Increased efficiency and reliability through an electro-mechanical differential system providing variable speed to pumps and compressors

Maximilian Hehenberger[1,*]

[1]SET Sustainable Energy Technologies GmbH, Sterneckstraße 19, 9020 Klagenfurt, Austria

***Correspondence:** Email: maximilian.hehenberger@set-solutions.net, Tel: +43 508988 288

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Abstract

The objective of this paper is to assess an electro-mechanical differential system (EMDS) system providing variable speed to a driven machine (e.g. compressor, blower, pump, etc.) in terms of applicability and energy efficiency. At the beginning of 2015 the European Union released a new standard, the EN 50598 series, leading to increased demand for variable speed drives. Beyond other drive train technologies, the EMDS is one possible solution for meeting the standard's requirements. In this connection, efficiency and the resulting life cycle costs are essential to ensure compliance. The assessment of the EMDS reveals that this drive train technology is a compatible solution to meet future challenges.

Abbreviations

ASM	asynchronous machine
EMDS	electro-mechanical differential system
HDC	hydro-dynamic coupling
HDVSD	hydro-dynamic variable speed drive
IGBT	insulated-gate bipolar transistor
LV	low voltage
MV	medium voltage
VFD	variable frequency drive

1. Introduction

Today industry worldwide is subject to major changes as a result of global warming, fast changing commercial conditions, and air pollution. The policy is to ensure the continued availability of natural resources and to prevent a collapse of the environmental system.

In Germany, for example, industry uses 30% of all electricity in the country. Of that figure, 70% is consumed by electrically driven machines. The energy costs of these machines account for at least 80% of the total life cycle costs [1]. In Strategy Europe 2030, the European Union (EU) has defined the goals for energy management until 2030. The agreement specifies a reduction in CO_2 emissions of 40% and an increase in both renewable energy and energy efficiency of 27% [2].

In 2011 the EU issued regulations stating minimum efficiency requirements for electric motors. At the beginning of 2015 a directive came into force requiring speed regulation in IE 3 motors between 7.5 and 375 kW, as reflected in the EN 50598 series standard [3], [1]. Thus, there is increasing pressure on industry to increase the efficiency of the whole drive train.

There is also a high demand for both cost effective and efficient drive train systems and the policy to develop extensive, forward-looking legislation.

2. State of Drive Train Concepts

There are a couple of ways to provide speed from an electric machine to a driven machine, as shown in Figure 1. The first and the easiest one is the direct drive, as shown in Figure 1 a). The driven machine is connected directly to the main drive (motor), which is directly connected to the grid – a variation of speed is not possible. To adjust the exact flow rate valves, dampers or bypasses are used. Nowadays, the majority of new installed drive trains are direct driven systems, due to initial cost driven motivations mostly. Although the apparent costs are low, the energy costs are very high due to the main drive’s continuously high energy consumption. In addition, the big disadvantage of this type of regulation is that the driven machine is not driven in an optimum point of efficiency at partial load, see Figure 2.

In power plants, including smaller fossil plants e.g. turbines utilizing by-products from refinery processes are often used to drive machines. The flow is adjusted by fuel or steam controls or adjustable turbine blades changing the speed of the turbine, shown in Figure 1 c). However, as efficiency increases with the size of the turbines, the investment may not be economically viable for medium power applications.

A much more effective way in terms of energy efficiency is to adjust the pump´s required speed according to the necessary flow. Firstly, this has a positive influence on the pump´s efficiency rate and secondly the electrical consumer´s demand will be adapted to the actual need.

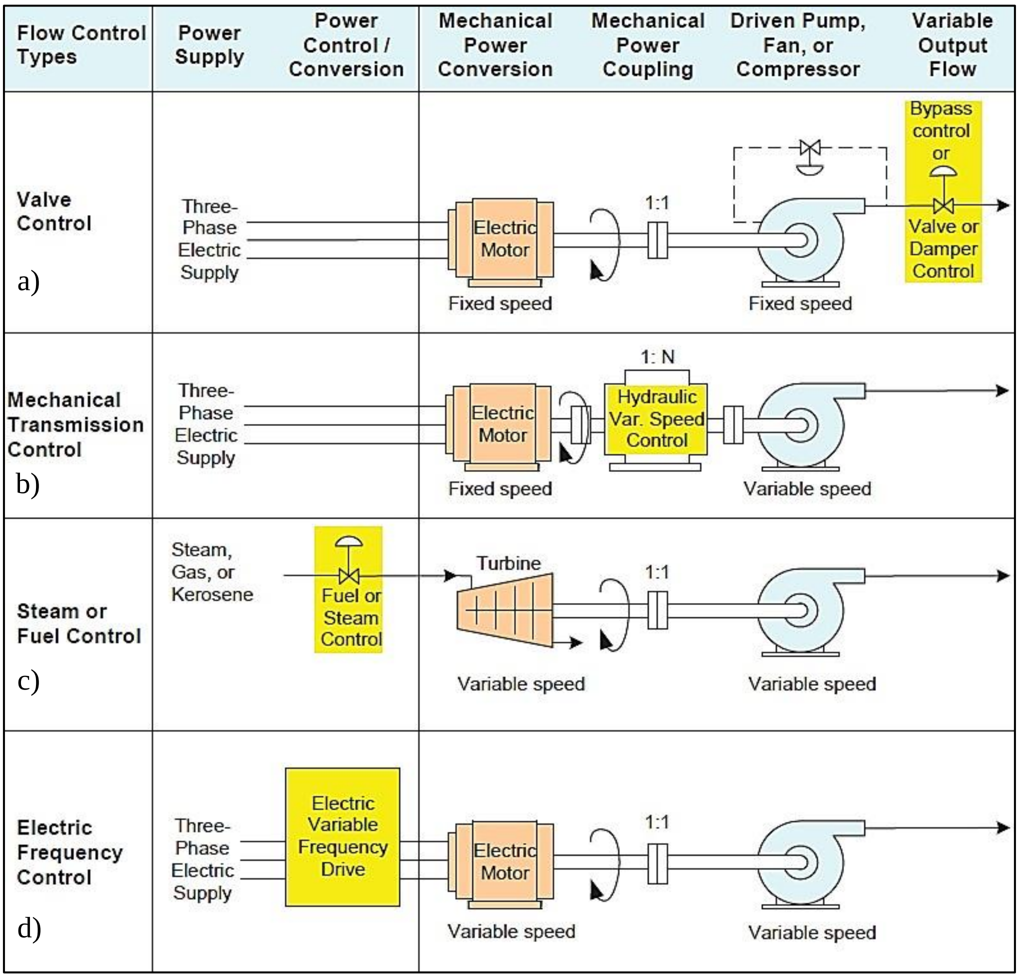


Figure 1: Schematic representation of common drive train systems [9]

Currently the most common systems providing variable speed to pumps and compressors are the variable frequency drive (VFD) and hydraulic variable speed control systems e.g. the HDC (hydro-dynamic coupling – e.g. RK, KGS by Voith) or the HDVSD (hydro-dynamic variable speed drive – e.g. Vorecon by Voith), shown in Figure 1 d) and b). For further information, please refer to the appropriate technical literature [4], [5].

These applications which provide variable speed achieve a much better performance in terms of energy efficiency, resulting in lower energy costs. However, while the VFD system appears to be cost effective for low power applications, the costs increase significantly for medium voltage VFD at a multi MW level. Furthermore, air conditioned rooms have to be provided to sustain the operation and furthermore, maintenance rates are empirically high, due to the sensitivity of

IGBT modules.

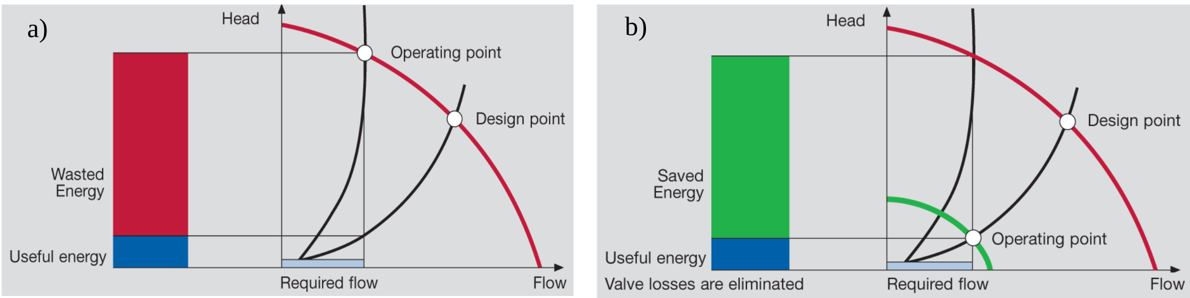


Figure 2: a) Energy consumption with valve controle b) Energy consumption by speed regulation [12]

With no power electronics along the main power path the hydraulic variable speed control systems have a statistically higher endurance. But the disadvantages of these systems are the larger footprint (including a complex lubrication system) and the low efficiency in case of speed deviation from rated speed.

An alternative approach is the EMDS (electro-mechanical differential system), a new drive train concept, to meet future industrial challenges. The next section briefly explains the system architecture and functionality.

3. Electro-Mechanical Differential System: Architecture and Functionality

Figure 3 shows the set-up configuration of the EMDS. It consists of a differential gear (see Detail Figure 3 below) including the spur gear unit (1), a three-phase motor with a low-voltage converter as the Servo drive (2+3), an electric motor as the medium-voltage main drive (4), a driven machine (5) e.g. a pump, and a variable-speed output shaft (6). The medium-voltage main drive (4) is connected directly to the medium voltage grid and drives the differential's ring gear at constant speed. Connected to the output shaft (6), the differential´s planet carrier transmits the variable speed through the optional spur gear unit to the pump. The differential's sun gear is connected to the Servo drive (2). The speed of the differential drive is controlled firstly in order to ensure the speed of the output shaft (6) is variable when the speed of the main drive (4) is constant, and secondly to control the torque in the driven machine's entire drive train.

The EMDS can be manufactured as a separate assembly and therefore installed and maintained independently of the main drive as a standalone unit and therefore well suitable for replacements of outdated technology. And if, in the case of a retrofit of existing systems, it is possible with such variable speed drive to provide this within a defined framework while keeping the existing main drive and the existing driven machine. However, it is also possible to do add supplemental power and speed to the existing drive train by an additional power and speed supply of the Servo drive.

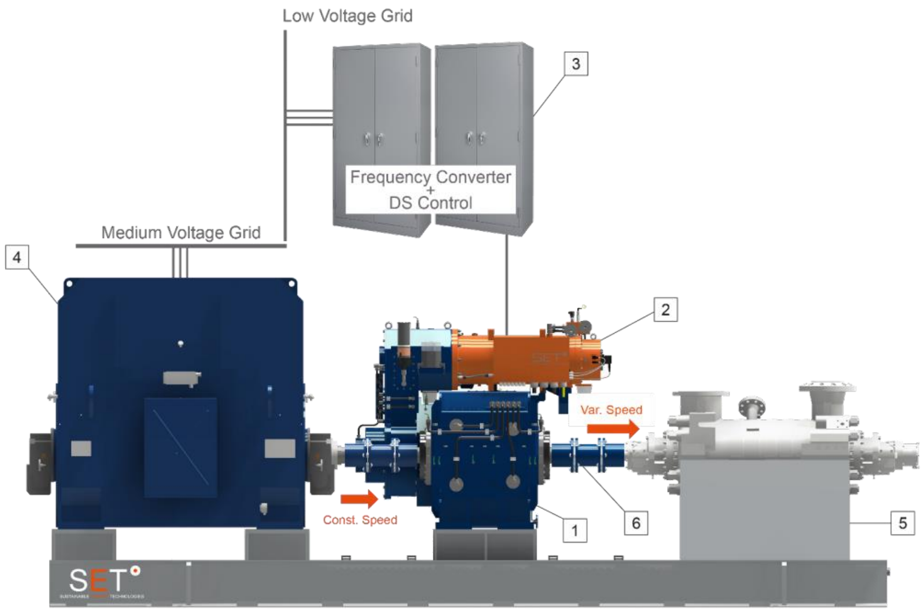
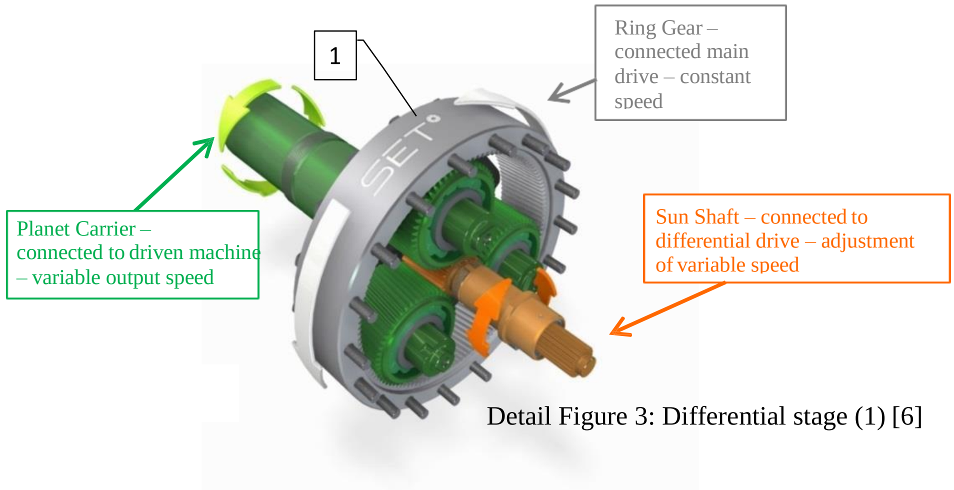


Figure 3: EMDS system architecture [6]

The system is self-contained and performs all control and feedback tasks automatically. The interface for controlling the system from outside can be maintained through a large variety of existing types of interfaces. In general, the system components do comply with standard components, widely used in the industry, which increases its reliability significantly.



Detail Figure 3: Differential stage (1) [6]

4. Technical Background

The relation between the speeds in the differential stage of the EMDS is shown in the following equation:

$$\mathbf{speed_{motor} = x * speed_{driven\ machine\ shaft} + y * speed_{Servo\ drive}}$$

where the motor speed is constant, and factors x and y can be derived from the transmission ratios of the pre-stage gear and the differential stage. The torque at the driven machine's shaft is determined by the delivery head and flow rate required. The ratio between the torque at the driven machine shaft and that at the Servo drive is constant, enabling the torque in the drive train to be controlled by the Servo drive. The torque equation for the Servo drive:

$\text{torque}_{\text{Servo drive}} = \text{torque}_{\text{driven machine shaft}} * y / x$

where the factor y/x is a measure of the necessary design torque for the Servo drive.
The Servo drive's power rating is essentially proportional to the product of the percentage the driven machine speed deviates from its "basic speed" time's shaft power. As a result, a wide speed range basically requires the Servo drive to be dimensioned accordingly.

Figure 4 shows an example of the power ratios of a differential stage for a driven machine. To work highly efficiently the Servo drive utilizes both speed directions and operates as a generator and a motor depending on the set speed for the driven machine. This means that power is supplied to the Servo drive in the motor range and withdrawn from the Servo drive in the generator range to be restored in the grid. The sum of motor power and Servo drive power is equal to the total power delivered to the driven machine's shaft, leading to a reduction of the main drive´s necessary power.

By using an (integrated) pre-stage gear, any speed required can be achieved for the driven machine and thus the use of multi-pole drive motors can be avoided for stepping down speed.

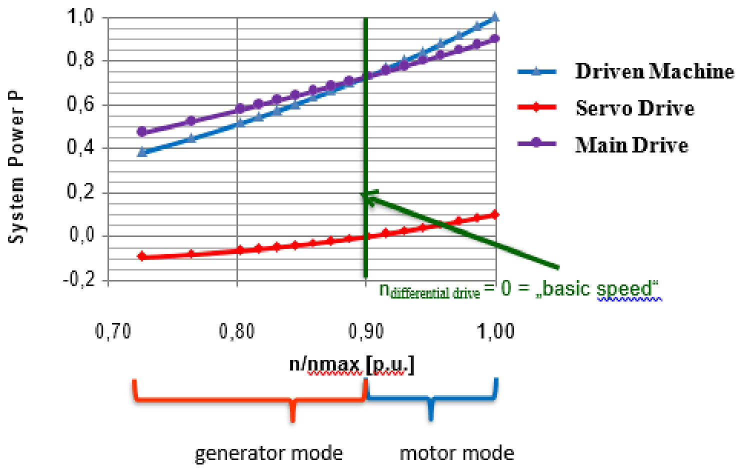


Figure 4: Speed and power ratios for a differential stage [7]

5. Efficiency Comparison

Based on the fact that the losses from the differential stage are insignificantly low for the EMDS, the efficiency limitations of the ASM (main drive), Servo drive and low-voltage frequency converter are decisive. Past investigations and analysis have shown that approximately only 8

kW are lost through friction for a 2 MW differential stage [8]. Higher power losses are expected for the frequency converter and its auxiliaries. But these influences are low, due to the fact that the power required for controlling the system is linked to the driven speed range. Only a maximal of approximately 20% of the power flows through the Servo path for a 100% driven machine’s speed variability, leading to minimum losses of the whole system for the EMDS.
In comparison the VFD system shows much lower overall efficiency, due to the losses from the frequency converter and auxiliary devices like harmonic filters, air-conditioning equipment, step-up gearbox, transformer station etc. designed for rated driven machine´s power.
At rated power the HDC (hydro dynamic gear coupling e.g. RK by Voith) shows comparable performance with the EMDS system, but when operating speed deviates from the design point, the efficiency rates, due to hydraulic system losses, increase significantly. The same applies for the hydro dynamic variable speed drive (HDVSD – Vorecon by Voith), although a higher overall performance is achieved.

Figure 5 shows the calculated efficiency rates of the most common drive train concepts for a speed range from 50% to 100% n/n_{max}.

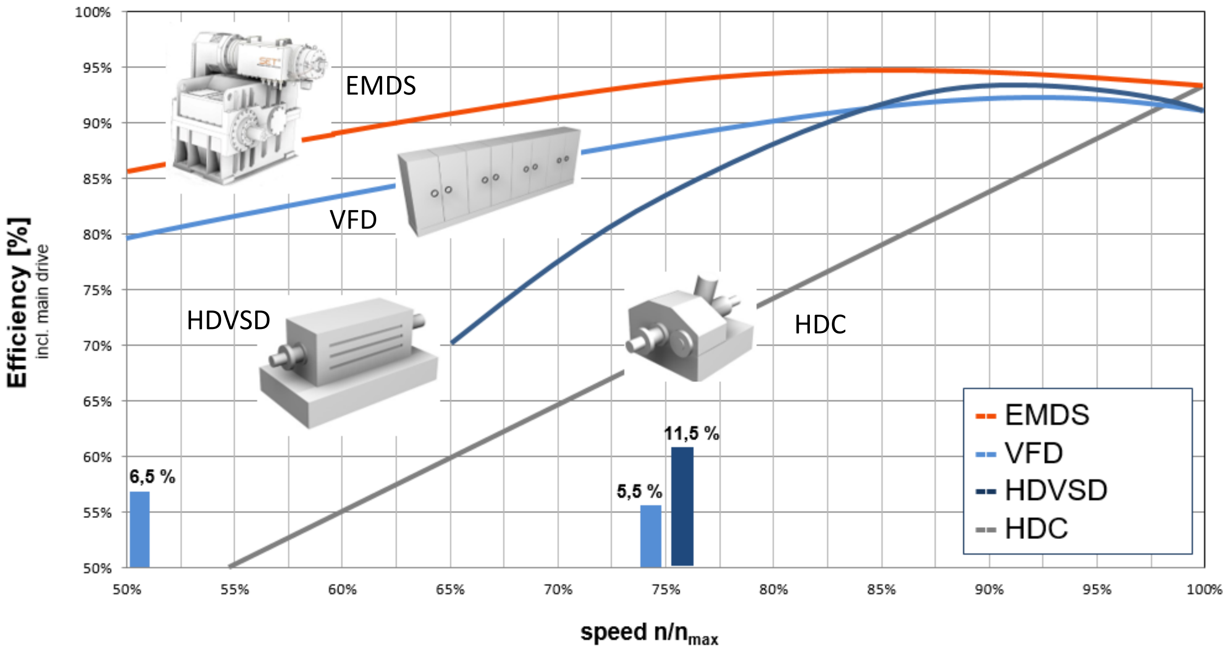


Figure 5: Calculated efficiency rates of various variable speed drive train concepts [5], [8], [9], [14], [15]

To underline the calculated outcomes Sulzer Pumpen (Deutschland) GmbH did investigations on the EMDS on their in-house test facilities. The pure output tests of Sulzer Pumpen (Deutschland) GmbH in Bruchsal, Germany pointed out that the EMDS shows excellent efficiency results in operation:” *The measured results confirm the project specifications without exception. If the differential gearbox, including its auxiliary systems and converter, is considered alone, the high efficiency specifications have been confirmed. Even in the partial* *load ranges, the gearbox with servo motor and low voltage frequency converter achieves an overall efficiency of >95 %. If the whole drive train is also taken into account, i.e. including the main motor, the measured efficiency of the system ranges between 92.7 % and 94.1 %.* "[10]

6. Energy Costs

For more and more operators in different industry sectors the energy consumption of their machines becoming increasingly important. Fact is, that the energy costs have a major influence on the LCCs (life cycle costs), especially if driven machines e.g. pumps run more than 2.000 hours a year [12]. *"In two thirds of pumps and pump systems currently installed, it is possible to save up to 60% energy by switching to pumps with high-efficiency motors and variable speed drives"* [13]. By comparing this statement with Figure 6, it becomes obvious that the initial costs have a minor impact on a pump´s life time. A typical ROI (return on investment) for variable speed drives compared to a direct drive system, depending very much on the required system power, efficiency rates and partial load points, is between one and three years. And the need of variable speed systems is growing.
One example is the increasing amount of installed alternative energy sources as e.g. wind turbines or solar plants, forces power plant operators to become more flexible in their energy productions to balance inconsistent *green* energy supply [16].

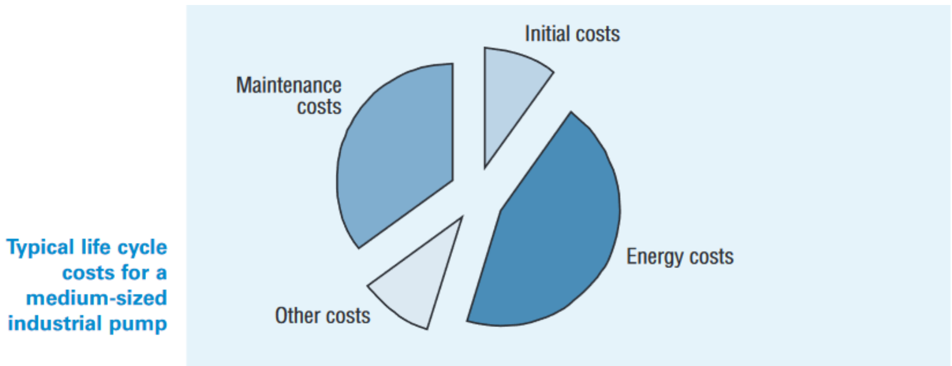


Figure 6: Influence of energy costs on LCC for a medium-sized industrial pump [12]

Table 1 illustrates the estimated savings by using a EMDS in comparison of alternative variable speed drive trains for a boiler feed pump, a typical industrial application. It clearly explains that each of the drives show high efficiency rates at its design point (100% n/n_{max}). By a deviation of the rated operating point a big difference of efficiency rates between the EMDS and VFD or hydrodynamic solutions is observed. The highest amount in yearly energy costs is determined between the EMDS and the HDC, results in a current value of 382.549 € per year.

Table 1: Energy consumption example of common variable speed drives [5], [8], [9], [14], [15], [17]

Operating Points (n/n_{max})	**Design 100%**	**Partial Load 75%**
Operating time	4300 hours/a	4300 hours/a
Boiler feed pump power consumption	9.200 kW	3.810 kW
Boiler feed pump operating speed	6.200 rpm	4.630 rpm
Drive with VFD		
Motor efficiency	97,3%	96,1%
VFD efficiency	98,0%	96,7%
Isolation transformer efficiency	99,0%	98,9%
Harmonic filter efficiency	99,0%	98,8%
Gearbox efficiency	98,5%	98,0%
Air condition equipment efficiency (MV-FC)	99,6%	99,4%
Overall efficiency	91,7%	88,5%
Energy consumption	43.140.676 kWh/a	18.511.864 kWh/a
Drive with HDVSD		
Motor efficiency	97,5%	96,2%
HDVSD efficiency	95,0%	87,6%
Overall efficiency	92,6%	84,3%
Energy consumption	42.721.382 kWh/a	19.434.163 kWh/a
Drive with HDC		
Motor efficiency	97,5%	96,2%
HDC efficiency	97,0%	87,6%
Overall efficiency	94,3%	71,0%
Energy consumption	41.951.219 kWh/a	23.074.648 kWh/a
Drive with EMDS		
Motor efficiency	97,5%	96,2%
EMDS efficiency incl. LW-FC and Servo Drive	97,0%	96,5%
Overall efficiency	94,4%	92,8%
Energy consumption	41.906.780 kWh/a	17.654.094 kWh/a
Comparison		
Energy Costs	0.07 €/kWh	0.07 €/kWh
Energy Savings		
EMDS - VFD	1.189.457 kWh/a	857.770 kWh/a
EMDS - HDVSD	770.163 kWh/a	1.780.069 kWh/a
EMDS - HDC	44.439 kWh/a	5.420.554 kWh/a
Savings per year		
EMDS - VFD	**143.304 €/a**	
EMDS - HDVSD	**178.516 €/a**	
EMDS - HDC	**382.549 €/a**	

*estimated efficiency rates – all data without guarantee

7. Conclusion

The industry demands powerful systems in the future, and at the same time these systems should become more efficient. Common systems like the VFD or hydraulic variable speed control systems meet the requirements unsatisfactory with respect to energy costs. The EMDS is a drive train concept which shows high potential for variable speed drives in industrial applications. The directly grid connected main drive and the small electronic parts for speed and torque control enable both investment costs and losses to be reduced to a minimum. This results in a highly efficient variable speed drive system. The minimum effort for power electronics for controlling the drive, the small design of the Servo drive and a simple gearbox design guarantee the highest possible reliability. Long-term operation will prove, if this approach does satisfy the industry's high standards and needs.

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