LCC research program findings for realising energy efficient fan, compressor and conveyor systems with a frequency converter

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Abstract
Frequency converters enable the energy efficient operation of pumping, fan, compressor and conveyor systems by varying the motor speed to desired value. Besides speed variation, a modern frequency converter can estimate the state and performance of the system operation without additional measurement sensors. This ability provides several possibilities to optimise system operation and the resulting life-cycle costs (LCC) that mainly consist of energy and maintenance costs.

LCC research program studies the advanced use of a frequency converter in the monitoring and control of fan, compressor and conveyor systems. The research is based on literature reviews, case studies and laboratory tests with an object to develop LCC optimising methods for these systems. Similar research project has been previously carried out for pumping systems with positive results, showing the converter's potential to improve both the system energy efficiency and reliability with proper selection of the rotational speed reference. As an example, a modern frequency converter can first identify the minimum allowable rotational speed for the pumping system and then select a feasible rotational speed reference with minimised system specific energy consumption.

This paper presents some findings and developed methods for realising energy efficient and reliable fan, compressor and conveyor systems. The methods are based on possibility to estimate system operating state without additional sensors on the device.

Introduction
Pumps, fans and compressors are the most common end-use devices driven by an electric motor, making them a notable contributor to the global energy consumption [1]. Generally the life-cycle costs of a single system are dominated by its energy consumption, followed by the maintenance and possibly occurring production loss costs. The magnitude of energy costs is practically bound in the design and selection phase of the equipment and surrounding system, meaning that a small change in the investment costs can result in notably larger change in the energy costs over the system lifetime [2].

Utilisation of variable-speed operation is one of the key factors to energy efficiently operating systems, as it allows regulation of device output without adding hydraulic losses into the surrounding process. Typically the variable-speed operation is realised by using a frequency converter for operating the electric motor at desired rotational speed: the common setup is to have a voltage source inverter and an induction motor that is coupled to the driven device [1], [4].

Modern frequency converters are versatile products, providing several application-specific monitoring and control functions for the motor-driven device [5], [6]. As an example, internal PID controllers and control functions for multi-pump systems are standard features in pump-focused frequency converters. Another increasing trend in frequency converters is to have an integrated programmable logic controller (PLC) that allows modification of the converter, and hence the system operation according to specific needs [7]. As these features are nowadays combined with a visually appealing user panel interface, converters start to resemble modern PLC systems. This provides several new possibilities for realising frequency converters that can truly optimise life-cycle costs of pumping,

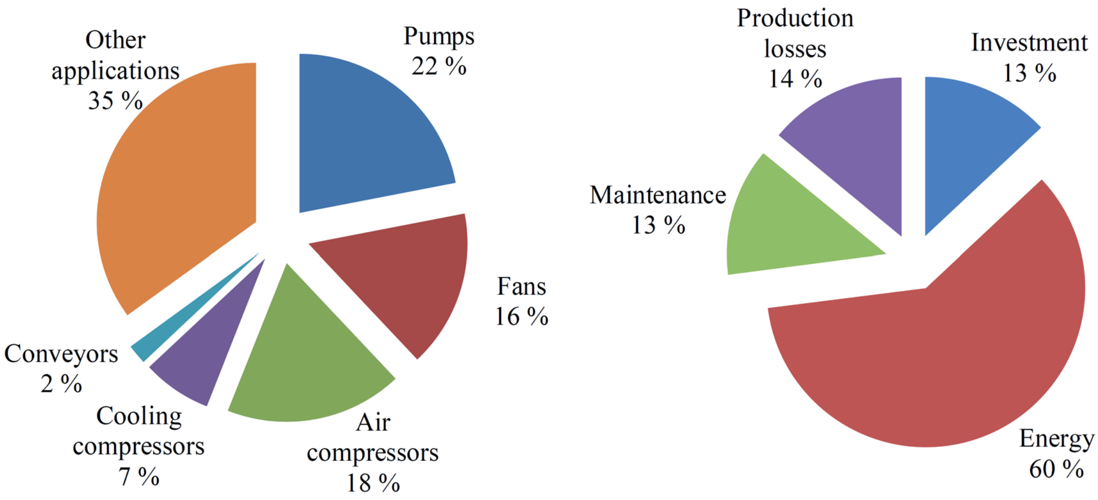

Figure 1. Estimated distribution of the motor electricity consumption according to the end-use in the EU industry and calculated life-cycle costs for a pulp pumping system [1], [3]. LCC distribution for the time period of ten years is dominated by energy costs, and is also affected by possible production losses.

fan, compressor and conveyor systems instead of just allowing the system operation at a desired rotational speed. For instance, ITT and Grundfos have launched products with tailor-made condition monitoring functions for pumps in 2000s [8], [9].

ABB Drives has started the LCC research program with Lappeenranta University of Technology (LUT) in 2006 concerning the advanced use of a frequency converter in the monitoring and control of pumping and fan systems. Right from the start, the main object in the research program has been the optimisation of life-cycle costs that can occur over the system lifetime. This viewpoint was selected since it is difficult to radically improve the motor and frequency converter energy efficiency within systems, where the major part of life-cycle costs is caused by the end-use device and its operation at different rotational speeds [10], [11]. Another main idea in the research program is to determine the capabilities of a modern frequency converter in the sensorless monitoring and control of pumping, fan and compressor systems.

The conducted research work is based on literature reviews, case studies and laboratory tests with an object to develop LCC optimising methods for these systems, which can improve the feasibility of a frequency converter in new and existing setups. Figure 2 illustrates how LUT researchers see the functions of a frequency converter in life-cycle cost efficient pumping systems: the converter needs to minimize both the system energy and the system maintenance costs with the developed methods. This is possible when the converter can accurately determine the present operational state of the system. This information can be further applied to identify the surrounding system characteristics, which have a direct effect on the energy-efficiency-based speed control schemes and also on the best attainable system performance. When both the present operational state and surrounding system characteristics are known, it is possible to drive the pump as energy efficiently as possible, and the effect of surrounding system on the pump specific energy consumption E_s (kWh/m^3) can be considered in the performance monitoring.

For pumping systems, the LCC research program has provided several positive results in the form of over ten published patent applications, published journal papers and doctoral theses [12]. As a practical example, a modern frequency converter can now identify surrounding system characteristics without additional sensors during the system start-up, and then determine the optimum rotational speed for the pumping system based on the present system E_s [13], [14].

At the moment, ABB and LUT are continuing the LCC research program with the main focus on fan and compressor systems. The object of this paper is to introduce present research findings and developed methods for realising energy efficient and reliable fan, compressor and conveyor systems. The methods are based on possibility to estimate system operating state without additional sensors on the device, which is one of the additional benefits of having a frequency converter in the setup.

Solutions for realising LCC efficient fan systems

Fan systems are responsible for approximately 10 % of the electricity consumption in industrial and municipal sectors, and it has been found that there is energy-saving potential in these systems. To this end, frequency converters are used to enhance the energy efficiency of fan systems. Usually, fan system operation is optimized based on measurements of the system, but there are seldom readily installed meters in the system that can be used for this purpose. Thus, sensorless methods are needed for the optimization of fan system operation. In addition, fan systems can be located so that their failure can lead to production losses. In such cases, loss in production can be the second largest contributor to life-cycle costs.

In the fan-related doctoral thesis by Jussi Tamminen [15], methods for the fan operational state estimation with a frequency converter are studied and discussed. A basic and well-known sensorless estimation method utilised in frequency converters is illustrated in Figure 3. It is based on the use of available fan characteristic curves for the flow rate Q vs. shaft power P and for the flow rate vs. fan pressure p_F together with the converter estimates for the fan rotational speed (n_{est}) and shaft power (P_{est})

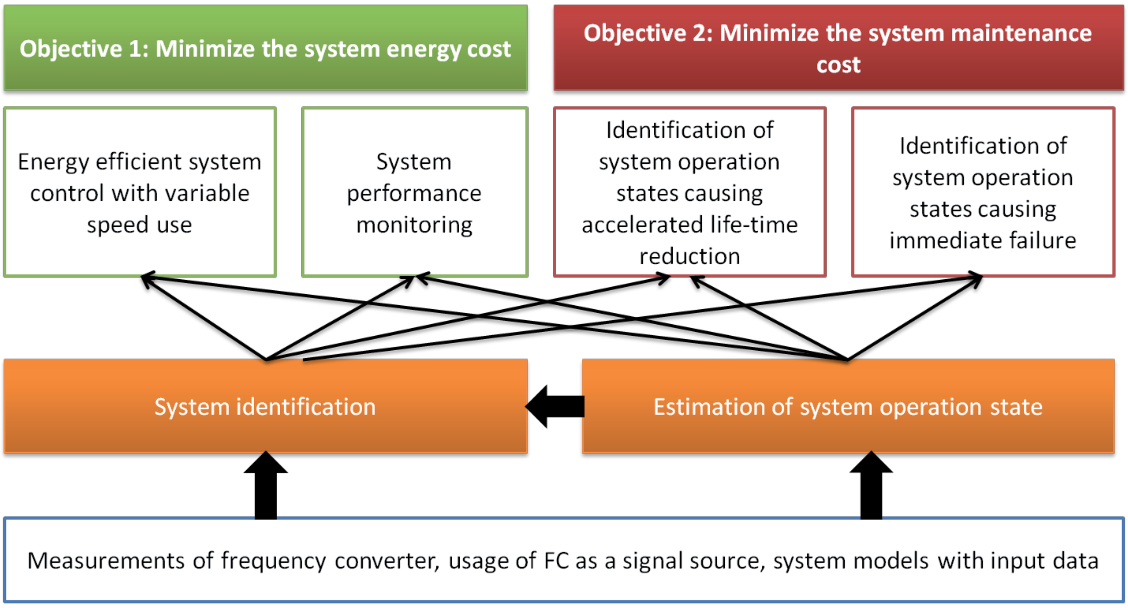

Figure 2. Functions that are needed in the frequency converter for realizing a LCC efficient pumping system.

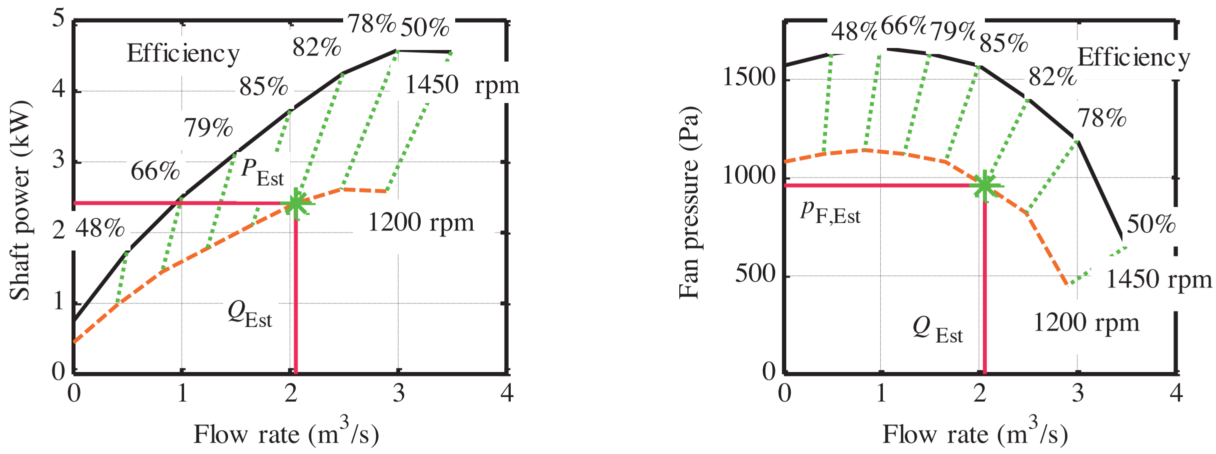

Figure 3. Example of the sensorless flow rate estimation used in fan systems.

[16]. Usually the fan characteristic curves are known for a single rotational speed, which is why they are first transformed to the present fan rotational speed with the help of affinity laws:

$$\frac{Q}{Q_{\text{nom}}} = \frac{n_{\text{est}}}{n_{\text{nom}}} \tag{1}$$

$$\frac{p_{\text{F}}}{p_{\text{F,nom}}} = \left(\frac{n_{\text{est}}}{n_{\text{nom}}}\right)^2 \tag{2}$$

$$\frac{P}{P_{\text{nom}}} = \left(\frac{n_{\text{est}}}{n_{\text{nom}}}\right)^3 \tag{3}$$

where subscript nom denotes the value at the nominal speed of the fan.

Then, the flow rate estimate Q_{Est} corresponding to the estimated shaft power P_{est} is found on the present curve for the flow rate vs. shaft power. After this, the fan pressure estimate $p_{\text{F,Est}}$ can be found on the present curve for the flow rate vs. fan pressure with the flow rate estimate.

According to results originally given in [17], this estimation method is often affected by inaccurate or unavailable characteristic curve information. This issue can be improved when a temporary reference measurement is introduced to the system, or the fan system is operated at zero flow rate [18]. This fixes one operating point of the fan curve and significantly improves the fan characteristic curves. However, the realization of these reference measurements is not a novel or easily realizable operation. To this end, Tamminen has developed two novel estimation methods that combine the benefits of existing estimation methods and improve the flow rate estimation accuracy.

If the fan is operated within a wide rotational speed range, the inaccuracy in the fan affinity laws can reduce the flow rate estimation accuracy when the fan is operated away from its nominal rotational speed. To combat this problem, a system curve estimate can be formed when the fan is operated near (within 10 %) the nominal rotational speed with the basic sensorless estimation method. The estimated system curve is then used in combination with the fan characteristic curve to produce flow rate estimates when the fan is operated away from the nominal rotational speed. This significantly improves the operational accuracy of sensorless estimation methods when operating over a wide speed range.

In addition, there are fan systems where both the pressure-measurement-based and sensorless flow rate estimation methods can be used. In these cases, the estimates can be combined to give a more accurate estimate of the actual flow rate. This can be accomplished by comparing the uncertainty of the estimation-based and pressure-measurement-based flow rate estimate with each other. This increases the accuracy and improves the reliability of the flow rate estimates.

DETECTION OF LIFE-TIME REDUCING PHENOMENA IN FAN SYSTEMS BY A FREQUENCY CONVERTER

In addition to their energy consumption, condition monitoring of fan systems is a key issue as fans are an integral part of various production processes. Fan system condition monitoring is usually carried out with vibration measurements, which again increase the system complexity. Also here a frequency converter can provide a cost-effective alternative with the sensorless detection methods studied within the LCC research program. In the following, the use of a frequency converter in the detection of surge, contamination build-up and the wrong rotational direction of a fan are shortly introduced.

Detection of surge in fans

Surge is an unwanted aerodynamic phenomenon in fan systems. The phenomenon is present especially in axial fans, and it is a result of insufficient flow through the fan. During the surging conditions in fans, the flow detaches from the impeller blades causing a notable reduction in the fan pressure output and efficiency. The flow can reattach to the impeller blades and detach again causing increased vibration and mechanical stress. It has been said that the fan seems to breathe when it is surging, which also indicates changing loading conditions. These loading conditions can be used as an indicator of the surge as presented in [19]. Modern frequency converters can be used in the detection of the fluctuation in the loading conditions as it is directly reflected on the torque and rotational speed estimates and are visible at low frequencies 0–4 Hz. The same approach is also utilised by SKF in their condition monitoring products that need to be separately installed into the motor control cabinet [20].

The baseline for the fluctuation in the loading conditions is estimated when the fan is known not to surge. This can be known for example from the operating point of the fan as presented in previous chapter. When the fan approaches the conditions where it may surge, the fluctuation in the loading is monitored. The fan is said to surge when the fluctuation exceeds a certain limit value compared with the acquired baseline fluctuation.

Detection of contamination build-up on fan impeller

The accumulation of dirt on a fan impeller can be considered as a root cause for imbalance of the fan. First the dirt accumulates on the impeller, afterwards some of the dirt detaches causing imbalance. Thus, if the accumulation of dirt on the impeller can be detected, the imbalance can be avoided with correctly timed maintenance. The dirt causes an increase in the mass and rotational inertia of the impeller, which can be detected with a frequency converter.

The mass increase can be detected from the acceleration of the fan impeller as presented in [21]. Also here the novelty lies in the advanced use of a frequency converter instead of having external measurement sensors on the fan [22]: the fan can be started with a constant torque reference and the change in the fan rotational speed can be observed. The fan rotational speed will increase linearly until the aerodynamic power becomes dominant. The impeller mass can be estimated from the linear acceleration and when the mass estimate is monitored over several start-ups, the accumulation of dirt can be detected. An example of the star-up of a fan with a constant torque is presented in Figure 4. The detection method was tested with a laboratory measurement setup and it was found that a 0.4 % change in the mass of the fan impeller can be detected with the developed method.

Detection of the correct rotational direction

Direction of flow in a centrifugal fan is independent of the rotational direction of the fan impeller. However, the result of an incorrect rotational direction is a dramatically reduced flow rate, pressure and efficiency of the fan, while the input power consumption remains approximately the same compared with the correct rotational speed. Thus, it is paramount to detect the correct rotational direction. The reduced flow and pressure are easy to detect with additional instrumentation. However, most fan systems do not have readily available instrumentation. Thus, sensorless methods are required for the detection.

The fluctuating loading conditions of the reverse rotational direction can be used as an indicator of the incorrect rotational direction as well as the indicator of adverse fan system operation in general. In Figure 5, the difference in the frequency converter estimates of the rotational speed and torque for the forward and reverse rotational directions are presented. There is a clear difference in the low frequency fluctuation and the supply frequency component when the fan is rotated in different directions. When the fan is rotated in both directions and these frequency components are observed, the correct rotational direction can be deduced.

As these results verify, the key finding of Tamminen's doctoral thesis is that a frequency converter can be used on its own as a monitoring and control device for the fan system energy efficiency, and it can also be used in the detection of certain lifetime-reducing phenomena.

Research findings concerning variable-speed-driven compressor systems

Compressor systems are the second largest end-use application for electric motors in industry. As their operation principle is analogous to fans, also their life-cycle costs have a similar distribution with pumping and fan systems. Figure 6 illustrates the determined life-cycle costs for two industrial compressor systems by Mika Lehtisare. In both cases, energy and maintenance costs clearly dominate the LCC distribution.

Because compressors produce air flow, similar to fans, the above-mentioned system estimation methods should be applicable especially to centrifugal compressors, but principally as well to screw compressor systems. As an exception to pumps and fans, the compression of air affects the applicability of the model-based methods. For instance, with pumps and fans it is common to use affinity laws to estimate the present operating point; however, with compressors, they are not applicable as such. This is because the affinity laws are based on dimensionless variables, which do not take into account the change in the fluid density.

Lauri Niinimäki has studied frequency-converter-based estimation of the compressor system operational state in [24]. According to his research findings illustrated in Figure 7, centrifugal compressor operational state can be determined with the accuracy of 9.5 % for the mass flow rate Q_m and 4.3 % for the pressure ratio ϕ, when a sensorless, Q_m vs. P curve-based estimation method is applied. Estimation accuracy for the mass flow rate can be improved with the use of pressure measurements and Q_m vs. ϕ curve-based estimation method, resulting in the accuracy of 2.1 %.

During laboratory tests, it was noted that the accuracies of the Q_mP and $Q_m\phi$ curve-based estimation methods are highly dependent on the rotational speed and power estimates of the frequency converter as already noted with fan systems. Especially with power, a small error in the power estimate has a great influence on the mass flow estimate, if the Q_mP characteristic curve is flat-shaped. This was also seen on the studied $Q_m\phi$ characteristic curve at low mass flows. For these methods to be feasible, the motor estimates of the frequency converter should be very accurate and characteristic curves steep enough. This is especially true with the Q_mP-curve-based estimation method, since it needs estimates both for the power and rotational speed, whereas the $Q_m\phi$ method only needs estimates for the rotational speed, which is also much easier to determine with the accuracy of 0.1 %.

If the compressor curves are not known for the present rotational speed, they can be estimated with the affinity laws, although they are not as accurate as with pumps and fans because of the compression of air. The accuracy of the affinity laws was

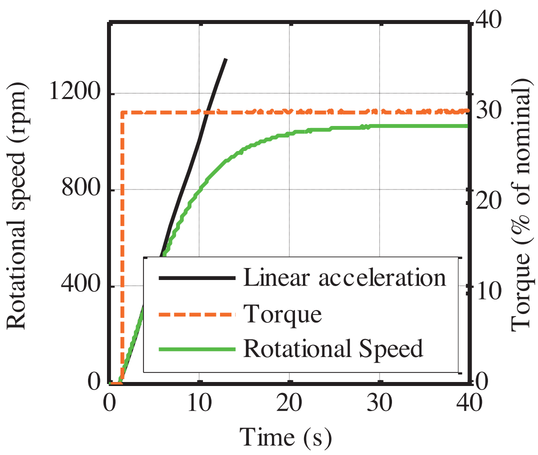

Figure 4. Example of the acceleration of a fan with constant torque and the linear part from which the impeller inertia can be estimated.

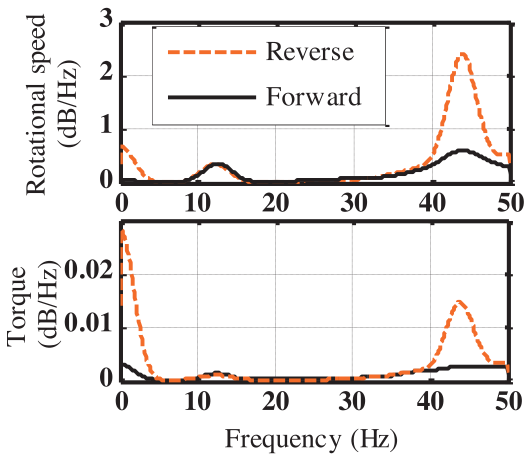

Figure 5. Spectra of the frequency converter rotational speed and torque estimates when the fan is rotated in the forward and reverse directions.

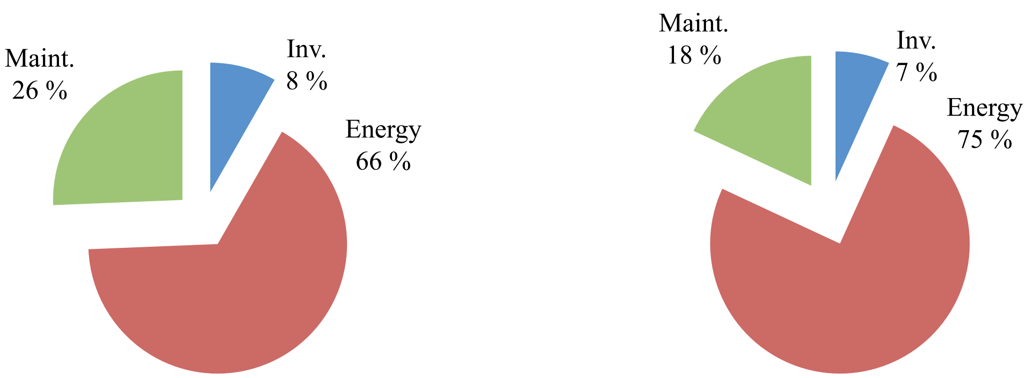

Figure 6. LCC distributions of two industrial compressor system located in Finnish paper mill [23]. LCC distributions were determined for the time period of ten years. Both distributions are dominated by energy costs and followed by maintenance costs. Failure of these two systems does not lead to cease in production.

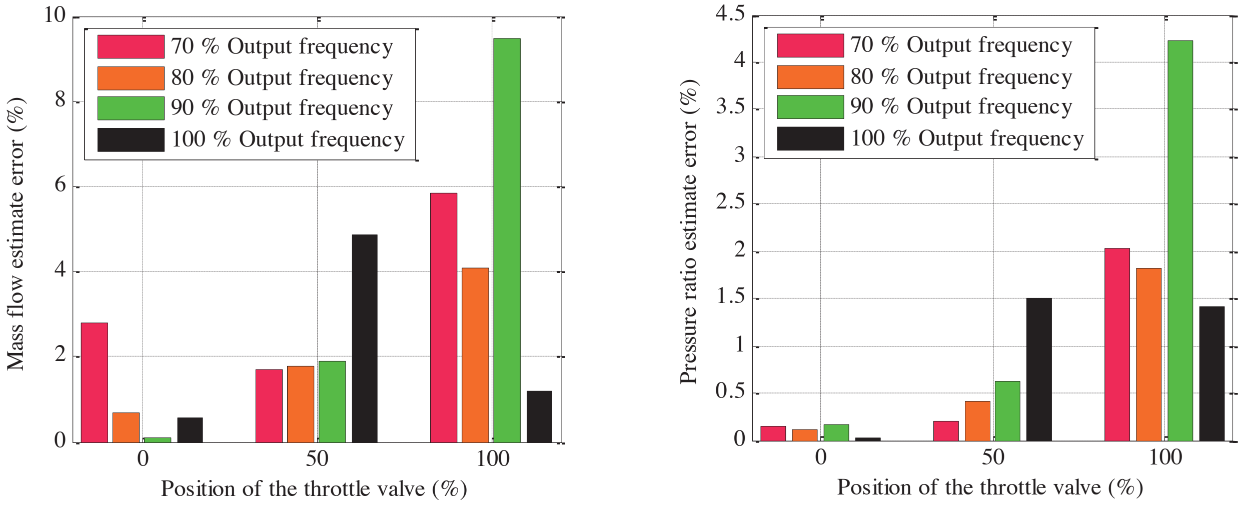

Figure 7. Laboratory test results for sensorless estimation of the centrifugal compressor operational state [24]. Values on the horizontal axis refer to the opening of the throttle valve. Hence, 100 % indicates compressor operation with the maximum flow.

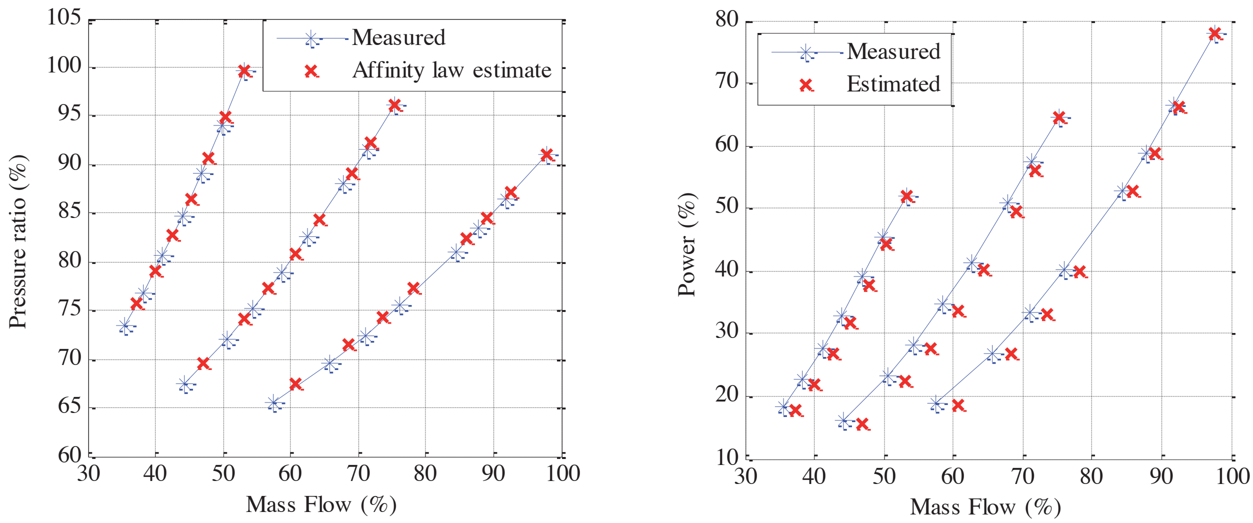

Figure 8. Test results for the estimation accuracy of affinity laws in the case of a centrifugal compressor [24].

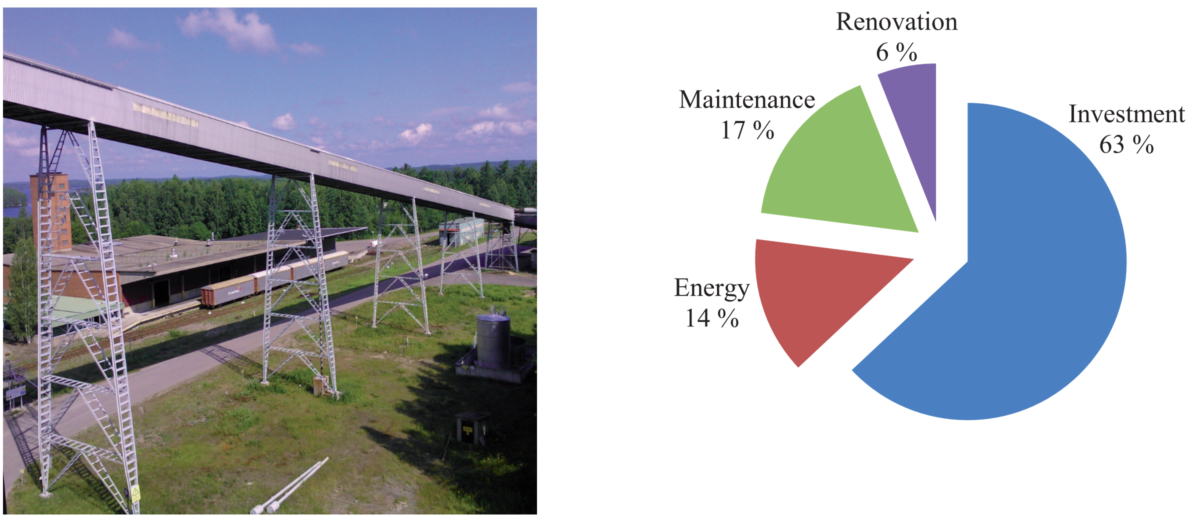

Figure 9. LCC distribution for an industrial belt conveyor system.

studied by comparing the measurements with the constant throttling curves against the results acquired with the affinity laws.

According to test results shown in Figure 8, there is a notable error in the pressure ratio estimates, when the rotational speed decreases below 90 % of the nominal (which corresponds to the second estimated operating point). The affinity laws produce a maximum error of 2.3 % compared with the nominal value. With the mass flow, the error is higher, and it increases with the increasing change in the rotational speed/output frequency. The highest deviation is approximately 3 % compared with the nominal value. In power estimates, the highest error is approximately 1.3 % of the measured value.

As a conclusion, compressor operational state estimation between the known characteristic curves is yet another possible source of error. Affinity laws can be used to produce the performance curves for different rotational speeds, if the curves are measured with small enough rotational speed steps. The results above show that the performance map should be measured with smaller than 40 % steps of the output frequency to achieve an error of 2 % of the nominal value.

In the near future, research on compressor systems will move closer to their energy-efficiency-based control: since compressor systems often comprise a pressure vessel, it offers possibilities ("degrees of freedom") to drive the system as energy efficiently as possible. Research will also be carried out with screw compressors.

Life-cycle costs in industrial conveyor system

The latest research topic in the LCC program are the industrial conveyor systems. They form the fourth largest end-use application for electric motors, and can be a critical part in the industrial production lines. However, their construction is totally different from pumps, fans and compressors. Therefore also their life-cycle cost distributions may not be dominated by the energy costs. At the moment, just life-cycle cost analyses have been formed for two conveyor systems located in Finnish paper mill to get an idea of typical LCC distribution for conveyor systems.

Figure 9 illustrates an industrial belt conveyor system and its estimated life-cycle cost distribution for the time period of thirty years. This conveyor system was built in 1960, and it is used throughout the year to transfer wood chips: therefore maintenance and energy consumption data were available for the estimation from the mill database, while the investment costs were approximated based on the requested tenders. It needs to be noted that in this case about 90 % of the investment costs are caused by the surrounding structures.

Based on the obtained results, life-cycle costs are dominated by the investment, maintenance and energy costs, meaning that the largest saving potential can be possibly found with improved operation of the conveyor system leading to decreased maintenance costs. In practice, this might be realised with reliability and process requirement based speed control for the conveyor, since it currently operates at a constant speed.

To further test the use possibilities of a modern frequency converter in conveyor systems, a test setup will be built to the laboratories of Lappeenranta University of Technology. This will allow testing and possible development of new methods for the optimization of life-cycle costs in conveyor systems.

Conclusion

The majority of the electrical energy consumption is caused by pumping, fan, compressor and conveyor systems. Hence, they are crucial end-use devices to direct energy efficiency actions on. In the LCC research program by ABB Drives and LUT, new frequency-converter-based monitoring and control methods are developed for realising frequency converters that can truly optimise the system life-cycle costs instead of just allowing the system operation at a desired rotational speed.

In fan and compressor systems there has been advances made to the sensorless operating point estimation, which can be used as a basis for all other energy efficiency actions. In addition, the frequency converter-based detection of surge, contamination

Table 1. LCC analysis details for the studied industrial belt conveyor system.

Time period	30	a			
Velocity	2.78	m/s			
Operational days in a year	350	d			
Discounting factor	4.01	%	Annual energy costs	7,131	€
Inflation factor	3.20	%	Annual maintenance costs	9,050	€
Effective discounting factor	0.78	%	Annual renovation costs	3,023	€
Investment	885,000	€	Annual production losses	0	€
Net present value of energy costs	189,949	€			
Net present value of maint. costs	241,065	€			
Net present value of renovation	80,524	€			
Sum of resulting life-cycle costs	1,396,538	€			
Investment	63	%			
Energy	14	%			
Maintenance	17	%			
Renovation	6	%			

build-up and the correct rotational direction is now possible thanks to the research done in the LCC research program. Besides the obtained results, LCC research program is a good example of fruitful co-operation between academia and industry.

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