niemelä, Interview 11.3.2008).

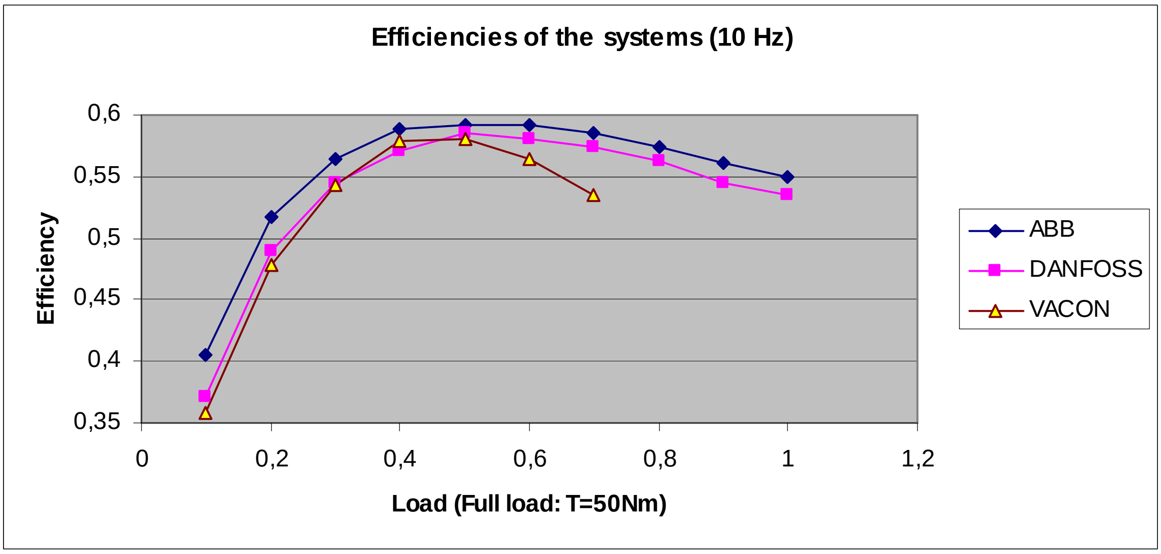



**Picture 38.** Efficiencies of the drive systems (Motor+VSD) as a function of the load at frequency of 20 Hz. The efficiencies of Siemens's VSD could be measured only with the load of 60% or less. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

## Frequency 10 Hz




**Picture 39.** Efficiencies of the variable speed drives at frequency of 10 Hz as a function of the load. The efficiencies vith Vacon's VSD could be measurer only with the load of 80% or less. The Siemens's VSD was left out of the measurements at this frequency because of the motor problems. Accuracy ±2 percentage units (Niemelä, Interview 11.3.2008).




**Picture 40.** Efficiencies of the drive systems (Motor+VSD) as a function of the load at frequency of 10 Hz. The efficiencies vith Vacon's VSD could be measurer only with the load of 80% or less. The Siemens's VSD was left out of the measurements at this frequency because of the motor problems. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

### 7.1.2 Efficiencies with flux optimization

In picture (41) are illustrated the effects of the energy optimization on the system efficiencies compared to the efficiencies without the optimization. The effect of the flux optimisation is calculated with following equation:

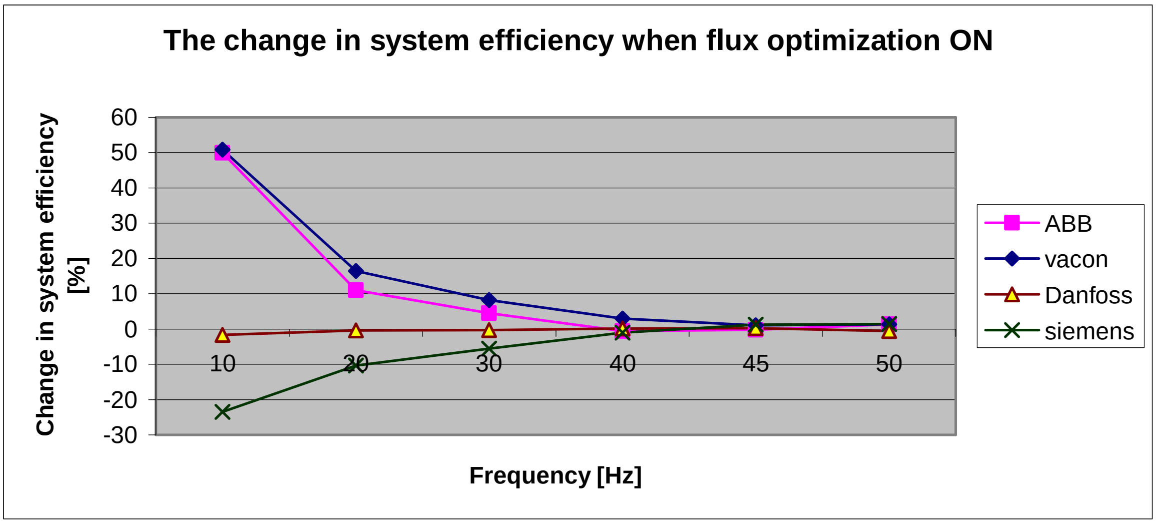
$$X = \frac{\eta - \eta_{e.o.}}{\eta} \cdot 100\% \,, \tag{16}$$

where $X$ = Change in efficiency [%]

$\eta$ = Efficienciy of the system without energy optimization

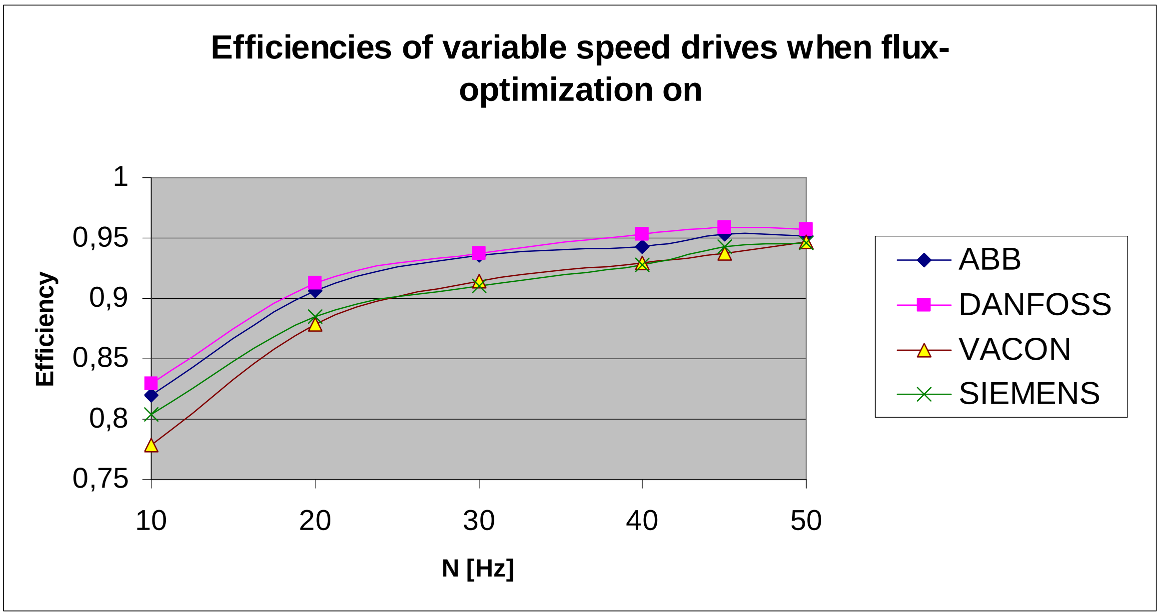
$\eta$ = Efficiency of the system with energy optimization on.

When comparing the magnitudes of the effects between different drives, it is noticed that with the VSDs from ABB and Vacon the effect of the optimization is positive. The system efficiencies with the Danfoss' drive did not change as a result of the flux optimization. The efficiencies of the Siemens's VSD dropped when flux optimisation was on. Without the flux optimization the efficiencies of the VSD and the system were better. Considering that, it may not be reasonable to compare these efficiencies of Siemens with the others, because clearly the flux optimization did not optimize the efficiency the way it was supposed to.



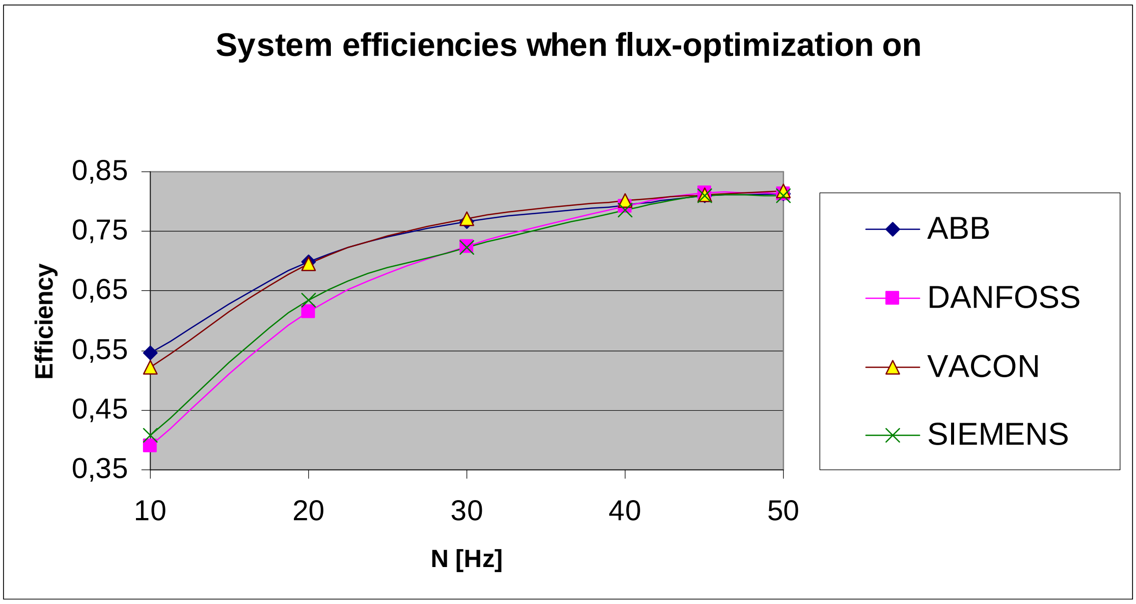

**Picture 41.** The change [%] in system efficiency when flux optimization on.

In the picture (42) are illustrated the VSDs' efficiencies with flux optimisation. When compared to each other the differences seem to be quite small, at maximum about five percents between the most efficient and least efficient VSDs.. The VSD of Danfoss has the best efficiencies and the VSD of ABB has almost as good efficiencies. The efficiencies of Siemens and Vacon have no big differences compared to each other, but are slightly lower than the efficiencies of Danfoss and ABB.



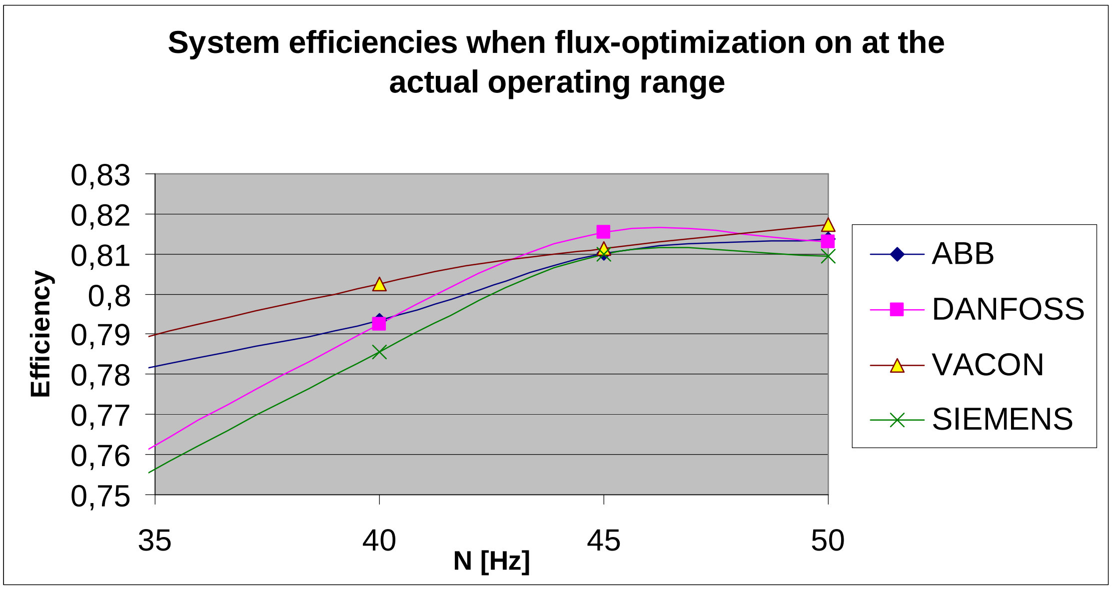

**Picture 42.** The efficiencies of the variable speed drives with flux optimization. Accuracy ±2 percentage units (Niemelä, Interview 11.3.2008).

In picture (43) there are illustrated the system efficiencies with flux optimization. The differences are much clearer with the system efficiencies. At low frequencies and loads the differences between the most efficient and the least efficient systems are at the most about 15 percents. The drives of ABB and Vacon seem to have no big differences in the efficiencies compared to each other, but the efficiencies are better from the others at the smaller frequencies and loads. The differences between the efficiencies of Siemens and Danfoss seem to be also quite small, but the differences compared to the drives of ABB and Vacon are clear at the smaller frequencies and loads. The differences get slighter as the frequency and the load grow.




**Picture 43.** The efficiencies of the systems with flux optimization. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

In picture (44) there is a zooming about the region of the curve, where the system normally operates. At this point of the curve the differences between the system efficiencies are smaller (notice the change in the efficiency scale in the picture). At the actual operating area near the nominal speed the differences are almost negligible, only parts of percent.



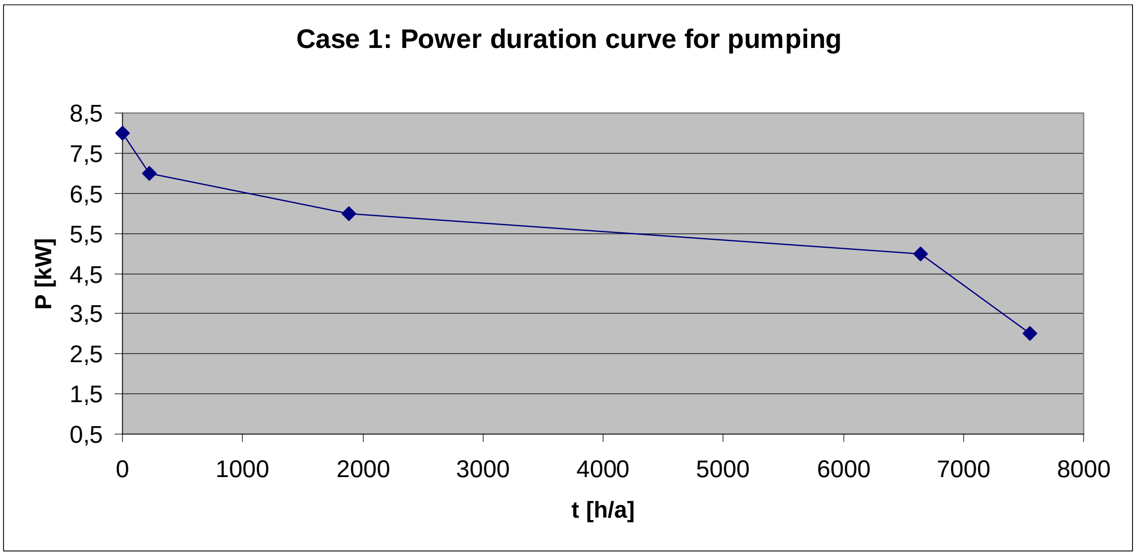

**Picture 44.** System efficiencies with flux optimization on at the actual operating range. Accuracy ±1,5 percentage units (Niemelä, Interview 11.3.2008).

## 7.2 Life cycle energy costs

To compare the variable speed drives the life cycle energy costs are calculated for imaginary pumping cases. The idea is to compare how the different variable speed drives are functioning as a control device of the pumping process, and what kind of an effect they have on the lifetime's energy costs. In all of the pumping cases under consideration the pumps operating time is 7550 hours per year and the and the life time of the pump is being ten years.

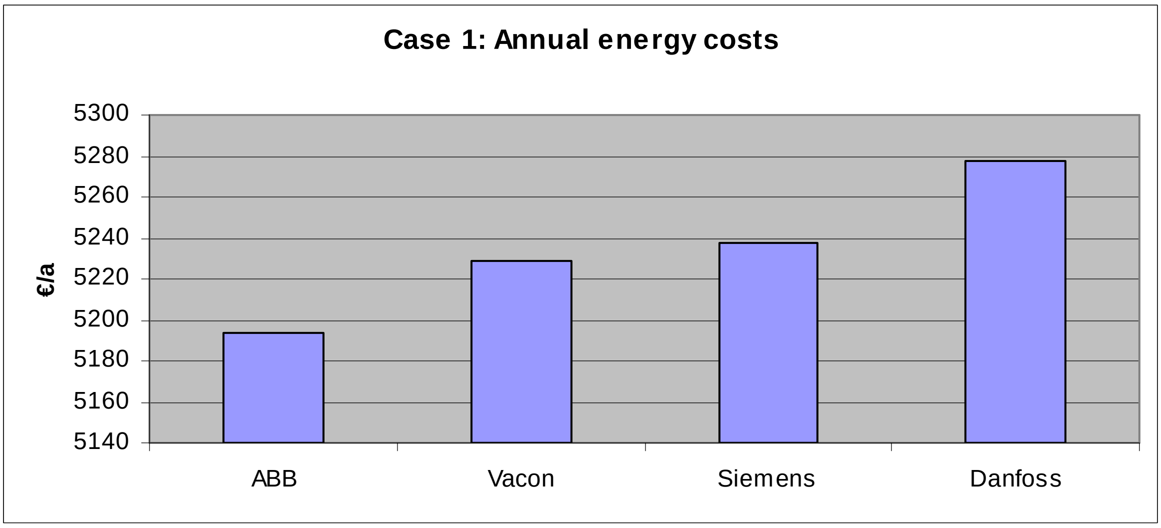
### 7.2.1 Pumping case 1

The life cycle energy costs are calculated to a pumping case illustrated in the picture (45). The first pumping case represents pretty typical pumping process as the pump is operating with big powers most of the time.



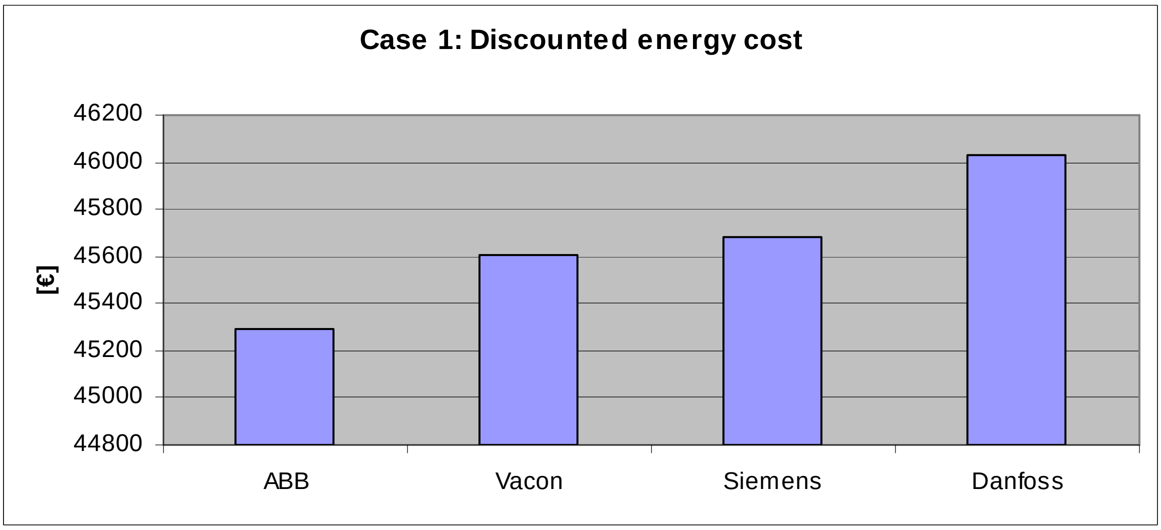

**Picture 45.** Power duration curve of a pumping case number one.

In the picture (46) are illustrated the calculated annual energy costs of the pumping process.




**Picture 46.** Case 1: The annual energy costs of the pumping case with different VSD's controlling the process.

The discounted life cycle energy costs are represented in the picture (47).



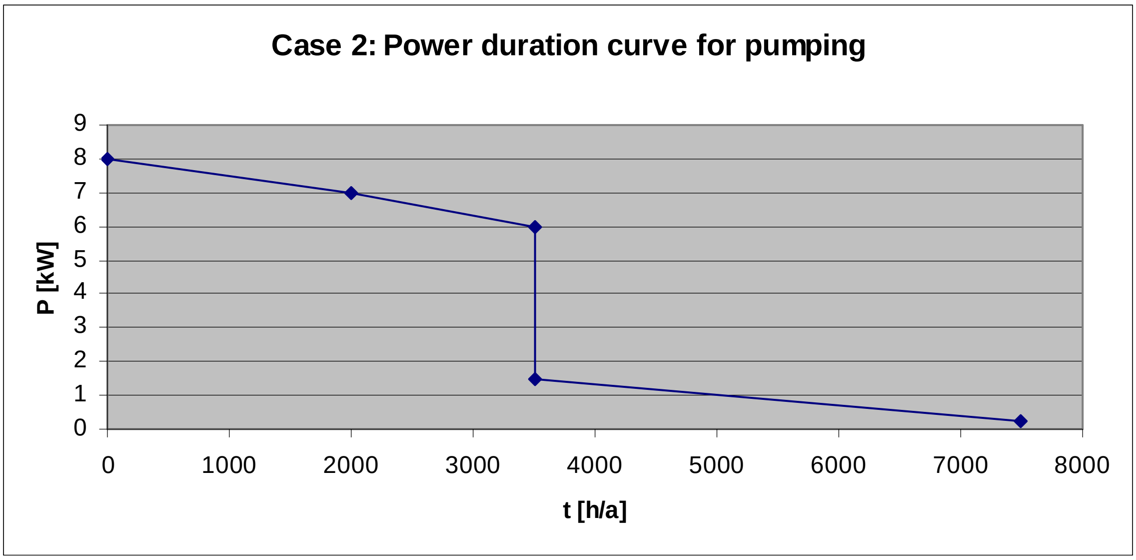

**Picture 47.** The life cycle energy costs of the pumping case with different VSD's controlling the process.

As can be seen from the pictures (46) and (47) the differences in the costs are very small. In the annual costs the difference between the VSDS' is at the most about 80 €/a. When discounting the costs the differences get even more marginal. The difference in the lifetime costs is at the most about 700€: The system with ABB's drive has 700e smaller energy costs in the lifetime period than the system with Danfoss' drive.

It must be remembered that this calculation is only suggestive.

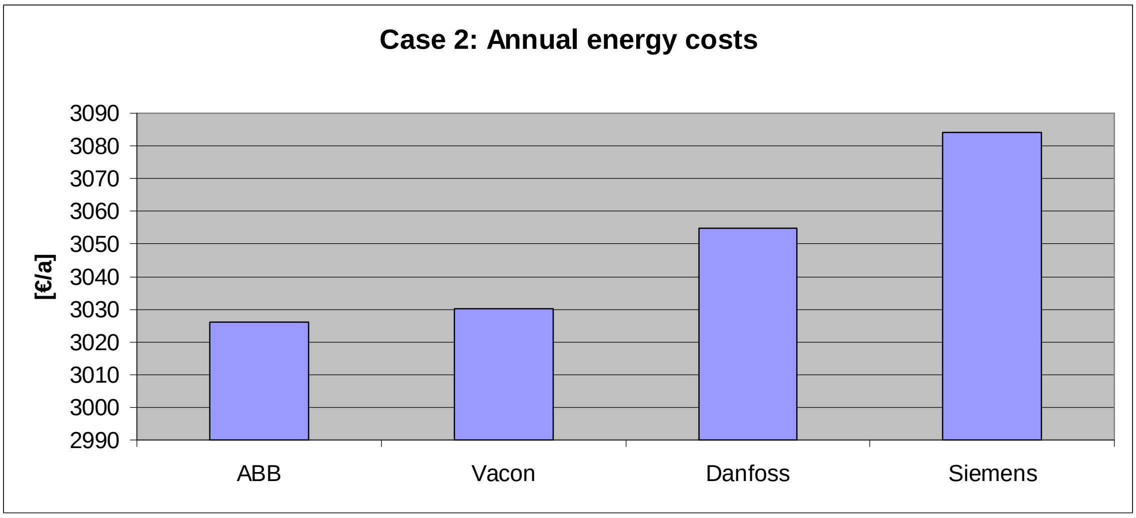
### 7.2.2 Pumping case 2

The second pumping case represents a process where the pump operates at the nominal power or close to it about half of the time, and half of the time with the small powers too. The power duration curve of the pumping process under consideration is illustrated in the picture (48).



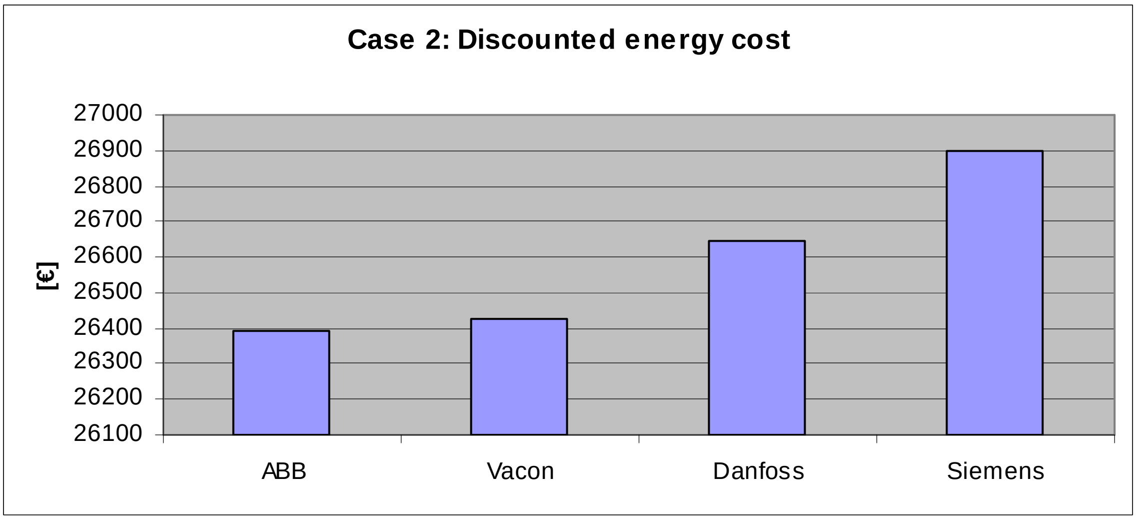

**Picture 48.** Power duration curve of a pumping case number two.

In the picture (49) are illustrated the calculated annual energy costs of the pumping process.




**Picture 49.** Case 2: The annual energy costs of the pumping case with different VSD's controlling the process.

The discounted life cycle energy costs are represented in the picture (50).

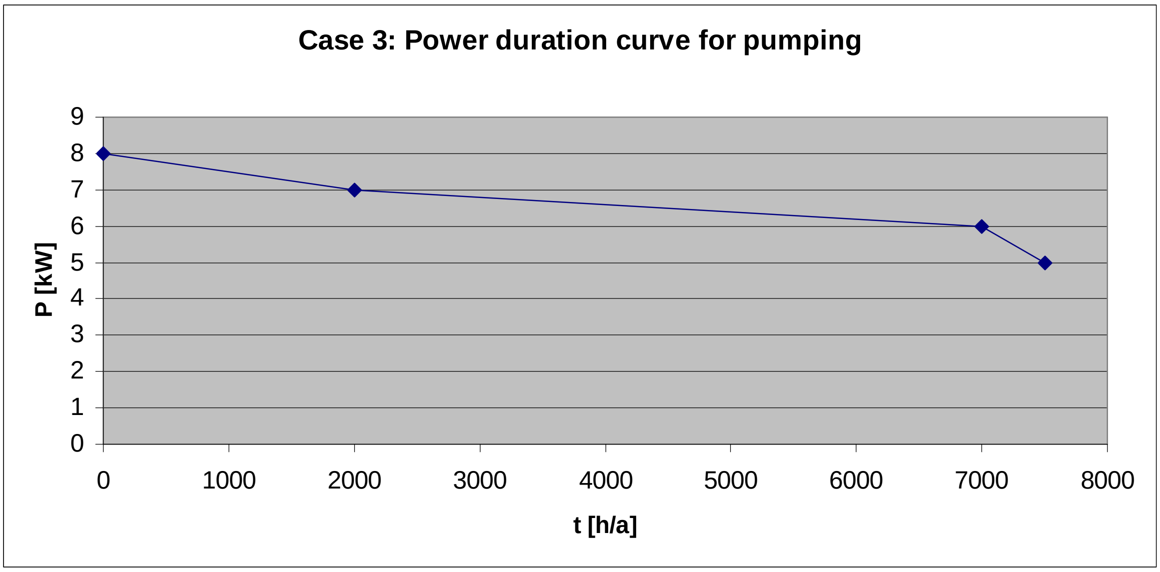



**Picture 50.** The life cycle energy costs of the pumping case with different VSD's controlling the process.

In this pumping case the differences are small as well. In the annual costs the difference between the VSDs' is at the most about 60 €/a. The difference in the lifetime costs is at the most about 500€.

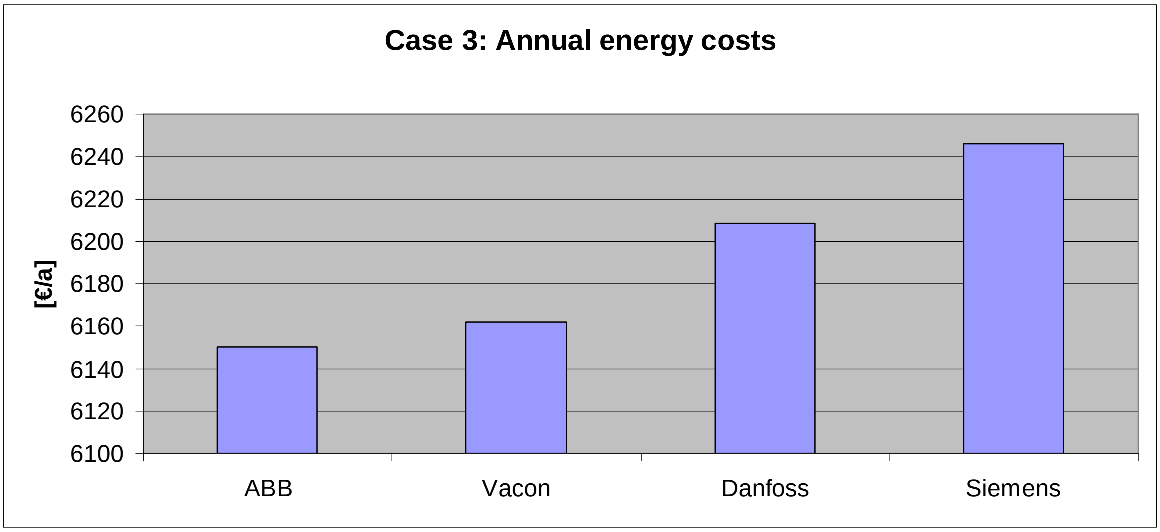
### 7.2.3 Pumping case 3

The third pumping case is quite similar with the first pumping case, but in this case the pump is run all the time with the big powers and not at all with the really small ones. The power duration curve of the pumping process under consideration is illustrated in the picture (51).



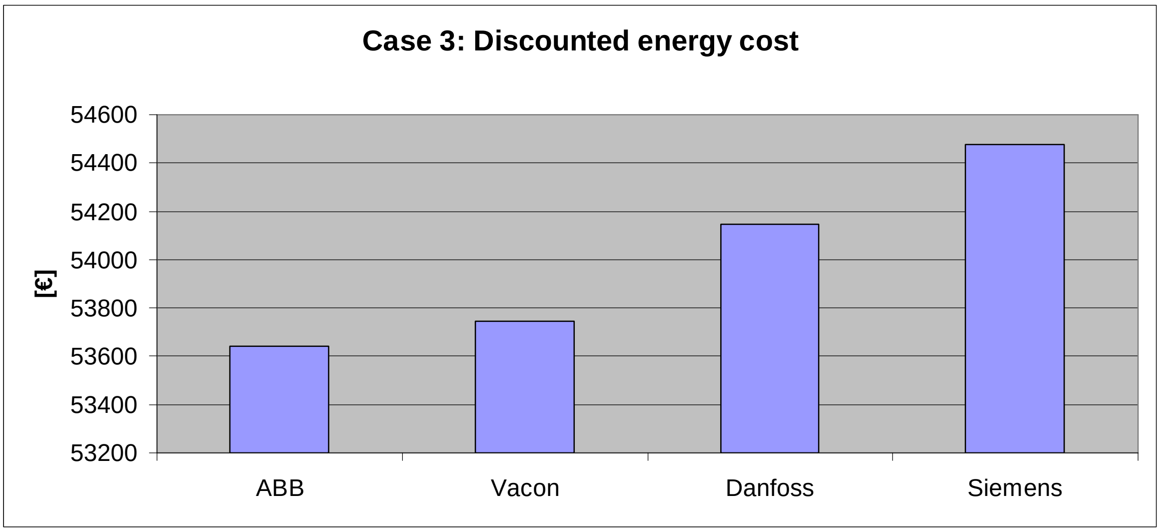

**Picture 51.** Power duration curve of a pumping case number three.

In the picture (52) are illustrated the calculated annual energy costs of the pumping process.




**Picture 52.** Case 3: The annual energy costs of the pumping case with different VSD's controlling the process.

The discounted life cycle energy costs are represented in the picture (52).




**Picture 53.** The life cycle energy costs of the pumping case with different VSD's controlling the process.

The order of the most low-cost variable speed drives for the process seems to be the same in all of the cases. The smallest energy costs are achieved with the ABB's VSD controlling the pumping process. Still the differences are small between the costs.  In the annual costs the difference between the VSDs is at the most about 100 €/a at the pumping case three. The difference in the lifetime costs is at the most about 900€ to ABB's advantage.

## 7.3 User-friendliness

The valuation in the category of user-friendliness is given on the grounds of empiric experience. Opinion of the easiness of the installation is given by a skilled installer. Opinions of the control panel, manuals and the easiness of the use are given by the measurer who can be compared to a person who uses the variable speed drive in a pumping application.

Because of the subjective nature of an opinion the evaluation of user-friendliness is more like a depiction of the problems and successes with different VSD's in the measurement situation.

### 7.3.1 ACS800 by ABB

Measurements with ABB's ACS800 were performed 21.-22.1. 2008. This was the first variable speed drive under testing.

#### 7.3.1.1 Installation

The installation work was done quickly. According to the installer (Nikku, interview 21.1. 2008) the installation of ACS800 is simple, and there are no complaints about it.

#### 7.3.1.2 Start up and use

After the installation the variable speed drive was turned on. There were no problems in entering the start-up data. The drive performed automatically an ID magnetisation at the first start.

The motor was run four an hour or two to heat up before the measurements were started. The motor used in all measurements was a new one and the ACS800 got to be the first drive to run with the motor.

At the first day were measured the efficiencies without flux optimization and at the second day were measured the efficiencies with the flux optimization. There were no problems in either of the measurements.

#### 7.3.1.3 Manuals

The help of the manual (Firmware Manual, ACS800 Pump Control Application Program 7.1 (+N687)) was needed fist when starting up. By following the instructions of the manual it was easy to get the system ready to run. In the manual there are detailed instructions of the start-up. The combination of instructions and a picture of the display in the manual makes it easy to stay in the right track when starting up.

The contest of the manual is logically arranged. After reading the chapter about the control panel, the use of it seemed pretty understandable from the first sight on. The functions of the different buttons on the control panel become clear. In the manual there are also detailed instructions with display pictures for basic actions. It is easy to find the needed instruction from the manual.

All together the manuals seem to be quite understandable, even if the user is not familiar with the drive before. After a short browsing of the control panels menu, the things that might have felt confusing on the manual at the first sight start to make sense.

### 7.3.1.4 Control panel

The control panel of the ACS800 has 16 buttons on it and the display has four lines (picture 54).


**Picture 54.** Overview of the panel.

With the instructions of the manual and a short browsing of the panels menu, the logic of the control panel became clear. It was easy to change the reference the specific amount: with two kinds of arrow keys it was possible to change the reference slow or fast.

The control panel has four operation modes. In a short using time the user gets most familiar with the Actual Signal Display Mode and the Parameter Mode. In parameter mode there are so many different parameters to browse that if the number of the needed parameter is unknown, the manuals parameter list is needed. Otherwise it is troublesome to try to find the needed parameter through all the others.

The co-operation of the manual and the control panel is good. By following the instructions of the manual the use of the variable speed drive trough the control panel is easy. In the measurement situation there were no kinds of problems.

### 7.3.2 VLT AQUA Drive FC 200 from Danfoss

Measurements with Danfoss' VLT AQUA Drive were performed 23.1. 2008.

#### 7.3.2.1 Installation

Installation work took more time than the installation of the ACS800. According to the installer (Nikku, interview 23.1. 2008) the installation was more troublesome than the last VSD under testing. The installer comments on the installation that there were narrow connection strips which made the installation more difficult. He also says that the bad location of the screw holes (which fasten the drive to the wall) makes it harder to screw it on.

#### 7.3.2.2 Start up and use

There was some confusion in the start up. For some reason the motor did not start when the rotation direction of the motor was tried to be checked. After a while the employees of the measurement laboratory got the motor running.

At the control panel there is a button “Quick Menu”, which involves the most used parameters. With the “Quick Menu” it was easy to enter the start-up data to the VSD. After entering the data there was some trouble also in performing the motor identification. After a little thought, the reason for that turned out to be a mistake in settings. After changing the right setting the motor identification was successfully performed.

All things considered, the start-up did not succeed too smoothly. There was a little confusion and problems here and there, and the whole starting up –process took quite a long time. It’s hard for a non-expert to specify the causes of the problems, but some of the problems were caused by the user’s mistakes in the settings.

After the start-up the use of the VSD was easy and there were no problems. The both test runs were performed at the same day.

#### 7.3.2.3 Manuals

There are many pictures in the manual which demonstrate the instructions, especially about the installation. After the chapters of installation the instructions of the start-up seemed to be a little dispersed. It is hard to say what caused the problems in the start-up, but maybe the manuals instructions about the start-up could have been more detailed and linear. Still all the needed information was found from the manual after a while of riffling through the pages.

7.3.2.4 Control panel

The control panels of the VLT AQUA Drive (Picture 55) and the ACS800 are the ones with the biggest number of buttons. The VLT AQUA Drive has 16 buttons on the control panel and the biggest display of the tested VSDs.


**Picture 55.** Overview of the panel.

The “Quick Menu” made the commissioning of the VSD pretty simple. The most commonly used AQUA-functions can be defined with it. The control panel has a great multiplicity of the buttons, but when using the VSD all the needed functions seemed to be under the “Quick Menu” or the “Status”. In a short using time the functions of many other buttons remained unclear. By pushing the “Info”-button more information about the function of the moment could be gained. That was in some points clarifying.

The logic of the navigation was easy to understand. On the big display there was also enough information about the actions on the menu, so it was pretty easy to find the needed action just by browsing the menu.

It was easy to change the reference frequency with the arrow keys. It was possible to change it either slow or fast.

### 7.3.3 NX -drive from Vacon

Measurements with NXS 00165A2H1 from Vacon were performed 24.1. 2008

#### 7.3.3.1 Installation

The installation work was done quickly. According to the installer (Nikku, interview 24.1. 2008) the drive was as easy to install as the ACS800 and there are no complaints about it.

#### 7.3.3.2 Start up and use

There was a little confusion at the start-up with the Vacon NX-drive as well. The problem occurred with the ID-run. It was confusing that some of the needed start-up instructions were in the instruction manual and some of them were in the “All in one” –application manual. The problem was that the parameter for id-run seemed to be missing in the panels menu. After the structure of the information in the manuals and the logic of the control panel started to become clearer, the parameter for id-run was found. Still there was confusion about the id-run: there was no sureness about whether it was successfully performed or not.

After the dubious ID-run the motor did not start. By changing the application it was managed to run successfully. The both test runs were performed at one day. Everything went well until at the frequency of 10 Hz with loads of (100, 90 and 80)% the motor stopped running and there was a fault message on the display. The efficiencies at these test points could not be measured.

#### 7.3.3.3 Manuals

At first there were problems with the start-up and the needed instructions seemed to be hard to find from the manuals. There was only couple of pages of instructions about the start-up at the end of the instruction manual and some of the needed information about the ID-run was at the application manual. It felt confusing to crisscross between the two manuals.

After the confusion at the start-up, the application manual turned out to be very analogous. It was easy to check from the manual which actions on the menu are available at different applications. After a while of wondering, the two manuals started to seem very sense making.

It is not easy to define what caused the problems at the start, but more linear and detailed instructions about the start up may have helped.

#### 7.3.3.4 Control panel

The control panel of the Vacon NX-drive has nine buttons and three text lines on the display (Picture 56). The content of the panel is arranged into the main menu and the lower menus. The actions on the lower menus vary depending on the chosen application. At first that caused some confusion, but after a while of reading the manuals and browsing the menus, the logic of the panel started to seem very understandable.

Browsing the menu was easy with the arrow keys. After a while of familiarizing with the control panel it was easy to find the needed parameter. On the display there was enough information of the action on the menu, so the manual was not necessary needed when finding a certain action.

Changing the reference frequency was not as easy as with the other VSDs under testing. When pushing the button the value changes only one unit of the smallest decimal. By keeping the button pushed the value starts to increase or decrease with accelerated speed. It is hard to stop the accelerated change of the value at the wanted frequency.


**Picture 56.** Overview of the panel.

### 7.3.4 Micromaster 430 from Siemens

Measurements with the Micromaster 430 were performed 28.1. 2008

7.3.4.1 Installation

The installation work didn’t take much time. According to the installer (Nikku, interview 28.1. 2008) the installation was quick and easy to do.

#### 7.3.4.2 Start up and use

When familiarising with a new device the instructions of the manual are needed the most. The manual which came with the Micromaster 430 was in a form of a DVD disk. When entering the settings to the VSD the instructions are needed to be in hand, so it felt complicated without a concrete handbook. Still there was in addition to the DVD manual a small booklet about the start-up, “Getting Started Guide”, so with that the start up went easily.

In spite of the fact that it is more complicated to read the instructions from the computer’s display at a field experiment, there were no problems using the VSD. By following the instructions of the “Quick commissioning” the VSD was soon ready to operate. With the “Quick commissioning” the VSD performed also some kind of a motor identification.

After the motor was heated up the measurements could be started. The both test runs were performed at the same day. At the first test run the measurements at the frequency of (40 and 50) Hz went well, but problems started to occur at the smaller frequencies with big loads. At the frequencies of 30 Hz and 20 Hz the motor stopped at full load. The motor did not start running again until the load was decreased to 60% of the full load. So the efficiencies could be measured at the frequencies of 30 Hz and 20 Hz only with the loads of 60% and less. The measurements at the frequency of 10 Hz were left out because of the motor problems.

The second test run with the flux optimisation went without any problems.

#### 7.3.4.3 Manual

The manual of the Micromaster 430 was in a form of a DVD disk. In addition to that there was a booklet about the start up (Getting Started Guide).

The form of a DVD disk was good in certain ways and complicated in other ways. On the credit side it was easy to find the needed instruction of the manual by using the “find” function to find a keyword among the test. On the other hand it is not always possible to have a computer near the VSD. In addition to that, it is easier to have an instruction book in hand than a computer on knees.

The manual itself was understandable and the use of the VSD was easy with the instructions in it.

7.3.4.4 Control panel

The control panel of the Micromaster 430 has only eight buttons on it and a small display (Picture 57).


**Picture 57.** Overview of the panel.

Changing the settings was easy by following the instructions. What made it complicated was the fact that the instructions had to be looked from the display of a computer, so it was necessary either to have a portable computer or print the instructions.

At the display there was just a number of the parameter instead of a written depiction of the action. That made it impossible to find the needed parameter just by browsing the menu. The number of the needed parameter must be checked from the manual unless the user memorises it.

Changing the reference frequency was easy. By one push of the button the frequency changed 0,1 Hz up or down. It was easy to change the frequency fast the required amount.

The logic of the panel was easy to understand and there were no problems in changing the settings and using the control panel, but the help of instructions was necessary.

# 8 CONCLUSIONS

When comparing the efficiencies between the different manufacturers' variable speed drives and systems it can be noticed that the results are quite parallel with all of the test runs. The order of the VSDs with the best system efficiency to the lowest system efficiency seems to be pretty much the same at the all tested frequencies. From the results it can be noticed that the differences in efficiencies between the tested drives are clearer at small loads and small frequencies.

The variable speed drives from ABB, Vacon and Danfoss have pretty parallel results compared to each other. The system with ABB's drive seems to have best efficiencies at the most of the tested frequencies. After that there comes the system with Vacon's drive and then the system with Danfoss' drive. The VSD from Siemens seems to step out from the crowd with better system efficiencies compared to others at the small loads and small frequencies. At the big frequencies and big loads the efficiencies of the system with Siemens' drive are much smaller than with the others.

A centrifugal pump loads the motor according a quadratic moment curve, so the efficiencies on the curve region are the ones that matter when using a variable speed drive controlling a centrifugal pump. Pumps operate mostly with powers near the nominal power. There were no big differences in efficiencies at the range where the pump usually operates. In the results of the life cycle energy cost calculation there were neither big differences. With more comprehensive LCC analysis the differences might have been clearer. The order of the VSDs with the most energy cost-efficient system at different pumping cases follows the results of efficiency measurements.

As a function of the load the efficiencies vary at different frequencies on average one to three percents, at some test points, especially with small loads, one to ten percents. From the measurement results it can be seen that the different variable speed drives have different kind of effect on the same motor and on the efficiency of the system. Even though the measurement system used in this study can be criticized, the measurements are done systematically and equitably for all the variable speed drives under testing. With systematic measurements can be achieved objective information for comparison about the efficiencies of drive systems with different variable speed drives.

In the comparison category of user-friendliness it is hard to name the order of the user-friendliest VSDs. This part of the study has a different kind of approach from the other categories being dependent of opinions of a user. That is why the evaluations of the user-friendliness should be seen as a depiction of a using experience of the VSDs.

# 9 SUMMARY

The energy demand all over the world is increasing and bringing along problems like the green house effect. A durable solution to control the increasing energy demand is to improve the energy efficiency of the processes. A great energy saving potential lies in pumping applications, because many of them are not operating even near the best possible efficiencies. Trough equipment or control system changes can remarkable amounts of energy be saved in existing as well as in new processes. Pumping applications account for nearly 20% of the world's electrical energy demand, so the energy saving potential with them is large. In pumping applications energy savings can be achieved with a right kind of process controlling. For many pumping application the use of a variable speed drive as a process control element is the most energy efficient solution.

The main target of this study is to examine the energy efficiency of a drive system that moves the pump. The drive system consists of a variable speed drive and an induction motor. In a larger scale the purpose of this study is to examine how the different manufacturers' variable speed drives are functioning as a control device of a pumping process. The idea is to compare the drives from a normal pump user's point of view. The things that are mattering for the pump user, concerning the variable speed drive he uses, are the efficiency of the process and the easiness of the use of the VSD.

The comparison is made between ACS800 from ABB, VLT AQUA Drive from Danfoss, NX-drive from Vacon and Micromaster 430 from Siemens. The efficiencies are measured in power electronics laboratory in the Lappeenranta University of Technology with a system that consists of a variable speed drive and an induction motor with DC-machine. The input powers to the variable speed drive an to the motor are measured with two power analyzers, one located before the variable speed drive and the other located between the VSD and the motor. The mechanical power on the motors shaft is measured with a torque transducer. The efficiency of the variable speed drive itself is examined as well as the efficiency of the drive system. The target of the efficiency measurements is not to give exact and absolute efficiency results of the different drive systems, but to compare the variable speed drives of different manufacturers functioning as a control device of the pumping process.

The efficiencies are measured as a function of a load at different frequencies. The measurement results depict that the differences between the measured system efficiencies are on average few percents. At some points the differences are bigger, especially with small loads and small frequencies. With smaller loads the differences in system efficiencies are at the most about ten percents. The best efficiencies seem to be with a system with ABB's drive. After that there comes the system with Vacon's drive and then the system with Danfoss' drive. The VSD from Siemens seems to step out of the crowd with better system efficiencies compared to others at the small loads and small frequencies. At the big frequencies and big loads the efficiencies of the system with Siemens' drive are much smaller than with the others.

All of the tested variable speed drives incorporate an energy optimizing or "flux optimizing" techniques, which saves energy reducing the magnetizing current at low mechanical loads. The second test run was performed with the energy optimizing on.

With the energy optimization on, at low frequencies and loads the differences between the most efficient and the least efficient systems are at the most about 15 percents. The drives of ABB and Vacon have no big differences in the system efficiencies compared to each other, but the efficiencies are better from the Siemens' and Danfoss' systems at the smaller frequencies and loads.  The differences between the efficiencies of Siemens and Danfoss are also quite small, but the differences compared to the drives of ABB and Vacon are clear. The differences get slighter as the frequency and the load grow.

When comparing the magnitude of the effect of the energy optimisation between different drives, it is noticed that with the VSDs from ABB and Vacon the effect of the optimization is positive. The system efficiencies with the Danfoss' drive did not change as a result of the flux optimization. The efficiencies of the Siemens's VSD dropped when flux optimisation was on.

On the grounds of the measured efficiencies are calculated life cycle energy costs for three imaginary pumping cases. The idea of the calculations is to examine how the different manufacturers' drives function as a part of different kinds of pumping cases, and what kind of an effect they have on the energy consumption of the processes. As a result of the calculations was gained life cycle energy costs for systems controlled with different variable speed drives. The differences in life cycle energy costs with different variable speed drives are not big. The order of the most cost-efficient to least cost-efficient variable speed drive followed the order of the efficiency measurement results. The pumping system with ABB's VSD seem to be most cost-efficient solution in all of the pumping cases under consideration.

Besides the efficiency the user-friendliness is an aspect of the comparison. The definition of the user-friendliness varies depending on the user, so it is impossible to give a comprehensive valuation about the user-friendliness of a device. Because of the user oriented nature of this point of comparison, the valuation of the user-friendliness is based on empiric experiences of the user and the installer of the drive. As the approach changes at this point of the study, the evaluation given of user-friendliness should be seen as a description of how the user succeeded with the drives at the experiment. The user-friendliness of a device is a sum of several factors. In this study the attention was paid in the easiness of the use of the VSD trough the control panel and with help of the manuals.

In a nutshell the main achievements of this study are:

1. Efficiency matrixes of the drive systems (motor + VSD) with different manufacturers' variable speed drives
2. Comparison results of the efficiencies of the different manufacturers' variable speed drives
3. Comparison results of the efficiencies of the drive systems with different manufacturers' variable speed drives
4. Life cycle energy costs of three different kind of pumping cases with different VSDs
5. Depictions of the user-friendliness of the different drives

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**APPENDIXES**

# Measuring equipment

**Specifications of the used measurement equipment**

**Variable speed drives:**

1. ABB: ACS800-01

2. Danfoss: VLT AQUA Drive FC 202 Advanced
   P=7,5 kW

3. Vacon: NXS 00165A2H1 + water treatment -application
   P=7,5kW,

4. Siemens: Micromaster 430
   P=7,5kW

**Power analyzers:**

1. Yokogawa Power Analyzer PZ4000

2. Yokogawa Power Analyzer PZ4000

**Motor:**

Siemens: 3~mot.,

LOW-VOLTG.SQUIRREL-CAGE MOTOR IP55, 4-POLE, 7,5 KW

**Torque transducer:**

Vibrometer TM212

**Current probes:**

FLUKE: AC/DC Current Probe (x3)
Model: 80i-110s

**Cable between VSD and motor:**

5m~MCMK 4*2,5/2,5

## Life cycle energy cost calculations: interpolation of efficiencies

Because efficiencies of all the possible combinations of torque and frequency are not measured, must some of the efficiencies needed in the calculations be interpolated from between the known efficiencies. The change of the efficiencies is assumed to be quite linear, so the method of two points is used.

If a value of a quantity is known for the moments $t_0$ and $t_1$, and it is wanted to be known for a moment $t$, it can be interpolated. (See the figure 1.) If the value of the quantity at moment $t_0$ is $f_0$ and at moment $t_1$ $f_0$, the value at the moment $t$ is about

$$f = f_0 + [\ (t - t_0) / (t_1 - t_0)\ ]\ (f_1 - f_0). \tag{1}$$

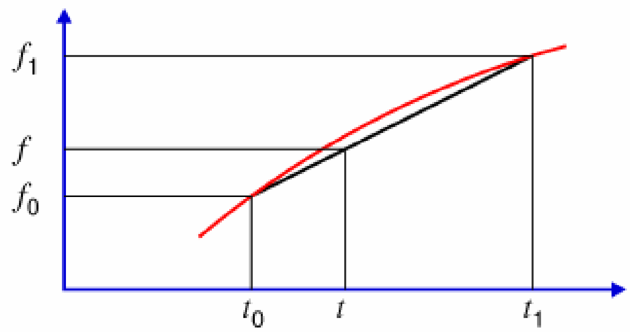


**Figure 1.** Interpolation.

The variable can also be other than time. Because the measured efficiencies vary as a function of the rotation speed (N) and the torque (T), must one of them keep as a constant so that the interpolation is possible. If the torque is constant, can efficiencies be interpolated by varying the rotation speed with following equation:

$$\eta = \eta_0 + [\ (N - N_0) / (N_1 - N_0)\ ]\ (\eta_1 - \eta_0), \tag{2}$$

and correspondingly by varying the torque with equation of:

$$\eta = \eta_0 + [\ (T - T_0) / (T_1 - T_0)\ ]\ (\eta_1 - \eta_0). \tag{3}$$

The torque curve of a centrifugal pump is quadratic. When modelling the imaginary duration curves for the energy calculations, the power points used in calculations are picked from the quadratic curve so that either the torque or the rotation speed is being constant in the measurements.

For example at the quadratic power curve the corresponding rotation speed and load of the power 6,5 are N=1387 rpm and T=45 Nm. Interpolation is possible when the rotation speed is the variable, because according to the measured efficiencies we know how the efficiencies vary when the torque is being constantly 45 Nm. By interpolating from the linear efficiency curve that is a function of rotation speed when the torque is constant (45 Nm), can the efficiencies for any rotation speed be interpolated by changing the rotation speed between the points of known efficiencies.

The points at the quadratic torque curve and the power curve (the corresponding torque and rotation speed for certain powers at the curve) are calculated according to affinity laws. After this the powers used in the imaginary pumping cases are picked so that the efficiencies at these points are known either from the measurements, or so that they can be interpolated. The powers used in the pumping cases are (7,5 ; 6,5 ; 5,5 ; 4 ; 1,5 ; 0,5) kW.

Points at the quadratic curve of pumping calculated according to affinity laws are introduced in table (1) below.

**Table 1**. Correspondence of the power, rotation speed and torque.

| P [kW] | N [rpm] | T [Nm] |
|---|---|---|
| 7,5 | 1455 | 50 |
| 7 | 1422 | 48 |
| 6,5 | 1387 | 45 |
| 6 | 1351 | 43 |
| 5,5 | 1312 | 41 |
| 5 | 1271 | 38 |
| 4,5 | 1227 | 36 |
| 4 | 1180 | 33 |
| 3,5 | 1129 | 30 |
| 3 | 1072 | 27 |
| 2,5 | 1009 | 24 |
| 2 | 937 | 21 |
| 1,5 | 851 | 17 |
| 1 | 743 | 13 |
| 0,5 | 590 | 8 |
| 0,25 | 468 | 5 |

Efficiencies interpolated as a function of the rotation speed are presented in table (2).

The equivalent efficiencies for 6,5 kW are calculated by interpolating between (40-50) Hz when the torque is held constant 90%. Efficiencies for 5,5 kW are calculated between (40-50) Hz when the torque is 80%. (Table 2.)

**Table 2.** Efficiencies interpolated as a function of the rotation speed.

| | N | $N_0$ | $\eta_0$ | $N_1$ | $\eta_1$ | T (constant) | $P$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|
| **Danfoss** | 1387 | 1152 | 0,80 | 1447 | 0,81 | 45 | 6,5 | **0,81** |
| | 1312 | 1157 | 0,79 | 1453 | 0,80 | 40 | 5,5 | **0,80** |
| | | | | | | | | |
| **ABB** | 1387 | 1155 | 0,80 | 1442 | 0,82 | 45 | 6,5 | **0,82** |
| | 1312 | 1160 | 0,81 | 1450 | 0,82 | 40 | 5,5 | **0,81** |
| | | | | | | | | |
| **Vacon** | 1387 | 1154 | 0,79 | 1452 | 0,82 | 45 | 6,5 | **0,82** |
| | 1312 | 1159 | 0,80 | 1458 | 0,82 | 40 | 5,5 | **0,81** |
| | | | | | | | | |
| **Siemens** | 1387 | 1139 | 0,77 | 1442 | 0,81 | 45 | 6,5 | **0,81** |
| | 1312 | 1146 | 0,79 | 1450 | 0,82 | 40 | 5,5 | **0,81** |

Efficiencies interpolated as a function of the torque are presented in table (3).

**Table 3.** Efficiencies interpolated as a function of the torque.

| | T [Nm] | $M_0$ | $\eta_0$ | $M_1$ | $\eta_1$ | n [Hz] (constant) | $P$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|
| **Danfoss** | 32,88 | 30,55 | 0,79 | 35,45 | 0,79 | 40 | 4 | **0,79** |
| | 17,1 | | | | | 30 | 1,5 | **0,71** |
| | 8,2 | 6,3 | 0,48 | 11 | 0,61 | 20 | 0,5 | **0,53** |
| | | | | | | | | |
| **ABB** | 32,88 | 31,31 | 0,80 | 36 | 0,81 | 40 | 4 | **0,80** |
| | 17,1 | | | | | 30 | 1,5 | **0,73** |
| | 8,2 | 7,3 | 0,54 | 12,1 | 0,69 | 20 | 0,5 | **0,57** |
| | | | | | | | | |
| **Vacon** | 32,88 | 31,4 | 0,80 | 36,1 | 0,80 | 40 | 4 | **0,80** |
| | 17,1 | | | | | 30 | 1,5 | **0,72** |
| | 8,2 | 7,3 | 0,50 | 11,9 | 0,61 | 20 | 0,5 | **0,52** |
| | | | | | | | | |
| **Siemens** | 32,88 | 31,3 | 0,80 | 36 | 0,79 | 40 | 4 | **0,80** |
| | 17,1 | | | | | 30 | 1,5 | **0,77** |
| | 8,2 | 7,1 | 0,68 | 11,75 | 0,71 | 20 | 0,5 | **0,69** |

The equivalent efficienciess for 4 kW are calculated by interpolating between (60-70) Hz when the rotation speed (= frequency) is held constant 40 Hz. Efficienciess for 1,5 kW did not need to be calculated by interpolating, because the equivalent efficiency is the efficiency when frequency is 30 Hz. The efficienciess for 0,5 Hz are calculated between (10-20) Hz when the torque is 20%.

# Offsets, harmonics and switching frequencies

## Offsets

| | Measurements | Torque sensor: Offset [Nm] |
|---|---|---|
| **ABB** | Day 1: Basic | -0,683 |
| | Day 2: Flux opt. | -0,03 |
| **Danfoss** | Day 1: Basic | -0,655 |
| | Day 2: Flux opt. | -0,435 |
| **Vacon** | Day 1: Basic | -0,068 |
| | Day 2: Flux opt. | -0,25 |
| **Siemens** | Day 1: Basic and fulx.opt. | -0,443 |

## Harmonics

Power analyzier 2.: Power to motor - Harmonics

| Manufact. | f [Hz] | $U_1$ [V] | $I_1$ [A] | P [kW] | λ |
|---|---|---|---|---|---|
| **ABB** | 50 | 217,93 | 16,0022 | 8,924 | 0,85304 |
| **ABB** | 39,93 | 189,3 | 15,7679 | 7,128 | 0,79469 |
| | | | | | |
| **Danfoss** | 50,013 | 223,67 | 15,823 | 8,824 | 0,83107 |
| **Danfoss** | 40,058 | 0,18601 | 15,831 | 7,176 | 0,81227 |
| | | | | | |
| **Vacon** | 49,995 | 227,11 | 15,9274 | 8,937 | 0,82351 |
| **Vacon** | 40,038 | 183,69 | 15,7186 | 7,133 | 0,82342 |
| | | | | | |
| **Siemens** | 49,995 | 221,07 | 16,4622 | 3,028 | 0,87154 |
| **Siemens** | 39,997 | 170,95 | 16,47 | 2,39 | 0,88837 |

## Switching frequency

| | Switching frequency [kHz] |
|---|---|
| **ABB** | 3 |
| **Danfoss** | 5 |
| **Vacon** | 10 |
| **Siemens** | ? |

# Measurement data from ACS800, first test run

Frequency 10 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 231,15 | 1,2792 | 0,5388 |
| 20 % | 231,24 | 1,5944 | 0,6898 |
| 30 % | 230,82 | 1,9659 | 0,8772 |
| 40 % | 230,94 | 2,3289 | 1,0662 |
| 50 % | 231,12 | 2,7088 | 1,2684 |
| 60 % | 231 | 3,0941 | 1,4725 |
| 70 % | 231,08 | 3,4802 | 1,6853 |
| 80 % | 231,31 | 3,8929 | 1,9157 |
| 90 % | 230,95 | 4,3045 | 2,1552 |
| 100 % | 231,3 | 4,7226 | 2,3888 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 154,9 | 8,2745 | 0,454 |
| 20 % | 156,02 | 8,5098 | 0,599 |
| 30 % | 157,14 | 8,9954 | 0,77 |
| 40 % | 158,86 | 9,6428 | 0,948 |
| 50 % | 160,23 | 10,4106 | 1,132 |
| 60 % | 162,45 | 11,267 | 1,327 |
| 70 % | 163,87 | 12,2113 | 1,522 |
| 80 % | 167,23 | 13,2121 | 1,733 |
| 90 % | 169,74 | 14,296 | 1,95 |
| 100 % | 172,53 | 15,4283 | 2,168 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 294 | 7,1 | 0,218592 |
| 20 % | 289 | 11,8 | 0,357115 |
| 30 % | 285 | 16,6 | 0,495429 |
| 40 % | 280 | 21,4 | 0,627481 |
| 50 % | 275 | 26,1 | 0,751626 |
| 60 % | 270 | 30,85 | 0,872263 |
| 70 % | 265 | 35,55 | 0,986539 |
| 80 % | 260 | 40,35 | 1,098615 |
| 90 % | 256 | 45,1 | 1,209052 |
| 100 % | 252 | 49,8 | 1,314191 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,84 | 0,41 |
| 20 % | 0,87 | 0,52 |
| 30 % | 0,88 | 0,56 |
| 40 % | 0,89 | 0,59 |
| 50 % | 0,89 | 0,59 |
| 60 % | 0,90 | 0,59 |
| 70 % | 0,90 | 0,59 |
| 80 % | 0,90 | 0,57 |
| 90 % | 0,90 | 0,56 |
| 100 % | 0,91 | 0,55 |

Frequency 20 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231,24 | 1,9408 | 0,8637 |
| **20 %** | 231,07 | 2,5584 | 1,1857 |
| **30 %** | 231,21 | 3,2709 | 1,5654 |
| **40 %** | 231,09 | 3,8322 | 1,8768 |
| **50 %** | 230,8 | 4,4506 | 2,2294 |
| **60 %** | 230,81 | 5,1259 | 2,5989 |
| **70 %** | 231,09 | 5,7562 | 2,9659 |
| **80 %** | 230,88 | 6,4048 | 3,3542 |
| **90 %** | 230,75 | 7,0222 | 3,7438 |
| **100 %** | 230,23 | 7,4975 | 4,1272 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 199,33 | 8,5512 | 0,765 |
| **20 %** | 199,71 | 8,8871 | 1,063 |
| **30 %** | 199,92 | 9,392 | 1,395 |
| **40 %** | 199,86 | 10,0309 | 1,723 |
| **50 %** | 200,45 | 10,782 | 2,058 |
| **60 %** | 200,41 | 11,631 | 2,4 |
| **70 %** | 200,89 | 12,5461 | 2,751 |
| **80 %** | 200,46 | 13,534 | 3,114 |
| **90 %** | 201,07 | 14,5718 | 3,478 |
| **100 %** | 201,18 | 15,6564 | 3,848 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 592 | 7,3 | 0,45 |
| **20 %** | 589 | 12,1 | 0,746327 |
| **30 %** | 585 | 16,89 | 1,034699 |
| **40 %** | 580 | 21,7 | 1,318003 |
| **50 %** | 575 | 26,5 | 1,595667 |
| **60 %** | 570 | 31,25 | 1,865321 |
| **70 %** | 566 | 36,05 | 2,136733 |
| **80 %** | 561 | 40,75 | 2,393972 |
| **90 %** | 556 | 45,65 | 2,657934 |
| **100 %** | 552 | 50,3 | 2,907607 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,89 | 0,52 |
| **20 %** | 0,90 | 0,63 |
| **30 %** | 0,89 | 0,66 |
| **40 %** | 0,92 | 0,70 |
| **50 %** | 0,92 | 0,72 |
| **60 %** | 0,92 | 0,72 |
| **70 %** | 0,93 | 0,72 |
| **80 %** | 0,93 | 0,71 |
| **90 %** | 0,93 | 0,71 |
| **100 %** | 0,93 | 0,70 |

Frequency 30 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 230,71 | 2,5665 | 1,2012 |
| 20 % | 230,7 | 3,3926 | 1,6507 |
| 30 % | 230,59 | 4,2945 | 2,1526 |
| 40 % | 230,93 | 5,2232 | 2,664 |
| 50 % | 230,57 | 6,0505 | 3,1723 |
| 60 % | 230,66 | 6,9407 | 3,6981 |
| 70 % | 230,63 | 7,6637 | 4,2328 |
| 80 % | 230,05 | 8,372 | 4,7752 |
| 90 % | 230,1 | 9,109 | 5,319 |
| 100 % | 229,9 | 10,0089 | 5,8651 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 226,51 | 8,6949 | 1,069 |
| 20 % | 226,45 | 9,0029 | 1,502 |
| 30 % | 226,3 | 9,5644 | 1,993 |
| 40 % | 226,48 | 10,2363 | 2,487 |
| 50 % | 225,81 | 10,9832 | 2,962 |
| 60 % | 225,18 | 11,685 | 3,471 |
| 70 % | 225,57 | 12,7481 | 3,972 |
| 80 % | 225,79 | 13,7236 | 4,485 |
| 90 % | 225,91 | 14,7588 | 5,007 |
| 100 % | 225,83 | 15,8506 | 5,527 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 893 | 7,47 | 0,698555 |
| 20 % | 889 | 12,25 | 1,140424 |
| 30 % | 885 | 17,02 | 1,577362 |
| 40 % | 880 | 21,9 | 2,018159 |
| 50 % | 875 | 26,6 | 2,437352 |
| 60 % | 871 | 31,5 | 2,873144 |
| 70 % | 866 | 36,6 | 3,319155 |
| 80 % | 862 | 41 | 3,701006 |
| 90 % | 857 | 45,9 | 4,119288 |
| 100 % | 853 | 50,55 | 4,515427 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,89 | 0,58 |
| 20 % | 0,91 | 0,69 |
| 30 % | 0,93 | 0,73 |
| 40 % | 0,93 | 0,76 |
| 50 % | 0,93 | 0,77 |
| 60 % | 0,94 | 0,78 |
| 70 % | 0,94 | 0,78 |
| 80 % | 0,94 | 0,78 |
| 90 % | 0,94 | 0,77 |
| 100 % | 0,94 | 0,77 |

Frequency 40 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231,51 | 3,0976 | 1,4866 |
| **20 %** | 230,88 | 4,2235 | 2,1031 |
| **30 %** | 231,14 | 5,3841 | 2,7633 |
| **40 %** | 230,36 | 6,4984 | 3,4317 |
| **50 %** | 230,84 | 7,5129 | 4,0924 |
| **60 %** | 230,39 | 8,5734 | 4,7857 |
| **70 %** | 229,92 | 9,4872 | 5,4436 |
| **80 %** | 229,91 | 10,4692 | 6,122 |
| **90 %** | 229,87 | 11,269 | 6,8254 |
| **100 %** | 229,48 | 12,4687 | 7,509 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 249,55 | 8,727 | 1,359 |
| **20 %** | 248,77 | 9,0634 | 1,946 |
| **30 %** | 248,39 | 9,5666 | 2,569 |
| **40 %** | 247,07 | 10,2514 | 3,211 |
| **50 %** | 247,46 | 11,2483 | 4,057 |
| **60 %** | 246,59 | 11,8769 | 4,517 |
| **70 %** | 246,28 | 12,742 | 5,145 |
| **80 %** | 246,48 | 13,697 | 5,802 |
| **90 %** | 246,67 | 14,7 | 6,47 |
| **100 %** | 246,22 | 15,7131 | 7,12 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 1193 | 7,5 | 0,93698 |
| **20 %** | 1189 | 12,2 | 1,519044 |
| **30 %** | 1184 | 16,94 | 2,10036 |
| **40 %** | 1179 | 21,8 | 2,691528 |
| **50 %** | 1175 | 26,55 | 3,266864 |
| **60 %** | 1170 | 31,31 | 3,836167 |
| **70 %** | 1165 | 36 | 4,391947 |
| **80 %** | 1160 | 40,7 | 4,944029 |
| **90 %** | 1155 | 45,35 | 5,485142 |
| **100 %** | 1150 | 50 | 6,021386 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,91 | 0,63 |
| **20 %** | 0,93 | 0,72 |
| **30 %** | 0,93 | 0,76 |
| **40 %** | 0,94 | 0,78 |
| **50 %** | 0,99 | 0,80 |
| **60 %** | 0,94 | 0,80 |
| **70 %** | 0,95 | 0,81 |
| **80 %** | 0,95 | 0,81 |
| **90 %** | 0,95 | 0,80 |
| **100 %** | 0,95 | 0,80 |

Frequency 50 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 230,82 | 3,7939 | 1,8569 |
| **20 %** | 230,89 | 5,1247 | 2,6093 |
| **30 %** | 231,1 | 6,4986 | 3,4192 |
| **40 %** | 230,52 | 7,664 | 4,211 |
| **50 %** | 230,54 | 8,888 | 5,046 |
| **60 %** | 230,01 | 9,915 | 5,9 |
| **70 %** | 230,11 | 11,438 | 6,789 |
| **80 %** | 230,06 | 12,449 | 7,569 |
| **90 %** | 230,42 | 13,608 | 8,477 |
| **100 %** | 230,3 | 14,861 | 9,262 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 263,9 | 8,1587 | 1,712 |
| **20 %** | 261,44 | 8,332 | 2,438 |
| **30 %** | 260,14 | 8,8279 | 3,214 |
| **40 %** | 257,54 | 9,3675 | 3,98 |
| **50 %** | 257,22 | 10,3171 | 4,821 |
| **60 %** | 256,91 | 11,2921 | 5,597 |
| **70 %** | 256,77 | 12,3846 | 6,459 |
| **80 %** | 256,25 | 13,3988 | 7,195 |
| **90 %** | 256,3 | 14,6476 | 8,06 |
| **100 %** | 256,39 | 15,7477 | 8,802 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 1492 | 8,2 | 1,281183 |
| **20 %** | 1487 | 13,09 | 2,038352 |
| **30 %** | 1482 | 17,72 | 2,75005 |
| **40 %** | 1476 | 22,5 | 3,477743 |
| **50 %** | 1470 | 27,45 | 4,225599 |
| **60 %** | 1464 | 32 | 4,905911 |
| **70 %** | 1457 | 36,85 | 5,622451 |
| **80 %** | 1450 | 40,9 | 6,210405 |
| **90 %** | 1442 | 46 | 6,946271 |
| **100 %** | 1437 | 50,4 | 7,584307 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,92 | 0,69 |
| **20 %** | 0,93 | 0,78 |
| **30 %** | 0,94 | 0,80 |
| **40 %** | 0,95 | 0,83 |
| **50 %** | 0,96 | 0,84 |
| **60 %** | 0,95 | 0,83 |
| **70 %** | 0,95 | 0,83 |
| **80 %** | 0,95 | 0,82 |
| **90 %** | 0,95 | 0,82 |
| **100 %** | 0,95 | 0,82 |

# Measurement data from VLT AQUA Drive, first test run

Frequency 10 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 231,26 | 1,2446 | 0,5071 |
| 20 % | 231,33 | 1,5713 | 0,6672 |
| 30 % | 231,51 | 1,9407 | 0,8488 |
| 40 % | 231,36 | 2,3027 | 1,0376 |
| 50 % | 231,5 | 2,6695 | 1,2314 |
| 60 % | 231,81 | 3,0653 | 1,4395 |
| 70 % | 231,53 | 3,4773 | 1,66 |
| 80 % | 231,54 | 3,9243 | 1,8883 |
| 90 % | 231,59 | 4,355 | 2,1284 |
| 100 % | 231,12 | 4,7931 | 2,3691 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 221,23 | 7,8027 | 0,422 |
| 20 % | 221,16 | 8,0718 | 0,565 |
| 30 % | 220,86 | 8,62 | 0,743 |
| 40 % | 221,02 | 9,302 | 0,924 |
| 50 % | 220,28 | 10,057 | 1,1 |
| 60 % | 220,85 | 10,9577 | 1,292 |
| 70 % | 220,82 | 11,9448 | 1,492 |
| 80 % | 220,8 | 13,0466 | 1,705 |
| 90 % | 220,58 | 15,404 | 2,148 |
| 100 % | 220,28 | 15,4285 | 2,142 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 294 | 6,1 | 0,187804 |
| 20 % | 290 | 10,75 | 0,326464 |
| 30 % | 285 | 15,5 | 0,4626 |
| 40 % | 280 | 20,2 | 0,592295 |
| 50 % | 275 | 25 | 0,719948 |
| 60 % | 269 | 29,7 | 0,836638 |
| 70 % | 264 | 34,5 | 0,953788 |
| 80 % | 258 | 39,3 | 1,061795 |
| 90 % | 252 | 44 | 1,161133 |
| 100 % | 247 | 49 | 1,267423 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,83 | 0,37 |
| 20 % | 0,85 | 0,49 |
| 30 % | 0,88 | 0,55 |
| 40 % | 0,89 | 0,57 |
| 50 % | 0,89 | 0,58 |
| 60 % | 0,90 | 0,58 |
| 70 % | 0,90 | 0,57 |
| 80 % | 0,90 | 0,56 |
| 90 % | 1,01 | 0,55 |
| 100 % | 0,90 | 0,53 |

Frequency 20 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 230,82 | 1,8753 | 0,8188 |
| 20 % | 230,84 | 2,471 | 1,1213 |
| 30 % | 230,89 | 3,1456 | 1,4743 |
| 40 % | 231,29 | 3,8017 | 1,8267 |
| 50 % | 231,23 | 4,439 | 2,1782 |
| 60 % | 231,15 | 5,1076 | 2,5437 |
| 70 % | 231,18 | 5,7595 | 2,9165 |
| 80 % | 231,12 | 6,396 | 3,2749 |
| 90 % | 230,91 | 7,1086 | 3,683 |
| 100 % | 230,59 | 7,8139 | 4,0838 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 197,86 | 8,2563 | 0,743 |
| 20 % | 197,92 | 8,5919 | 1,033 |
| 30 % | 198,17 | 9,1558 | 1,364 |
| 40 % | 198,47 | 9,8354 | 1,699 |
| 50 % | 198,76 | 10,5828 | 2,026 |
| 60 % | 199,13 | 11,6186 | 2,441 |
| 70 % | 199,32 | 13,1161 | 3 |
| 80 % | 199,17 | 13,3929 | 3,089 |
| 90 % | 199,36 | 14,4423 | 3,449 |
| 100 % | 199,59 | 15,5762 | 3,812 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 593 | 6,3 | 0,391223 |
| 20 % | 590 | 11 | 0,679631 |
| 30 % | 584 | 16 | 0,978501 |
| 40 % | 580 | 20,7 | 1,257265 |
| 50 % | 575 | 25,35 | 1,526421 |
| 60 % | 570 | 30,2 | 1,802646 |
| 70 % | 565 | 35 | 2,070833 |
| 80 % | 560 | 39,9 | 2,339858 |
| 90 % | 555 | 44,6 | 2,592128 |
| 100 % | 551 | 49,8 | 2,873489 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,91 | 0,48 |
| 20 % | 0,92 | 0,61 |
| 30 % | 0,93 | 0,66 |
| 40 % | 0,93 | 0,69 |
| 50 % | 0,93 | 0,70 |
| 60 % | 0,96 | 0,71 |
| 70 % | 1,03 | 0,71 |
| 80 % | 0,94 | 0,71 |
| 90 % | 0,94 | 0,70 |
| 100 % | 0,93 | 0,70 |

Frequency 30 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231 | 2,466 | 1,112 |
| **20 %** | 231,21 | 3,3127 | 1,5629 |
| **30 %** | 230,9 | 4,2842 | 2,0862 |
| **40 %** | 230,95 | 5,2197 | 2,6039 |
| **50 %** | 230,88 | 6,1353 | 3,1194 |
| **60 %** | 231 | 7,0503 | 3,6395 |
| **70 %** | 230,97 | 7,9495 | 4,1573 |
| **80 %** | 231,28 | 8,885 | 4,7199 |
| **90 %** | 230,85 | 9,7807 | 5,2748 |
| **100 %** | 230,62 | 10,5421 | 5,8072 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 229,03 | 8,1403 | 1,046 |
| **20 %** | 228,43 | 8,4962 | 1,469 |
| **30 %** | 227,93 | 9,1318 | 1,976 |
| **40 %** | 227,94 | 9,819 | 2,45 |
| **50 %** | 227,95 | 10,6349 | 2,942 |
| **60 %** | 227,87 | 11,5439 | 3,453 |
| **70 %** | 227,75 | 12,4665 | 3,939 |
| **80 %** | 227,69 | 13,507 | 4,456 |
| **90 %** | 227,6 | 14,5577 | 4,97 |
| **100 %** | 227,82 | 15,7016 | 5,5 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 893 | 6,52 | 0,609716 |
| **20 %** | 889 | 11,22 | 1,044536 |
| **30 %** | 884 | 16,1 | 1,490413 |
| **40 %** | 879 | 20,9 | 1,923817 |
| **50 %** | 874 | 25,7 | 2,352194 |
| **60 %** | 870 | 30,45 | 2,774183 |
| **70 %** | 865 | 35,2 | 3,188507 |
| **80 %** | 860 | 40 | 3,60236 |
| **90 %** | 855 | 44,7 | 4,002232 |
| **100 %** | 850 | 49,55 | 4,410534 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta sys$ |
|---|---|---|
| **10 %** | 0,94 | 0,55 |
| **20 %** | 0,94 | 0,67 |
| **30 %** | 0,95 | 0,71 |
| **40 %** | 0,94 | 0,74 |
| **50 %** | 0,94 | 0,75 |
| **60 %** | 0,95 | 0,76 |
| **70 %** | 0,95 | 0,77 |
| **80 %** | 0,94 | 0,76 |
| **90 %** | 0,94 | 0,76 |
| **100 %** | 0,95 | 0,76 |

Frequency 40 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 231,16 | 3,0145 | 1,4098 |
| 20 % | 231,47 | 4,1717 | 2,0426 |
| 30 % | 231,16 | 5,3955 | 2,7116 |
| 40 % | 231,29 | 6,5966 | 3,4008 |
| 50 % | 230,98 | 7,7365 | 4,0529 |
| 60 % | 231,04 | 8,9005 | 4,75 |
| 70 % | 230,85 | 9,9496 | 5,4385 |
| 80 % | 230,17 | 10,8431 | 6,1139 |
| 90 % | 230,02 | 11,8271 | 6,8275 |
| 100 % | 230,03 | 12,786 | 7,5491 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 250,82 | 7,9771 | 1,308 |
| 20 % | 250,02 | 8,4142 | 1,915 |
| 30 % | 249,39 | 9,1446 | 2,651 |
| 40 % | 249,02 | 9,7773 | 3,191 |
| 50 % | 248,1 | 10,632 | 3,856 |
| 60 % | 247,48 | 11,5371 | 4,499 |
| 70 % | 247,24 | 12,5212 | 5,167 |
| 80 % | 247,1 | 13,544 | 5,835 |
| 90 % | 247,11 | 14,6011 | 6,502 |
| 100 % | 247,26 | 15,7524 | 7,204 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 1193 | 6,7 | 0,837035 |
| 20 % | 1188 | 11,3 | 1,4058 |
| 30 % | 1183 | 16,2 | 2,006912 |
| 40 % | 1178 | 21 | 2,590557 |
| 50 % | 1173 | 25,8 | 3,169176 |
| 60 % | 1168 | 30,55 | 3,736652 |
| 70 % | 1162 | 35,45 | 4,31371 |
| 80 % | 1157 | 40 | 4,84643 |
| 90 % | 1152 | 45 | 5,428672 |
| 100 % | 1147 | 50 | 6,005678 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,93 | 0,59 |
| 20 % | 0,94 | 0,69 |
| 30 % | 0,98 | 0,74 |
| 40 % | 0,94 | 0,76 |
| 50 % | 0,95 | 0,78 |
| 60 % | 0,95 | 0,79 |
| 70 % | 0,95 | 0,79 |
| 80 % | 0,95 | 0,79 |
| 90 % | 0,95 | 0,80 |
| 100 % | 0,95 | 0,80 |

Frequency 50 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231,2 | 3,7645 | 1,8076 |
| **20 %** | 231,35 | 5,247 | 2,638 |
| **30 %** | 231,17 | 6,771 | 3,499 |
| **40 %** | 231,1 | 8,087 | 4,268 |
| **50 %** | 230,95 | 9,432 | 5,104 |
| **60 %** | 230,98 | 10,611 | 5,986 |
| **70 %** | 230,84 | 11,836 | 6,787 |
| **80 %** | 230,52 | 12,933 | 7,685 |
| **90 %** | 230,57 | 14,052 | 8,493 |
| **100 %** | 320,51 | 15,339 | 9,359 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 264,68 | 7,9466 | 1,693 |
| **20 %** | 263,28 | 8,4543 | 2,48 |
| **30 %** | 261,18 | 9,021 | 3,274 |
| **40 %** | 260,25 | 9,8166 | 4,051 |
| **50 %** | 258,51 | 10,4871 | 4,843 |
| **60 %** | 258,51 | 11,614 | 5,658 |
| **70 %** | 258,08 | 12,511 | 6,478 |
| **80 %** | 257,64 | 13,5288 | 7,268 |
| **90 %** | 257,81 | 14,681 | 8,111 |
| **100 %** | 257,27 | 15,9215 | 8,97 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 1492 | 7,35 | 1,148378 |
| **20 %** | 1487 | 12,1 | 1,884191 |
| **30 %** | 1482 | 16,9 | 2,62279 |
| **40 %** | 1476 | 21,7 | 3,35409 |
| **50 %** | 1471 | 26,4 | 4,066729 |
| **60 %** | 1465 | 31,5 | 4,832555 |
| **70 %** | 1459 | 36,25 | 5,538497 |
| **80 %** | 1453 | 40,6 | 6,177607 |
| **90 %** | 1447 | 45,6 | 6,909745 |
| **100 %** | 1440 | 50,3 | 7,585061 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,94 | 0,64 |
| **20 %** | 0,94 | 0,71 |
| **30 %** | 0,94 | 0,75 |
| **40 %** | 0,95 | 0,79 |
| **50 %** | 0,95 | 0,80 |
| **60 %** | 0,95 | 0,81 |
| **70 %** | 0,95 | 0,82 |
| **80 %** | 0,95 | 0,80 |
| **90 %** | 0,96 | 0,81 |
| **100 %** | 0,96 | 0,81 |

# Measurement data from VLT AQUA Drive, first test run

Frequency 10 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 231,26 | 1,2446 | 0,5071 |
| 20 % | 231,33 | 1,5713 | 0,6672 |
| 30 % | 231,51 | 1,9407 | 0,8488 |
| 40 % | 231,36 | 2,3027 | 1,0376 |
| 50 % | 231,5 | 2,6695 | 1,2314 |
| 60 % | 231,81 | 3,0653 | 1,4395 |
| 70 % | 231,53 | 3,4773 | 1,66 |
| 80 % | 231,54 | 3,9243 | 1,8883 |
| 90 % | 231,59 | 4,355 | 2,1284 |
| 100 % | 231,12 | 4,7931 | 2,3691 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 221,23 | 7,8027 | 0,422 |
| 20 % | 221,16 | 8,0718 | 0,565 |
| 30 % | 220,86 | 8,62 | 0,743 |
| 40 % | 221,02 | 9,302 | 0,924 |
| 50 % | 220,28 | 10,057 | 1,1 |
| 60 % | 220,85 | 10,9577 | 1,292 |
| 70 % | 220,82 | 11,9448 | 1,492 |
| 80 % | 220,8 | 13,0466 | 1,705 |
| 90 % | 220,58 | 15,404 | 2,148 |
| 100 % | 220,28 | 15,4285 | 2,142 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 294 | 6,1 | 0,187804 |
| 20 % | 290 | 10,75 | 0,326464 |
| 30 % | 285 | 15,5 | 0,4626 |
| 40 % | 280 | 20,2 | 0,592295 |
| 50 % | 275 | 25 | 0,719948 |
| 60 % | 269 | 29,7 | 0,836638 |
| 70 % | 264 | 34,5 | 0,953788 |
| 80 % | 258 | 39,3 | 1,061795 |
| 90 % | 252 | 44 | 1,161133 |
| 100 % | 247 | 49 | 1,267423 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,83 | 0,37 |
| 20 % | 0,85 | 0,49 |
| 30 % | 0,88 | 0,55 |
| 40 % | 0,89 | 0,57 |
| 50 % | 0,89 | 0,58 |
| 60 % | 0,90 | 0,58 |
| 70 % | 0,90 | 0,57 |
| 80 % | 0,90 | 0,56 |
| 90 % | 1,01 | 0,55 |
| 100 % | 0,90 | 0,53 |

Frequency 20 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 230,82 | 1,8753 | 0,8188 |
| 20 % | 230,84 | 2,471 | 1,1213 |
| 30 % | 230,89 | 3,1456 | 1,4743 |
| 40 % | 231,29 | 3,8017 | 1,8267 |
| 50 % | 231,23 | 4,439 | 2,1782 |
| 60 % | 231,15 | 5,1076 | 2,5437 |
| 70 % | 231,18 | 5,7595 | 2,9165 |
| 80 % | 231,12 | 6,396 | 3,2749 |
| 90 % | 230,91 | 7,1086 | 3,683 |
| 100 % | 230,59 | 7,8139 | 4,0838 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 197,86 | 8,2563 | 0,743 |
| 20 % | 197,92 | 8,5919 | 1,033 |
| 30 % | 198,17 | 9,1558 | 1,364 |
| 40 % | 198,47 | 9,8354 | 1,699 |
| 50 % | 198,76 | 10,5828 | 2,026 |
| 60 % | 199,13 | 11,6186 | 2,441 |
| 70 % | 199,32 | 13,1161 | 3 |
| 80 % | 199,17 | 13,3929 | 3,089 |
| 90 % | 199,36 | 14,4423 | 3,449 |
| 100 % | 199,59 | 15,5762 | 3,812 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 593 | 6,3 | 0,391223 |
| 20 % | 590 | 11 | 0,679631 |
| 30 % | 584 | 16 | 0,978501 |
| 40 % | 580 | 20,7 | 1,257265 |
| 50 % | 575 | 25,35 | 1,526421 |
| 60 % | 570 | 30,2 | 1,802646 |
| 70 % | 565 | 35 | 2,070833 |
| 80 % | 560 | 39,9 | 2,339858 |
| 90 % | 555 | 44,6 | 2,592128 |
| 100 % | 551 | 49,8 | 2,873489 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,91 | 0,48 |
| 20 % | 0,92 | 0,61 |
| 30 % | 0,93 | 0,66 |
| 40 % | 0,93 | 0,69 |
| 50 % | 0,93 | 0,70 |
| 60 % | 0,96 | 0,71 |
| 70 % | 1,03 | 0,71 |
| 80 % | 0,94 | 0,71 |
| 90 % | 0,94 | 0,70 |
| 100 % | 0,93 | 0,70 |

Frequency 30 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231 | 2,466 | 1,112 |
| **20 %** | 231,21 | 3,3127 | 1,5629 |
| **30 %** | 230,9 | 4,2842 | 2,0862 |
| **40 %** | 230,95 | 5,2197 | 2,6039 |
| **50 %** | 230,88 | 6,1353 | 3,1194 |
| **60 %** | 231 | 7,0503 | 3,6395 |
| **70 %** | 230,97 | 7,9495 | 4,1573 |
| **80 %** | 231,28 | 8,885 | 4,7199 |
| **90 %** | 230,85 | 9,7807 | 5,2748 |
| **100 %** | 230,62 | 10,5421 | 5,8072 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 229,03 | 8,1403 | 1,046 |
| **20 %** | 228,43 | 8,4962 | 1,469 |
| **30 %** | 227,93 | 9,1318 | 1,976 |
| **40 %** | 227,94 | 9,819 | 2,45 |
| **50 %** | 227,95 | 10,6349 | 2,942 |
| **60 %** | 227,87 | 11,5439 | 3,453 |
| **70 %** | 227,75 | 12,4665 | 3,939 |
| **80 %** | 227,69 | 13,507 | 4,456 |
| **90 %** | 227,6 | 14,5577 | 4,97 |
| **100 %** | 227,82 | 15,7016 | 5,5 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 893 | 6,52 | 0,609716 |
| **20 %** | 889 | 11,22 | 1,044536 |
| **30 %** | 884 | 16,1 | 1,490413 |
| **40 %** | 879 | 20,9 | 1,923817 |
| **50 %** | 874 | 25,7 | 2,352194 |
| **60 %** | 870 | 30,45 | 2,774183 |
| **70 %** | 865 | 35,2 | 3,188507 |
| **80 %** | 860 | 40 | 3,60236 |
| **90 %** | 855 | 44,7 | 4,002232 |
| **100 %** | 850 | 49,55 | 4,410534 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,94 | 0,55 |
| **20 %** | 0,94 | 0,67 |
| **30 %** | 0,95 | 0,71 |
| **40 %** | 0,94 | 0,74 |
| **50 %** | 0,94 | 0,75 |
| **60 %** | 0,95 | 0,76 |
| **70 %** | 0,95 | 0,77 |
| **80 %** | 0,94 | 0,76 |
| **90 %** | 0,94 | 0,76 |
| **100 %** | 0,95 | 0,76 |

Frequency 40 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 231,16 | 3,0145 | 1,4098 |
| 20 % | 231,47 | 4,1717 | 2,0426 |
| 30 % | 231,16 | 5,3955 | 2,7116 |
| 40 % | 231,29 | 6,5966 | 3,4008 |
| 50 % | 230,98 | 7,7365 | 4,0529 |
| 60 % | 231,04 | 8,9005 | 4,75 |
| 70 % | 230,85 | 9,9496 | 5,4385 |
| 80 % | 230,17 | 10,8431 | 6,1139 |
| 90 % | 230,02 | 11,8271 | 6,8275 |
| 100 % | 230,03 | 12,786 | 7,5491 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 250,82 | 7,9771 | 1,308 |
| 20 % | 250,02 | 8,4142 | 1,915 |
| 30 % | 249,39 | 9,1446 | 2,651 |
| 40 % | 249,02 | 9,7773 | 3,191 |
| 50 % | 248,1 | 10,632 | 3,856 |
| 60 % | 247,48 | 11,5371 | 4,499 |
| 70 % | 247,24 | 12,5212 | 5,167 |
| 80 % | 247,1 | 13,544 | 5,835 |
| 90 % | 247,11 | 14,6011 | 6,502 |
| 100 % | 247,26 | 15,7524 | 7,204 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 1193 | 6,7 | 0,837035 |
| 20 % | 1188 | 11,3 | 1,4058 |
| 30 % | 1183 | 16,2 | 2,006912 |
| 40 % | 1178 | 21 | 2,590557 |
| 50 % | 1173 | 25,8 | 3,169176 |
| 60 % | 1168 | 30,55 | 3,736652 |
| 70 % | 1162 | 35,45 | 4,31371 |
| 80 % | 1157 | 40 | 4,84643 |
| 90 % | 1152 | 45 | 5,428672 |
| 100 % | 1147 | 50 | 6,005678 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,93 | 0,59 |
| 20 % | 0,94 | 0,69 |
| 30 % | 0,98 | 0,74 |
| 40 % | 0,94 | 0,76 |
| 50 % | 0,95 | 0,78 |
| 60 % | 0,95 | 0,79 |
| 70 % | 0,95 | 0,79 |
| 80 % | 0,95 | 0,79 |
| 90 % | 0,95 | 0,80 |
| 100 % | 0,95 | 0,80 |

Frequency 50 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231,2 | 3,7645 | 1,8076 |
| **20 %** | 231,35 | 5,247 | 2,638 |
| **30 %** | 231,17 | 6,771 | 3,499 |
| **40 %** | 231,1 | 8,087 | 4,268 |
| **50 %** | 230,95 | 9,432 | 5,104 |
| **60 %** | 230,98 | 10,611 | 5,986 |
| **70 %** | 230,84 | 11,836 | 6,787 |
| **80 %** | 230,52 | 12,933 | 7,685 |
| **90 %** | 230,57 | 14,052 | 8,493 |
| **100 %** | 320,51 | 15,339 | 9,359 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 264,68 | 7,9466 | 1,693 |
| **20 %** | 263,28 | 8,4543 | 2,48 |
| **30 %** | 261,18 | 9,021 | 3,274 |
| **40 %** | 260,25 | 9,8166 | 4,051 |
| **50 %** | 258,51 | 10,4871 | 4,843 |
| **60 %** | 258,51 | 11,614 | 5,658 |
| **70 %** | 258,08 | 12,511 | 6,478 |
| **80 %** | 257,64 | 13,5288 | 7,268 |
| **90 %** | 257,81 | 14,681 | 8,111 |
| **100 %** | 257,27 | 15,9215 | 8,97 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 1492 | 7,35 | 1,148378 |
| **20 %** | 1487 | 12,1 | 1,884191 |
| **30 %** | 1482 | 16,9 | 2,62279 |
| **40 %** | 1476 | 21,7 | 3,35409 |
| **50 %** | 1471 | 26,4 | 4,066729 |
| **60 %** | 1465 | 31,5 | 4,832555 |
| **70 %** | 1459 | 36,25 | 5,538497 |
| **80 %** | 1453 | 40,6 | 6,177607 |
| **90 %** | 1447 | 45,6 | 6,909745 |
| **100 %** | 1440 | 50,3 | 7,585061 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,94 | 0,64 |
| **20 %** | 0,94 | 0,71 |
| **30 %** | 0,94 | 0,75 |
| **40 %** | 0,95 | 0,79 |
| **50 %** | 0,95 | 0,80 |
| **60 %** | 0,95 | 0,81 |
| **70 %** | 0,95 | 0,82 |
| **80 %** | 0,95 | 0,80 |
| **90 %** | 0,96 | 0,81 |
| **100 %** | 0,96 | 0,81 |

# Measurement data: Micromaster 430, first test run

Frequency 20 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| 10 % | 231,51 | 2,329 | 0,636 |
| 20 % | 231,3 | 3,414 | 0,993 |
| 30 % | 231,34 | 4,627 | 1,39 |
| 40 % | 231,33 | 5,911 | 1,824 |
| 50 % | 231,48 | 7,345 | 2,33 |
| 60 % | 231,14 | 8,849 | 2,881 |
| 70 % | | | |
| 80 % | | | |
| 90 % | | | |
| 100 % | | | |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| 10 % | 220,05 | 4,4755 | 0,557 |
| 20 % | 219,44 | 5,9341 | 0,885 |
| 30 % | 218,62 | 7,8559 | 1,248 |
| 40 % | 218,25 | 10,0736 | 1,627 |
| 50 % | 217,19 | 12,7793 | 2,084 |
| 60 % | 216,23 | 15,8727 | 2,5772 |
| 70 % | | | |
| 80 % | | | |
| 90 % | | | |
| 100 % | | | |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| 10 % | 584 | 7,1 | 0,43421 |
| 20 % | 573 | 11,75 | 0,705052 |
| 30 % | 558 | 16,55 | 0,967076 |
| 40 % | 541 | 21,3 | 1,206717 |
| 50 % | 519 | 26 | 1,413088 |
| 60 % | 493 | 30,8 | 1,590107 |
| 70 % | | | |
| 80 % | | | |
| 90 % | | | |
| 100 % | | | |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| 10 % | 0,88 | 0,68 |
| 20 % | 0,89 | 0,71 |
| 30 % | 0,90 | 0,70 |
| 40 % | 0,89 | 0,66 |
| 50 % | 0,89 | 0,61 |
| 60 % | 0,89 | 0,55 |
| 70 % | | |
| 80 % | | |
| 90 % | | |
| 100 % | | |

Frequency 30 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231,49 | 3,348 | 0,968 |
| **20 %** | 231,34 | 4,887 | 1,476 |
| **30 %** | 231,13 | 6,429 | 2,002 |
| **40 %** | 231,12 | 7,931 | 2,534 |
| **50 %** | 230,91 | 9,498 | 3,106 |
| **60 %** | 231,31 | 10,961 | 3,689 |
| **70 %** | | | |
| **80 %** | | | |
| **90 %** | | | |
| **100 %** | | | |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 235,84 | 5,113 | 0,873 |
| **20 %** | 234,71 | 6,041 | 1,345 |
| **30 %** | 233,65 | 7,2339 | 1,831 |
| **40 %** | 232,49 | 8,5945 | 2,326 |
| **50 %** | 231,24 | 10,1628 | 2,852 |
| **60 %** | 230,48 | 11,8446 | 3,401 |
| **70 %** | | | |
| **80 %** | | | |
| **90 %** | | | |
| **100 %** | | | |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 889 | 7,2 | 0,67029 |
| **20 %** | 882 | 12 | 1,108354 |
| **30 %** | 874 | 16,8 | 1,537621 |
| **40 %** | 865 | 21,5 | 1,947526 |
| **50 %** | 856 | 26,4 | 2,366499 |
| **60 %** | 846 | 31,1 | 2,75524 |
| **70 %** | | | |
| **80 %** | | | |
| **90 %** | | | |
| **100 %** | | | |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,90 | 0,69 |
| **20 %** | 0,91 | 0,75 |
| **30 %** | 0,91 | 0,77 |
| **40 %** | 0,92 | 0,77 |
| **50 %** | 0,92 | 0,76 |
| **60 %** | 0,92 | 0,75 |
| **70 %** | | |
| **80 %** | | |
| **90 %** | | |
| **100 %** | | |

Frequency 40 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 230,87 | 4,519 | 1,356 |
| **20 %** | 231,27 | 6,452 | 2,002 |
| **30 %** | 231,2 | 8,31 | 2,675 |
| **40 %** | 230,72 | 10,182 | 3,373 |
| **50 %** | 230,88 | 11,848 | 4,053 |
| **60 %** | 230,86 | 13,166 | 4,754 |
| **70 %** | 230,94 | 14,325 | 5,498 |
| **80 %** | 230,83 | 15,526 | 6,184 |
| **90 %** | 230,85 | 16,718 | 6,957 |
| **100 %** | 230,7 | 18,064 | 7,696 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 253,57 | 6,3389 | 1,238 |
| **20 %** | 252,75 | 6,9349 | 1,845 |
| **30 %** | 261,38 | 7,7381 | 2,479 |
| **40 %** | 249,58 | 8,7168 | 3,13 |
| **50 %** | 247,87 | 9,7674 | 3,76 |
| **60 %** | 246,8 | 10,9783 | 4,438 |
| **70 %** | 246,66 | 12,2746 | 5,123 |
| **80 %** | 245,8 | 13,5365 | 5,765 |
| **90 %** | 245,4 | 14,9917 | 6,484 |
| **100 %** | 244,7 | 16,4333 | 7,169 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 1191 | 7,4 | 0,922937 |
| **20 %** | 1186 | 12 | 1,490372 |
| **30 %** | 1180 | 16,9 | 2,088321 |
| **40 %** | 1174 | 21,75 | 2,673967 |
| **50 %** | 1167 | 26,5 | 3,238511 |
| **60 %** | 1161 | 31,3 | 3,805443 |
| **70 %** | 1153 | 36 | 4,346708 |
| **80 %** | 1146 | 40,9 | 4,908362 |
| **90 %** | 1139 | 45,2 | 5,391266 |
| **100 %** | 1133 | 50,1 | 5,944239 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,91 | 0,68 |
| **20 %** | 0,92 | 0,74 |
| **30 %** | 0,93 | 0,78 |
| **40 %** | 0,93 | 0,79 |
| **50 %** | 0,93 | 0,80 |
| **60 %** | 0,93 | 0,80 |
| **70 %** | 0,93 | 0,79 |
| **80 %** | 0,93 | 0,79 |
| **90 %** | 0,93 | 0,77 |
| **100 %** | 0,93 | 0,77 |

Frequency 50 Hz

1. Power analyzer, power to system

| T [Nm] | U [V] | I [A] | *P(in) [kW] |
|---|---|---|---|
| **10 %** | 231,21 | 6,388 | 1,974 |
| **20 %** | 230,89 | 8,725 | 2,801 |
| **30 %** | 230,86 | 10,595 | 3,546 |
| **40 %** | 230,05 | 12,248 | 4,35 |
| **50 %** | 230,87 | 13,653 | 5,14 |
| **60 %** | 231,12 | 14,98 | 6 |
| **70 %** | 230,81 | 16,472 | 6,8 |
| **80 %** | 230,62 | 17,833 | 7,668 |
| **90 %** | 230,86 | 19,505 | 8,636 |
| **100 %** | 230,61 | 20,904 | 9,527 |

2. Power analyzer, power to motor

| T [Nm] | U [V] | I [A] | P [kW] |
|---|---|---|---|
| **10 %** | 269,68 | 8,7671 | 1,795 |
| **20 %** | 267,29 | 9,0571 | 2,581 |
| **30 %** | 265,77 | 9,2538 | 3,264 |
| **40 %** | 261,54 | 9,5626 | 4,045 |
| **50 %** | 260,94 | 10,4272 | 4,846 |
| **60 %** | 259,85 | 11,2677 | 5,59 |
| **70 %** | 258,49 | 12,4042 | 6,465 |
| **80 %** | 255,71 | 13,4985 | 7,206 |
| **90 %** | 255,65 | 14,981 | 8,178 |
| **100 %** | 254,83 | 16,419 | 9,031 |

Torque transducer

| T [Nm] | n [r/min] | T [Nm] | *P(out,mech) [kw] |
|---|---|---|---|
| **10 %** | 1492 | 8,15 | 1,273371 |
| **20 %** | 1487 | 12,8 | 1,993194 |
| **30 %** | 1482 | 17,5 | 2,715907 |
| **40 %** | 1476 | 22,4 | 3,462286 |
| **50 %** | 1470 | 27,2 | 4,187115 |
| **60 %** | 1464 | 32 | 4,905911 |
| **70 %** | 1456 | 36,8 | 5,610968 |
| **80 %** | 1450 | 41,5 | 6,301511 |
| **90 %** | 1442 | 46,5 | 7,021774 |
| **100 %** | 1433 | 50,8 | 7,623221 |

Efficiencies

| T [Nm] | $\eta_{VSD}$ | $\eta_{sys}$ |
|---|---|---|
| **10 %** | 0,91 | 0,65 |
| **20 %** | 0,92 | 0,71 |
| **30 %** | 0,92 | 0,77 |
| **40 %** | 0,93 | 0,80 |
| **50 %** | 0,94 | 0,81 |
| **60 %** | 0,93 | 0,82 |
| **70 %** | 0,95 | 0,83 |
| **80 %** | 0,94 | 0,82 |
| **90 %** | 0,95 | 0,81 |
| **100 %** | 0,95 | 0,80 |

# Measured efficiencies with energy optimization, second test run

| | | ABB | | Danfoss | | Vacon | | Siemens | |
|---|---|---|---|---|---|---|---|---|---|
| T [%] | n [Hz] | $\eta_{VSD}$ | $\eta_{sys.}$ | $\eta_{VSD}$ | $\eta_{sys.}$ | $\eta_{VSD}$ | $\eta_{sys.}$ | $\eta_{VSD}$ | $\eta_{sys.}$ |
| 10 | 10 | 0,82 | 0,55 | 0,83 | 0,39 | 0,78 | 0,52 | 0,80 | 0,41 |
| 20 | 20 | 0,91 | 0,70 | 0,91 | 0,62 | 0,88 | 0,70 | 0,88 | 0,63 |
| 30 | 30 | 0,94 | 0,77 | 0,94 | 0,73 | 0,91 | 0,77 | 0,91 | 0,72 |
| 50 | 40 | 0,94 | 0,79 | 0,95 | 0,79 | 0,93 | 0,80 | 0,93 | 0,79 |
| 70 | 45 | 0,95 | 0,81 | 0,96 | 0,82 | 0,94 | 0,81 | 0,94 | 0,81 |
| 100 | 50 | 0,95 | 0,81 | 0,96 | 0,81 | 0,95 | 0,82 | 0,95 | 0,81 |

Measured efficiencies at the same test points without energy optimization:

| | | ABB | | Danfoss | | Vacon | | Siemens | |
|---|---|---|---|---|---|---|---|---|---|
| T [%] | n [Hz] | $\eta_{VSD}$ | $\eta_{sys.}$ | $\eta_{VSD}$ | $\eta_{sys.}$ | $\eta_{VSD}$ | $\eta_{sys.}$ | $\eta_{VSD}$ | $\eta_{sys.}$ |
| 10 | 10 | 0,83 | 0,36 | 0,83 | 0,40 | 0,77 | 0,35 | 0,80 | 0,53 |
| 20 | 20 | 0,90 | 0,63 | 0,91 | 0,62 | 0,87 | 0,60 | 0,89 | 0,71 |
| 30 | 30 | 0,93 | 0,73 | 0,94 | 0,73 | 0,91 | 0,71 | 0,92 | 0,77 |
| 50 | 40 | 0,99 | 0,80 | 0,95 | 0,79 | 0,93 | 0,78 | 0,93 | 0,79 |
| 70 | 45 | 0,94 | 0,81 | 0,95 | 0,81 | 0,94 | 0,80 | 0,93 | 0,80 |
| 100 | 50 | 0,95 | 0,80 | 0,95 | 0,82 | 0,95 | 0,81 | 0,95 | 0,80 |