Sensorless frequency-converter-based methods for realizing life-cycle cost efficient pumping and fan systems

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Abstract

Frequency converters provide means for the energy efficient flow and pressure control in pumping and fan systems by varying the motor speed. Besides speed variation, a modern frequency converter can estimate the state and performance of system operation without additional measurement sensors. This ability provides several possibilities to optimize pumping or fan system operation and the resulting life-cycle costs (LCC) that mainly consist of energy and maintenance costs.

First, information on the present operating state directly informs that how energy efficiently the system is driven, and does the system fulfill the given process requirements. Estimation of the pump or fan operating state can be further applied to determine the surrounding process characteristics, which is essential information for energy audits. This information can also be used for the optimization of the system operation with energy-efficiency-based speed control schemes that are a key factor to LCC efficient pumping and fan systems.

Another, a less studied topic is the detection of lifetime reducing operating states with the frequency converter: it is shown that the occurrence of high flow cavitation, fluid recirculation and fan stalling have an effect on the frequency converter estimates for the motor rotational speed and shaft torque. Correspondingly, mass increase in the fan impeller caused by the contamination build-up can be detected with the converter estimates before the occurrence of impeller imbalance. In both cases, the successful detection of adverse operating state can provide notable cost savings, if the resulting production losses and their effect on the system LCC can be avoided.

This article presents frequency-converter-based monitoring and optimization methods that can be used to optimize pumping and fan system life-cycle costs. The study is done both for commercially available products and for ideas that are verified with laboratory or pilot tests.

Introduction

Pumps and fans are the most common end-use devices driven by electric motors, making them a notable contributor to the global energy consumption [1]. Generally the life-cycle costs of a single pumping or fan 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 system and surrounding process, meaning that a change in the investment costs can result in notably larger change in the energy costs over the system lifetime [2]–[3].
Variable-speed operation of pumps and fans is one of the key factors to energy efficiently operating systems, as it allows regulation of output flow or pressure without adding hydraulic losses into the surrounding process [4]. Typically the variable-speed operation is realized 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 a centrifugal pump or fan [1], [5].

Modern frequency converters are versatile devices, providing several application-specific monitoring and control functions for the motor-driven device [6]–[7]. As an example, internal PID controllers and control functions for multi-pump systems are standard features in pump-focused frequency converters [8]. Another increasing trend in frequency converters is to have an integrated programmable logic controller (PLC) that allows modification of the converter, and hence system operation according to specific needs [9]. As these features are nowadays combined with visually appealing user panel interface, converters start to resemble modern PLC systems.

Some frequency converters allow sensorless estimation of the pump or fan operating state, which can be further used for identification and monitoring purposes. This is primarily possible by accurate estimates for the motor rotational speed ($n_{est}$) and shaft torque ($T_{est}$), which are commonly available in vector and direct-torque-controlled frequency converters [10]. When these estimates are supplied to the characteristic-curve-based model for the pump or fan operation, for instance the flow rate and specific energy consumption can be determined without additional sensors on the device.

Information on the system operating state can be considered as a starting point for other functions that can improve the pumping or fan system operation in terms of LCC. Also the characteristics of the surrounding process are possible to identify with the frequency converter, and this can be further used by the monitoring and control functions especially in pumping systems. Frequency converters provide also several possibilities for detecting operating states that can make the pump or fan more prone to failure and thus reduce service-life of the system. In the worst case, mechanical failure of the pump or fan can reduce or even temporarily cease production with notable cost effects (e.g. 10 000 € per hour). Together these abilities can affect the main contributors of pumping and fan system LCC as visualized in Fig. 2.
The object of this article is to present frequency-converter-based monitoring and control methods that can efficiently reduce life-cycle costs in pumping and fan systems. The study is done both for commercially available products and for ideas that have been verified with laboratory or pilot tests. Primary focus of the article is in sensorless methods that do not require additional measurement sensors on the pump or fan (later referred to as flow device). Therefore motor optimization methods, such as the flux optimization, are not further discussed in this article although they often improve the system efficiency at partial motor loads [12].

The study is started by revising an existing estimation method for the flow device operating state. After this, identification of surrounding process characteristics and their use in monitoring and control purposes is described. Fourth section describes some existing control schemes that seek to optimize energy efficiency while the pumping task is fulfilled. Finally, possible methods for detecting service-life reducing operating states, such as high flow cavitation and fluid recirculation in pumps, are discussed.

Operating state estimation by a frequency converter

Operating characteristics of a centrifugal flow device are commonly described by their characteristic curves for the flow rate $Q$ vs. head $H$ (or pressure $p$) and for the flow rate $Q$ vs. shaft power consumption $P$ at the nominal rotational speed $n_{\text{nom}}$. When the latter curve is compared with the present shaft power estimate ($P_{\text{est}}$) adjusted to this rotational speed, converter can determine an estimate for the flow rate ($Q_{\text{est}}$) and further an estimate for the head or pressure ($H_{\text{est}}$, $p_{\text{est}}$). Typically the adjustment of $P_{\text{est}}$ or characteristic curves is done with Affinity laws ($Q \sim n$, $H \sim n^2$, $P \sim n^3$), which normally assume constant device efficiency regardless of the change in rotational speed.

When $Q_{\text{est}}$ and $P_{\text{est}}$ are known, also an estimate for the flow device specific energy consumption ($E_{s,\text{est}}$) is provided according to

$$E_{s,\text{est}} = \frac{P_{\text{est}}}{Q_{\text{est}}} \text{,}$$

which is also affected by the surrounding process:

$$E_{s,\text{est}} = \frac{\rho \cdot g \cdot (H_{\text{st}} + k \cdot Q^2)}{\eta} \text{,}$$

where $\rho$ is the fluid density, $g$ the acceleration due gravity, $H_{\text{st}}$ the process static head, $k$ the friction loss factor, and $\eta$ the flow device efficiency. If the efficiencies of motor and frequency converter are known, (2) can also be used for the calculation of total system $E_s$. 
Fig. 3. Estimation of the flow rate and head with adjusted $QP$ and $QH$ characteristic curves.

Accuracy of this estimation method is primarily affected by the accuracy and shape of the device $QP$ curve together with the accuracy of rotational speed and shaft power estimates (see [10] and [13] for further information). Thus the $QP$-curve-based model is primarily recommended for radial-flow flow devices that transfer clean water or air, and it is only available in frequency converters applying the vector or direct torque control method with internal motor model (such as Danfoss VLT 6000 HVAC and ABB ACQ810) [14]–[15].

In addition, some frequency converter models (such as ITT PS200) provide additional functions to check the accuracy of given $QP$ curve and exact exponent of the power affinity law with ramp test against a closed valve [16]. In some models (such as Danfoss VLT 6000 HVAC), there is also possibility to provide individual pump characteristic curves to the device memory for several rotational speeds. According to laboratory tests with an accurate $QP$ characteristic curve, estimation accuracy of flow rate can be within 5% of the measured flow rate [17]. In practice the estimation results may be less accurate, for instance within 10–20% of the measured flow rate because of the inaccurate or nearly horizontal $QP$ curve shape.

**Identification of surrounding process**

Operating state estimates can be further used to identify the surrounding process, where the flow device is located. This information is for instance needed in the configuration of allowed rotational speed range, so the flow device would not be driven in adverse operating states. The identification data can also be used for predicting system operation at different rotational speeds, as the resulting flow device operating points are always located in the intersection of the device $QH$ characteristic curve and the surrounding process curve. Often the surrounding process comprises both static and dynamic head, describing the amount of static (pressure) elevation and friction losses between the start and end points of the fluid flow.

Identification of surrounding process is based on collecting operating state estimates ($Q_{est}$, $H_{est}$) at various rotational speeds either during normal operation or during specific identification run, when the surrounding process is known to remain constant. As illustrated in Fig. 4, values for the process static head $H_{st}$ and friction loss factor $k$ can be then determined by finding their best-fit values with the least squares and Simplex methods:

$$H_{process} = H_{st} + k \cdot Q^2$$  \hspace{1cm} (3)

$$S = \sum_{i=1}^{m} (H_{est,i} - H_{st} - k \cdot Q_{est,i}^2)^2,$$  \hspace{1cm} (4)

which reaches its minimum value ($S \approx 0$) when $H_{st}$ and $k$ form the best-fit curve compared with the estimated operating states [13].
As an alternative, just the static head in the surrounding process can be identified with the use of start-up test method described in [18]. In this method, the $H_{st}$-related minimum rotational speed $n_{\text{min}}$ required for the flow production is determined by observing the derivatives of $T_{\text{est}}$ or $P_{\text{est}}$ as a function of rotational speed. Fig. 5 illustrates an example how the production of flow around 750–800 rpm clearly increases the present torque derivative $dT/dn$ against its cumulative average, allowing the identification of $n_{\text{min}}$ for the pumping system.

When the surrounding process is known, it can be used for several configuration and control purposes. For instance, the flow device operation at zero flow rate condition can be avoided with $n_{\text{min}}$. As another example, the determined $H_{st}$ can be used in the energy audits as reference information.

Information on the surrounding process also allows the determination of the most energy efficient rotational speed for the system by calculating its specific energy consumption $E_s$ (Wh/m$^3$) at a range of rotational speeds. This utilization of surrounding process information is especially feasible in wastewater systems where reservoirs are periodically drained with level-controlled pumps, and the process static head changes during the reservoir draining [19].
Fig. 6 provides an example how the $E_s$-related optimum rotational speed is linearly affected by the change in process static head: if the frequency converter is equipped with level measurement sensor or suitable sensorless estimation method, it could be modified to select the applied rotational speed reference according to the present process static head and this kind of $H_{st}/E_s$-based control curve. Compared with fixed-speed operation, $E_s$-based rotational speed ramp can provide further energy savings ranging from few to tens of percent. So far, possibility for having a linear speed reference against the measured fluid level has only been available in the additional software package for Vacon NX frequency converters [20], as the level control is commonly performed in a separate PLC. ABB’s ACQ810 frequency converter has a dedicated level control macro, but it only allows setting the normal and high level for the rotational speed [15].

![Graph showing the effect of process static head on the $E_s$-based optimum rotational speed.](image)

Fig. 6. The effect of process static head on the $E_s$-based optimum rotational speed.

Third interesting application to use identified process could be in the setting of reference values for the system specific energy consumption that can be monitored by the frequency converter. It has been previously shown how relative $E_s$ could be used as a criterion for determining the best energy efficiency area of the pump. In [21], base value for the $E_s$ was selected according to the pump best efficiency point at its nominal speed, although it should rather reflect the base situation for the pumping system operation in the surrounding process. With properly selected $E_s$ base value and the use of trend monitoring feature, the need for air duct or water piping cleaning and other adverse events can be seen as the increase in the relative $E_s$.

**Energy efficiency optimizing control methods**

The use of variable-speed operation instead of valves and bypass lines for flow and pressure control is the first and often the most effective step towards a LCC efficient system. If the system or surrounding process does not possess any degrees of freedom\(^1\), then the required flow rate or pressure can be provided with speed-controlled operation: a laboratory demonstration of the sensorless pressure control with ABB ACQ810 frequency converter is given in [22].

When degrees of freedom are available, even further energy savings are possible with intelligent use of variable-speed operation. In the case of reservoir pumping applications, the previously-introduced $E_s$-based control of pump operation is often possible, as the pumping task is to empty (or fill) a reservoir without strict time limits. A sensorless method to realize this $E_s$-based operation is described in [23]. $E_s$-based control of rotational speeds should also be possible with parallel-connected pumps, where the desired flow rate (or head) can be realized multiple ways. An example of improved control for parallel-connected systems is given in [25], and a similar version of it is available in Vacon frequency converters as the Multifollower PFC application [8].

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\(^1\) Degrees of freedom (DoF) allow realization of the given task in various ways. Typical examples are the applied rotational speed, execution time and duration, and the opportunity to use parallel-connected pumps with or without speed control [24].
In some cases, variable-speed operation can be used to optimize both the pumping system and surrounding process operation in terms of energy efficiency. Fig. 7 provides an example of central heating system equipped with thermostats that act as control valves. In these systems, the circulator pump must be able to provide enough pressure to the radiators regardless of the thermostat valve setting. The required pressure for radiators is ensured by operating the circulator pumping system with a constant pressure reference; traditionally this has been realized with the use of a pressure relief valve and currently with the use of variable-speed operation.

![Fig. 7. An example of central heating system having a circulator pump and two radiators equipped with thermostat valves [26].](image)

However, the use of constant pressure reference is not the most energy efficient approach for these systems, where the primary task is to provide flow to the radiators according to the present need, not a constant pressure into the system. Control-wise this means that as thermostat valves close down because of the reduced need for flow\(^2\), rotational speed of the circulator pump can be decreased to result in the opening of thermostats and the reduced flow rate with less power consumption [26]. In circulator pumps this idea was first realized in 1995 by Grundfos [27], and provided as sensorless version in 2003 by Vogel Pumpen/Lowara with the Hydrovar brand (see Fig. 8 for an example) [28]. This feature is nowadays available in several frequency converters under the name advanced pressure control or flow compensation.

Another example of control feature that may save energy is the sleep boost mode that prevents the pump operation at low and inefficient rotational speed during low demand periods. In this feature, only boost runs at normal rotational speed are done periodically to maintain for instance certain pressure in the system. This feature is available for instance in the ABB ACQ810 frequency converter [15].

\(^2\) Closing the thermostat valve increases friction loss factor \(k\). This has a detrimental effect on the system energy efficiency and specific energy consumption \(E_s\), as seen in (2).
When flow demand decreases (C→C₁), close of thermostat valves is compensated by decreasing the rotational speed until the pump operates on the desired process curve (C₂, G₂) that is detected by monitoring the converter power estimate [28].

Detection of service-life reducing operating states

Besides realizing energy efficient system operation, a frequency converter can be used as a sensorless condition monitoring unit for the pumping or fan system. Information on the system operating state (Q_{est}, H_{est}) can indicate if the flow device is more prone fluid recirculation, stalling, or high flow cavitation: as a simplified version of this, frequency converters can warn if the power consumption of the flow device too small or high that may indicate a dry running pump or pipe leak, respectively [7], [29].

In the case of centrifugal pumps, both the high flow cavitation and fluid recirculation can also affect the time-domain behavior of \( n_{est} \) and \( T_{est} \) while the pump is operating in steady state. Hence, the continuous comparison of these estimates (\( n_{RMS} \), \( T_{RMS} \)) with their base values (\( n_{RMS,N} \), \( T_{RMS,N} \)) has been proposed to be used for the detection of adverse pumping system operation [30]. Fig. 9 introduces how the relative time-domain variation in rotational speed and shaft torque estimates has acted at different flow rates, when a Sulzer APP22-80 centrifugal pump was driven at constant 1450 rpm. One can see increase in the relative time-domain variations, when the flow rate falls below 7.5 l/s that is the manufacturer-informed limit for continuously allowable operating region.
This phenomenon is also present when high flow cavitation occurs in the pump, and it has been verified with three centrifugal pumps in [30]. The proposed method has also been verified to be usable with centrifugal fans, where stalling occurs when there is not sufficient air flow through the fan impeller and the flow detaches from the blade surface [31].

A frequency converter can also provide means for the detection of contamination buildup on the fan impeller even before it leads to the imbalance in impeller. In [32], a method is proposed to determine present mass (i.e. condition) of the impeller. It is based on the step-wise torque startup of the fan system and calculation of the fan moment of inertia from the acceleration of the fan. By repeating this startup test periodically, increase in the impeller mass caused by the contamination buildup can be detected in time. Fig. 10 illustrates the possible effect of contaminated (or jammed) impeller on the fan rotational speed, when a step-wise torque reference is applied to rotate the fan.

The proposed method has been verified with laboratory measurements for a radial flow fan system that consists of a FläktWoods Centripal EU 4 MD 630 radial blower, an ABB induction motor, and an ABB ACSM1 frequency converter that uses direct torque control. The test setup and portion of the obtained estimation results are illustrated in Fig. 11.

Fig. 9. Detection of fluid recirculation occurrence (red bars) is possible by monitoring relative time-domain variation of $n_{est}$ and $T_{est}$ [30].

Fig. 10. Effect of impeller contamination on the resulting fan speed, when a step-wise torque is applied [32].
As the sensorless sensing of adverse operating states and different failure modes has been extensively studied with fixed-speed systems and frequency converters allow new possibilities for condition monitoring, authors expect to see more research, such as [33], and also commercial products related to this topic.

Summary

A modern frequency converter can estimate the state and performance of system operation without additional measurement sensors. This ability provides several possibilities to optimize pumping or fan system operation and the resulting life-cycle costs (LCC) that mainly consist of energy and maintenance costs. Especially new, energy-efficiency-based control methods can provide notable cost savings: pressure control in heating systems is a sophisticated example how the rotational speed decrease can improve both the pumping system and surrounding process operation in terms of energy efficiency. In addition to this, modern frequency converter can be used for condition monitoring purposes, allowing optimization of maintenance and production loss costs.

References


Ahonen T., Tamminen J., Ahola J. and Niemelä M. Accuracy study of frequency converter estimates used in the sensorless diagnostics of induction-motor-driven systems. Proc. of the 14th European Conference on Power Electronics and Applications EPE’11 (Birmingham, United Kingdom, 30 August-1 September 2011).

Ahola J. Introduction to energy efficiency and life-cycle cost efficient pump and fan systems. Proc. of the XXth International on Electrical Machines ICEM’2012 (Marseille, France, 2-5 September 2012).


[29] Danfoss. VLT HVAC Drive, For HVAC it has to be VLT, 2011.


[33] Lane M. Using the AC Drive Motor as Transducer for Detecting Electrical and Electromechanical Faults, University of Huddersfield (United Kingdom), 2011. Can be downloaded at: http://eprints.hud.ac.uk/10167/