THE ARCHIVE OF MECHANICAL ENGINEERING

VOL. LVII 2010 Number 4

10.2478/v10180-010-0023-x

Key words: pump, diagnosis, control, burner industry

STEFAN KLEINMANN [*], *ANNA DĄBROWSKA* [**], *AGATHE KOLLER-HODAC* [***],
DOMENICO LEONARDO [****], *RALF STETTER* [*****]

MODEL OF A COMBINED PUMP AND DRIVE SYSTEM FOR ADVANCED CONTROL AND DIAGNOSIS

An elaborate study executed in the direction of exploring energy saving potential shows that more than 20% of electrical energy used in industry is used for pump systems. Experts calculate that more than 30% of this energy can be saved by improving control and diagnosis for pump systems. Unfortunately, the application ratio of such system is small and consequently a large demand for such technological advanced systems can still be observed in the pump industry. Because of this reason and still growing demand of saving energy in industry, two Universities in Germany and Switzerland together with leading German pump manufacturer decided to join their knowledge and skill to work on the project called “Smart Pump”. This paper presents one of the first results of this project, which goal is the development of future control methods and diagnosis systems for intelligent pumps.

1. Introduction

In 21st century the simple word “energy” has a global and huge meaning. Similar to the human body, a contemporary modern world cannot function properly without a continuous supply of energy. Unfortunately, commonly known conventional energy sources are slowly running out. Analytics anticipate that over the next several decades coal and oil sources are going to run out. Therefore, ecological factors and climate protection programs are

---

[*] *Allweiler AG, 78315 Radolfzell, Germany, E-mail: S.Kleinmann@allweiler.de*

[**] *Hochschule Ravensburg-Weingarten, 88250 Weingarten, Germany, Email: dabrowska@hs-weingarten.de*

[***] *Hochschule Rapperswil, CH-8640 Rapperswil, Switzerland, Email: agathe.koller@hsr.ch*

[****] *Hochschule Rapperswil, CH-8640 Rapperswil, Switzerland, Email: domenico. leonardo@hsr.ch*

[*****] *Hochschule Ravensburg-Weingarten, 88250 Weingarten, Germany, Email: stetter@hs-weingarten.de*

getting more and more important nowadays. Many institutes all around the world are focusing on studying energy saving potential in industry. Europump, the European Association of Pump Manufacturers, which represents more than 450 companies with 100,000 employees and roughly € 6 billion sales in Europe, assumes that as much as 30 or even 50 percent of the energy consumption can be reduced with optimized pump systems. This indicates a great energy saving opportunity, if we take into consideration that in Europe (EU-15) 20% of the total industrial energy consumption is applied to operate pumps and pump systems [1].

One may think that a pump system in industrial applications such as power plants is a perfect example for a system which has at its disposal an elaborate control system. However, in current applications, most pumps are not controlled at all. Until now, only small amount of money was invested in control systems for pumps [2]. Many pump systems have the potential of considerable energy conservation. The systems are mainly concerned with their ability to operate at several different work points (relation between volume/pressure and delivery volume). For this purpose, certain work points must be given either by a machine control or by a leading vantage point or an adaptive control (i.e. a control which reacts independently on divergent operating conditions) has to be realized.

In particular, revolutionary changes require extensive control concepts. A special requirement in this case is the claim for developing a system without sensor, i.e. the available components – pump and motor could operate as ”sensors”.

Because of the large energy saving potential, and because of the requirement to implement measures according to climate protection programs, two Universities (Hochschule Ravensburg-Weingarten, Germany and Hochschule Rapperswil, Switzerland) together with a leading German pump manufacturing company (Allweiler AG) decided to start a research project. The project is funded by the European Union in the scope of the European Fond for regional development in the Interreg IV program Alpenrhein-Bodensee-Hochrhein together with the Schweizer Bund and the Fürstentum Lichtenstein as well as the Internationale Bodensee-Hochschule. The main goal of the project is development of a well-founded prognosis of future control and diagnosis technologies for intelligent pump systems. Figure 1 gives an overview of the project.

This paper presents one of the first results of this project, which is based on building a pump system model for typical industrial application. A detailed analysis of many different factors (market requirements, extending knowledge) moved the project into the direction of research centering around three screw spindle pumps SPF in burner industry applications. As a technical challenge, this application is also in many aspects representative for further applications.

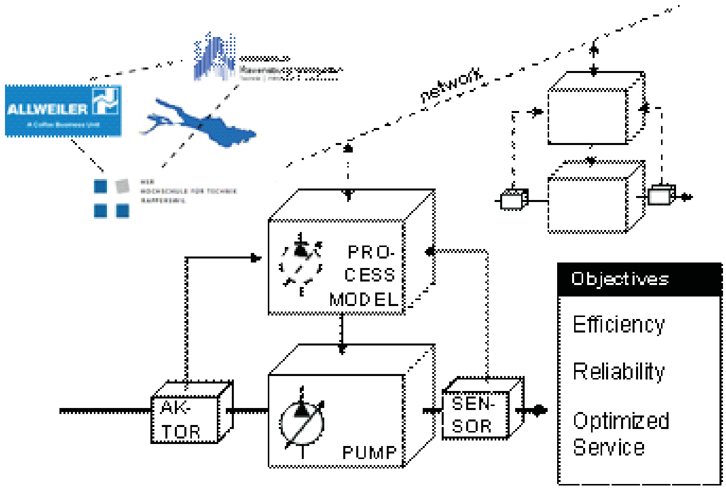

Fig. 1. Project overview

2. System description

Pump systems are usually composed of a pump, an asynchronous motor with frequency converter and a consumer part (process load); therefore, each of these components must be taken into consideration for modeling this system. As a consumer system, a model was constructed which corresponds to the typical burner industry application. As one of the first steps of this project, one realized a combined model for the pump, the motor and the process load. Each of the model blocks was modeled separately in Matlab/Simulink, and later the blocks were connected into an overall system (Figure 2). The motor speed n_2 is the input to the pump system block and the torque load from the pump side M_{load} is the input to the motor converter system block. The theoretical flow rate Q_{act} from the pump is the input to the consumer system block and the required pressure p is the input to the pump system block. These three components are described in the following sections.

2.1. Model of the motor

The so-called vector control method of asynchronous motors is widely used in industrial circuits where the control quality is the determining factor in the whole technological process. This fact was one of the most important reasons for using in this research project the vector method called DFOC

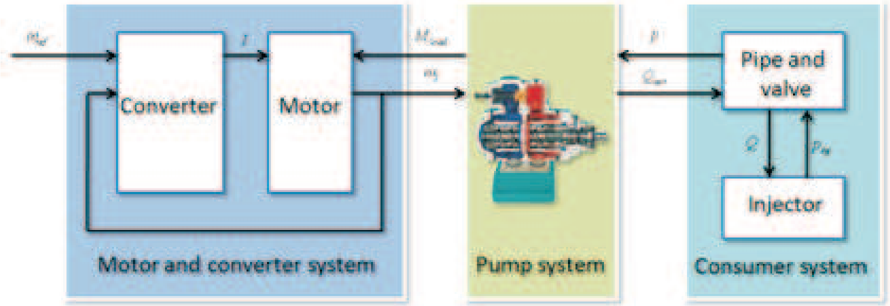

Fig. 2. Overall pump system

(Direct Field Oriented Control). Concerning the principle of control, this method is based on separation of components of the stator current vector into:

- active – responsible for motor torque control and
- passive – responsible for flux.

The induction motor is getting the linear control object by forcing the stator current in the rectangular coordinate system oriented relatively to the rotor flux vector. In the coordinate system rotating in parallel with the rotor flux vector $\boldsymbol{\Psi}_r$, the stator current $\boldsymbol{i}_s$ can be decomposed into two rectangular components $\boldsymbol{i}_{sd}$ and $\boldsymbol{i}_{sq}$. Thanks to this solution, torque and flux in the asynchronous motor can be controlled independently [3]. Because a frequency converter cannot directly constrain the components $(\boldsymbol{d}-\boldsymbol{q})$ of the stator vector currents, the basic block in FOC control methods is the coordinates transformation block $(\boldsymbol{d}-\boldsymbol{q})/(\boldsymbol{\alpha}--\boldsymbol{\beta})$ and $(\boldsymbol{\alpha}--\boldsymbol{\beta})/(\boldsymbol{d}-\boldsymbol{q})$.

In Matlab/Simulink, one realized the most popular method of regulation based on the harmonic of output voltage of the frequency converter called Pulse Width Modulation (PWM). The vector modulator calculates frequency converter steering signals $\boldsymbol{S}_A, \boldsymbol{S}_B, \boldsymbol{S}_C$ by comparison of sinusoidal and triangular signals.

The motor model is equivalent (the same parameters) to the real asynchronous motor with nominal power $\boldsymbol{P}_n = 2.2$ kW and nominal angular velocity $\boldsymbol{n}_n = 1415$ rpm. The control model of this motor gives good results in static and also in dynamic states. Figure 3 shows this realization.

2.2. Model of the pump

The three screw spindle pump has not yet been extensively described in literature and was not the subject of scientific research (in contrary to other pump types). Available are rather simple mathematical equations [4] and closely related scientific mathematical models of two-screw spindle pumps

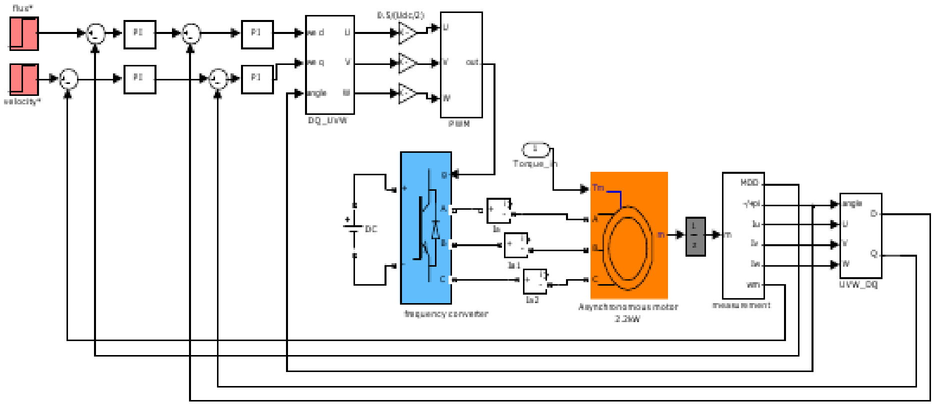

Fig. 3. Realization of DFOC method in Matlab/Simulink

for multiphase applications. In literature one can find description of chamber to chamber backflow through circumferential, radial and rotational leakage losses ([5], [6]). Because of lack of a mathematical model of three-screw pumps, the model which was realized, also in Matlab/Simulink environment, will produce the desired output from the given input on the basis of rather simple mathematical equations prepared by the employees of Allweiler AG. These equations are similar but more sophisticated than the models presented in literature (e. g. [4]). This means that the present model of the pump is not yet a real dynamic model. Currently, the project team is working on validation of the existing model in the real test field and on expanding this model to represent the dynamic conditions.

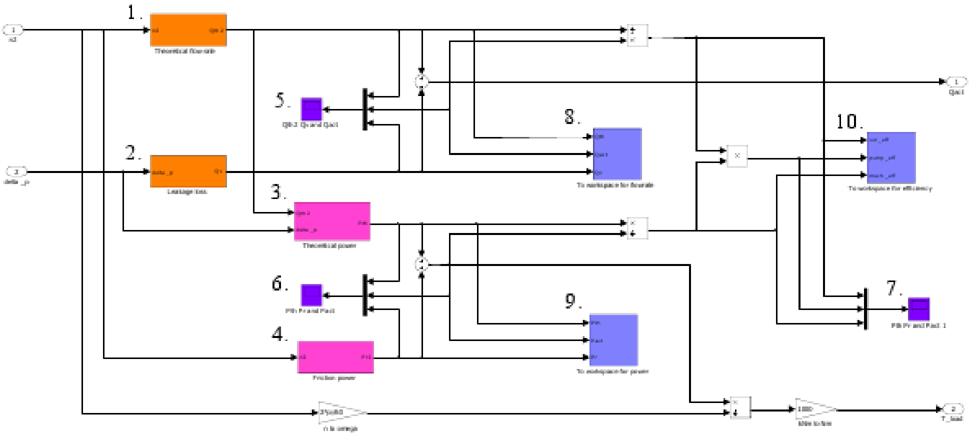

Fig. 4. Realization of three screw pump model in Matlab/Simulink

There are four important blocks in the SPF pump system model, which are illustrated in Figure 4; the theoretical flow rate Q_{th} in (No. 1 in Figure 4), the leakage loss $\boldsymbol{Q}_v$ (No. 2), the theoretical power $\boldsymbol{P}_{th}$ in (No. 3) and the friction power $\boldsymbol{P}_r$ in (No. 4). The actual flow rate $\boldsymbol{Q}_{act}$, total power consumption $\boldsymbol{P}_{act}$, the volumetric- $\boldsymbol{\eta}_{vol}$, the mechanical- $\boldsymbol{\eta}_{mech}$ and the pump efficiency $\boldsymbol{\eta}_{pump}$ are calculated from the model blocks mentioned above.

2.3. Process load

Screw pumps have been used in many different application domains. The hydraulic process can vary from a simple load to an extensive system. Therefore, some hydraulic components, such as a pipe or a nozzle, can be modeled individually and stored in a model library. The modular system configuration allows the user or a diagnostic routine to observe conditions between the components. This facilitates the control tuning for all components in the chain.

The resulting library consists of five standard hydraulic components, like a pipe, a pipe bend, a regulating valve, a y-pipe and a nozzle. These components can be easily combined to build almost every model of a process load. Using a simple user interface, each component model can be parameterized and adjusted according to the real component properties. The y-pipe is the only component with one inlet point and two outlet points. Depending on the hydraulic resistance on the outlet points, the y-pipe divides the incoming medium into the outlets in the correct way. For example, if the regulating valve in the picture below (Fig. 5) produces more resistance to the return thread in the tank, then the largest amount of fluid will pass through the nozzle.

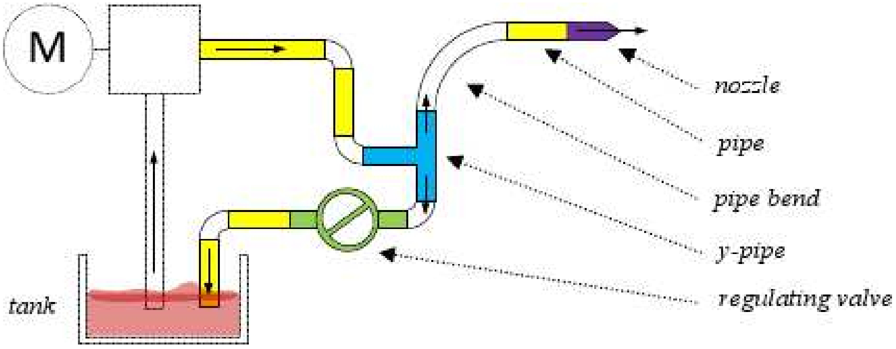

Fig. 5. Simplified simulation model for a burner application

Based on the actual flow rate $\boldsymbol{Q}$ of the pump, the simulation program calculates the whole back pressure of the system Δp_{tot} that will affect the pump in different ways. The derivation of the whole back pressure is illustrated in Figure 6. Each load n calculates its pressure loss Δp_n by the actual flow rate $\boldsymbol{Q}$ and passes the actual incoming flow rate $\boldsymbol{Q}$ to the next component in the chain. Furthermore, each load element adds to the own pressure loss $\boldsymbol{\Delta} p_n$ the pressure loss of the successive component $\boldsymbol{\Delta} p_{n+1}$. Consequently, the first component in the chain directly after the pump contains the total back pressure $\boldsymbol{\Delta} p_{tot} = \boldsymbol{\Delta} p_n + \boldsymbol{\Delta} p_{n+1} + \boldsymbol{\Delta} p_{n+2}$ on the pump.

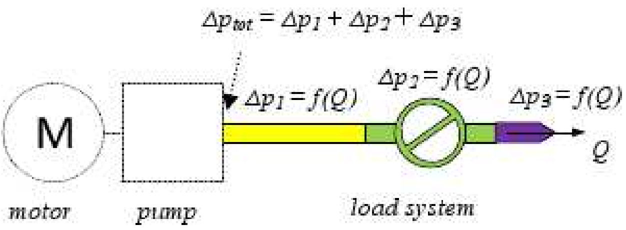

Fig. 6. Basic mathematical concept for simulation model

The flow velocity $\boldsymbol{w}$ of the fluid is a linear function of the flow rate $\boldsymbol{Q}$, as described in equation (1). This also depends on physical properties such as the diameter $\boldsymbol{b}$ of a pipe.

$$w = Q \cdot b \tag{1}$$

The pressure loss $\boldsymbol{\Delta} p$ depends on the fluid flow velocity $\boldsymbol{w}$, the friction factor ζ and the density ϱ of the fluid passing through a component. The pressure loss can be calculated using equation (2).

$$\Delta p = \zeta \cdot \frac{e}{2} \cdot \bar{w}^2 \tag{2}$$

The friction factor ζ varies depending on the component geometry as well as the viscosity of the medium and accordingly its temperature. This factor can be derived by a calculation, in the simple case of a straight pipe, or can be obtained in an empiric way for components with more complicated inner construction. In literature [7], the main equations and empiric derivations used to develop the mathematical model are described. The roughnesses of the interior wall surface as well as hydrostatic effects have also been taken into account in the calculation.

The previously described mathematical model of the process loads has been implemented in Matlab/Simulink. Each component model has been designed in a similar way. It consists of an input $\boldsymbol{Q}$ for the incoming flow rate, an output $\boldsymbol{Q}$ for the successive component, an input $\boldsymbol{p}$ for the pressure loss of the successive component and an output $\boldsymbol{p}$ to give back the pressure loss to the previous component. The equations have been implemented graphically and structured using sub-functions.

3. Simulation results

The complete simulation model consists of the three main components: motor, pump and load which form an integrated system. Figure 7 shows a setup of a complete system with the motor on the left side, the pump in the middle and the process load on the right hand side. The process load is made of two straight pipe segments and a nozzle.

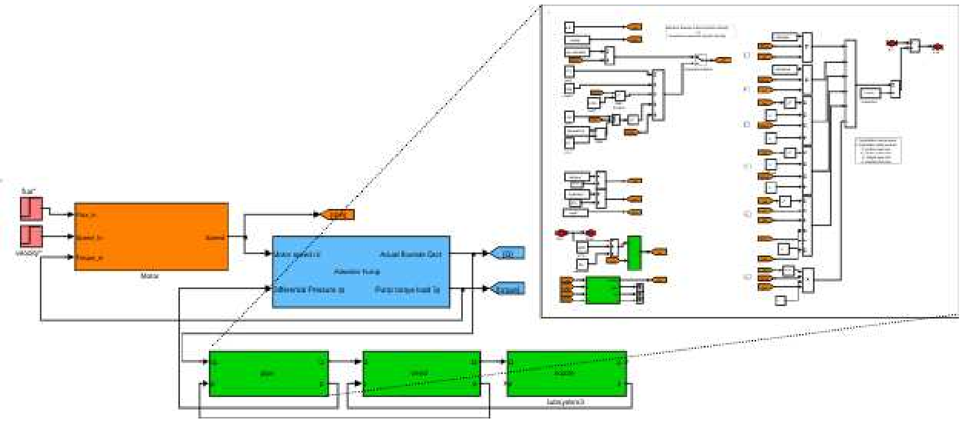

Fig. 7. Complete System in the simulation environment and example of implementation of pipes part in Matlab/Simulink

The speed output of the motor block is connected directly with the pump. According to the motor speed, the pump delivers a flow rate that passes through the process load. The sum of the total back pressure of the process load is connected to the pump block. Therefore, the torque on the pump shaft and the leakage loss in the pump increase when the back pressure in the load system gets higher. Finally, the torque output of the pump block is connected to the motor and closes the loop. In this way, the frequency converter can control the process correctly.

The simulation starts with a fast speedup of the motor. The hydraulic pump and the load system react immediately to the motor acceleration, because the transient effects have not been implemented in the simulation model yet. Figure 8 shows the simulation graphs for a preset motor speed of 1146 rpm.

The overall model is characterized by very good correlation between the simulation results and the corresponding static calculated values. The static dataset was calculated using equations provided by the pump producer. The resulting discrepancy between calculation and measurement by the model is equal to 0.02% for motor speed and actual flow rate, and 0.1% for back pressure.

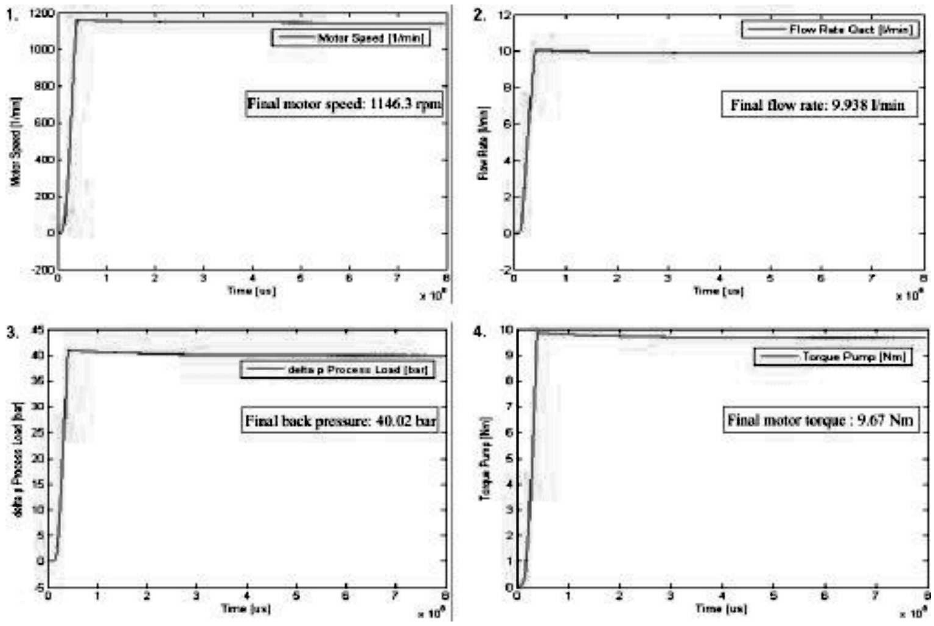

Fig. 8. Simulation results: 1.) motor speed, 2.) pump flow rate, 3.) back pressure, 4.) motor torque

4. Summary

An exact system model allows the pump provider to test any pump or system configuration without requiring expensive setup and time-consuming testing. In particular, the efficiency of a complex system can be evaluated in advance.

Considering the burner applications, the model-based supervision makes it possible to monitor real systems under operating conditions without requiring numerous and expensive sensors in the apparatus. Potential dysfunctions, such as a clogged filter or a pipe line rupture in the system, can be detected automatically, which will greatly enhance diagnostic capabilities of real hydraulic systems.

Manuscript received by Editorial Board, October 01, 2010

REFERENCES

[1] Kleinmann S., Dabrowska A.: “Analysis of Possible Applications of the Advanced Modelling and Diagnosis System AMandD in German Industry”, Proceedings of ACD 2009, Zielona Gora, Poland.

[2] Kleinmann S., Dabrowska A. Hoffmann, M., Kühn, H., Koller-Hodac, A., Stetter, R.: “Advanced Control of Industrial Pump Systems”, ACD 2009, Zielona Gora, Poland.

[3] Orlowska-Kowalska T.: “Sensorless drive systems with induction motors”; Wroclaw University of Technology, Publishing House, 2003 (in Polish).

[4] Faragallah W., Surek D.: “Rotierende Verdrängermaschinen”.Sulzbach : Verlag und Bildarchiv, 2004 (in German).

[5] Wincek M.: “Zur Berechnung des Förderverhaltens von Schraubenspindelpumpe bei der Förderung von Flussigkeiten / Gas-Gemischten”.Erlangen: Technische Fakultat der Universität Erlangen-Nürnberg, 1992 (in German).

[6] Körner H.: “Zum Förderverhalten von Schraubenspindelpumpen für zweiphasengemische hohen Gasgehalts”. Erlangen: Technische Fakultät der Universität Erlangen-Nürnberg, 1998 (in German).

[7] Bohl W., Elmendorf W.: “Technische Strömungslehre”, Vogel Verlag und Druck, 2008 (in German).

Zintegrowany model pompy z system napędowym jako podstawa zaawansowanej kontroli i diagnostyki

Streszczenie

Szczegółowa analiza, przeprowadzona w kierunku poszukiwania potencjału oszczędności energii, wykazuje, że ponad 20% energii elektrycznej używanej w przemyśle, jest wykorzystana przez systemy pomp. Eksperci szacują, że ponad 30% tej energii może być zaoszczędzone poprzez udoskonalenie kontroli oraz diagnostyki w systemach wykorzystujących pompy. Niestety, współczynnik zastosowania takich systemów jest niewielki, dlatego konsekwentnie można zaobserwować wzrost zainteresowania zaawansowanymi technicznie systemami kontrolno-diagnostycznymi w przemyśle pompowym. Ten właśnie czynnik oraz ciągle rosnące zapotrzebowania na oszczędzanie energii, były powodem dzięki któremu dwa uniwersytety w Niemczech oraz Szwajcarii, razem z czołowym niemieckim producentem pomp, zdecydowali połączyć swoją wiedzę i umiejętności w celu pracy nad projektem zwanym „Inteligentne pompy“. Poniższy artykuł przedstawia jeden z pierwszych etapów danego projektu, którego głównym celem jest rozwój nowoczesnych metod kontroli oraz diagnostyki w systemach pomp.