Performance monitoring and failure cause isolation of submersible pumps

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Introduction

Drinking water harvested from aquifers via boreholes using submersible pumps are types of installations where direct access to the pump is impossible, meaning that maintenance is complicated and expensive, and the harsh environment can result in failures due to wear and tear. Boreholes often operate for a long time without proper maintenance, leading to the risk of high energy consumption and potential over-pumping which can harm aquifer. It is often impossible to distinguish between pump wear and tear and problems in the aquifer or borehole from the available sensor information. Distinguish between failure types is addressed in this paper.

Different approaches have been used for fault detection in centrifugal pumps (e.g. Hernandez-Solis, A. and Carlsson, F. 2010; Mahalik et al. 2012). The approach proposed here builds on earlier results (Kallesøe et al. 2004), (Kallesøe et al. 2006), where it was shown that, using performance sensors for pressure, flow, speed and power, it is possible to isolate centrifugal pump failure into different sets of failure causes.

Problem statement

Problem statement: Using sensors and measurements often available in submersible pump application, it is possible to

1. Detect that the pump is not operating as intended.
2. Isolate the cause of the degradation of the operation.

We seek to automatically answer the above problems using a digital twin of the submersible pump in question.

Method

Data collection: Data is collected via data loggers at the borehole or gathered from an existing SCADA system, and automatically sent to the calculation server. The following data points are needed for the detection method:

- Outlet pressure from the borehole p
- Water level in the borehole h
- Flow out of the borehole installation q
- Power consumption of the pump P
- Speed of the pump n

The outlet pressure and the water level are used for calculating the pressure across the pump Δp. The measurement points are shown in Fig. 1.

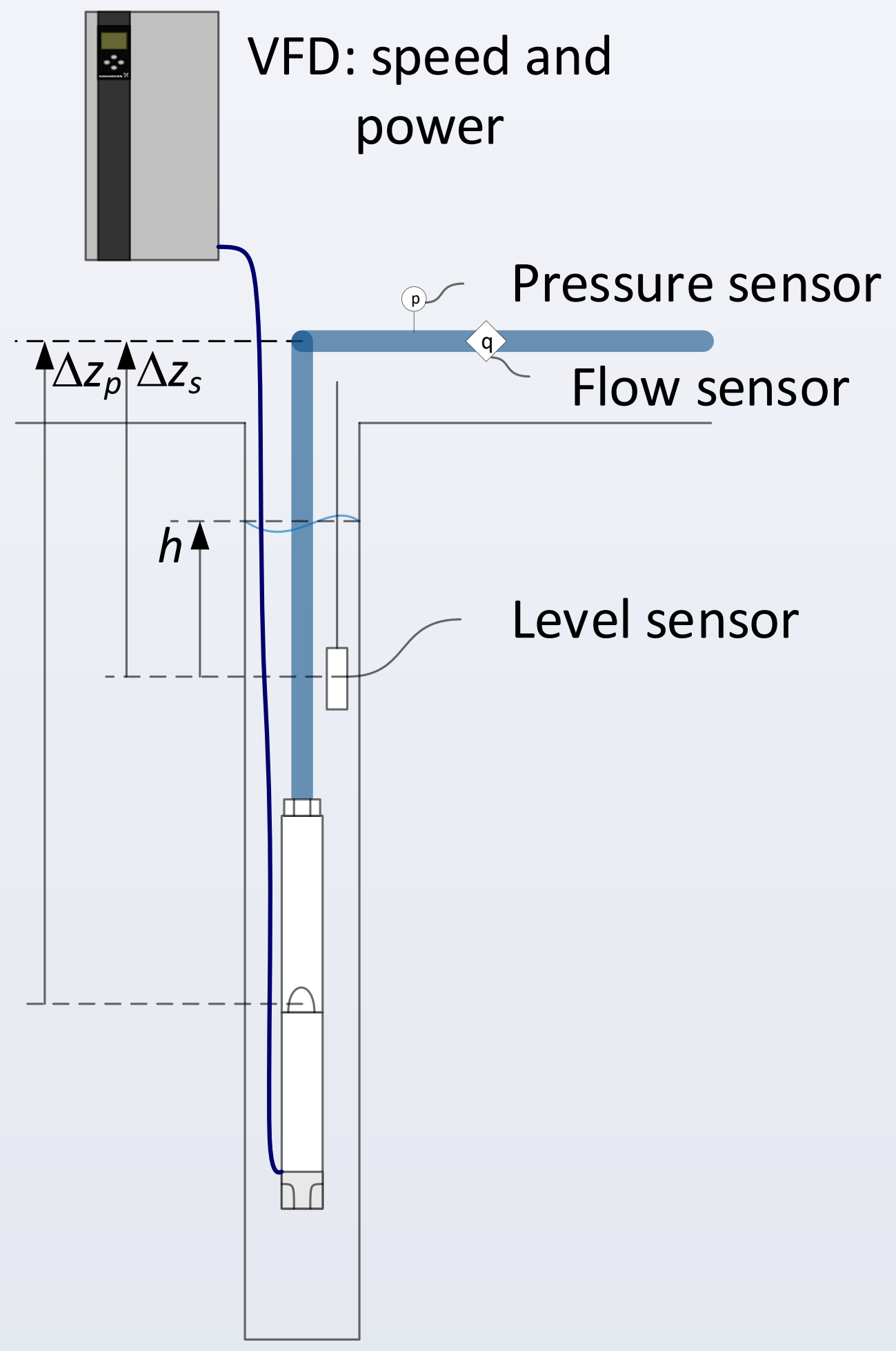


Fig 1: borehole *with sensors*

Collected data are filtered such that only data from quasi steady state operation is in the data set. This is necessary as the digital twin describes the pump under steady state operation. Likewise, the fault signatures are only valid during steady state operation.

Fault detection and isolation algorithm: The detection contains three steps:

1. Obtain data to form a digital twin of the pump in question. In our case the data are obtained from Grundfos Product Center.
2. Measure the difference between the digital twin and the actual pump.

$$r_1 = \Delta p - f(q,n), \qquad r_2 = P - g(q,n),$$
$$r_3 = \Delta p - h(P,n).$$

   Here f, g, and h are the models forming the digital twin.

3. Evaluate the residual set $r = (r_1, r_2, r_3)$ to isolate the cause of the abnormal operation. The residual set is evaluated against an error model derived from the digital twin, and the fault is parametrized by the parameter $\theta \in \Theta$.

$$Q^{type} = \min_{\theta \in \Theta} \sum_{i=1}^{3} \left(r_i - e_i^{type}(\Delta p, P, q, \omega, \theta) \right)^2$$

$$d^{type} = 1 - \frac{Q^{type}}{r^T r}$$

   Good correspondence between r and $e^{type} = (e_1^{type}, e_2^{type}, e_3^{type})$, or equivalently d_{type} close to 1 means that the $type$ is likely to cause the degradation of the pump operation.

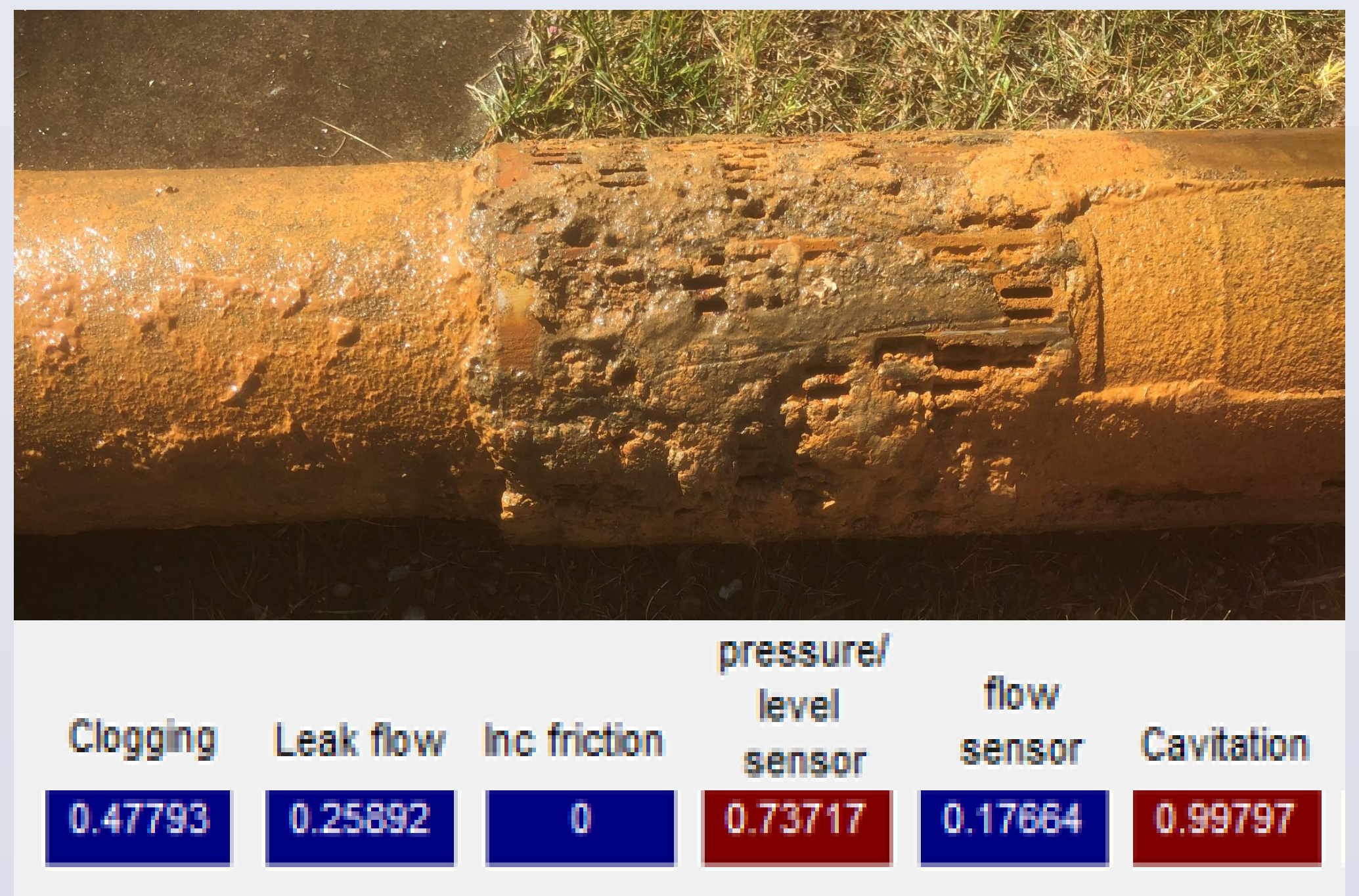
Results

The algorithm is designed to handle the fault types:

- Clogging in the pump, inlet filer, and riser.
- Leakage flow inside the pump or in the riser.
- Increase friction.
- Pressure or level sensor faults.
- Flow sensor faults.
- Cavitation.

In the following test results from a clogging/cavitation case and a leakage case are shown, both from a test site in Viborg, Denmark. The result in form of the decision variable d^{type} is shown along with a picture of the pump failure.

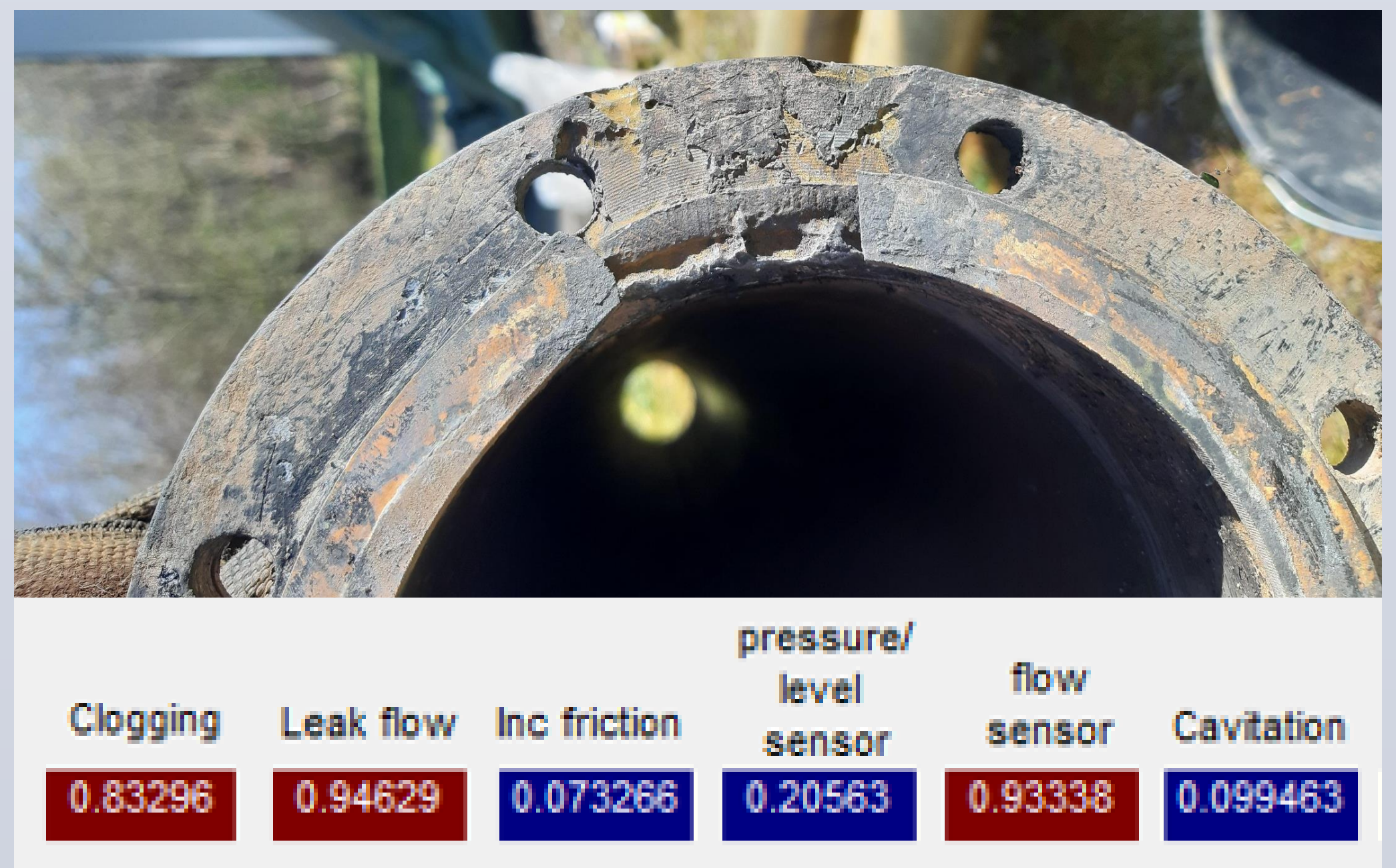
In the first case ocher has clogged the inlet filter creating low suction pressure, which often causes cavitation. See Fig 2, where a picture of the inlet filter and the decision variables are shown.



Clogging	Leak flow	Inc friction	pressure/ level sensor	flow sensor	Cavitation
0.47793	0.25892	0	0.73717	0.17664	0.99797

Fig 2: Ocher clogging the inlet filter. The fault leads to decision variables "pressure sensor fault" and "cavitation" close to 1.

In the second case a leak is found in the riser leading to a leakage flow. See Fig 3, where a picture of the leak and the corresponding decision variables are shown.



Clogging	Leak flow	Inc friction	pressure/ level sensor	flow sensor	Cavitation
0.83296	0.94629	0.073266	0.20563	0.93338	0.099463

Fig 3: Leak in the riser. The fault leads to decision variables "clogging", "leak flow," and "flow sensor fault" close to 1.

Discussion and conclusion

Results from two fault cases are presented here. The first is clogging at the inlet filter, see Fig 2, and the second is a leaking riser, see Fig 3. In both cases the fault type indicator, indicating the actual fault has the highest value. However, other fault type indicators also have high values. This behavior is due to the nature of the faults, which results in similar residual behaviors. Hence, at the given operating point it is not possible to distinguish between the fault types.

In the first case with clogging in the inlet filter, the cavitation indicator lights up along with the pressure sensor fault. Clogging at the inlet filter leads to low suction pressure and cavitation. This means that it is expected that the cavitation indicator lights up. The pressure sensor fault indicator also lights up as cavitation affects the pressure generated by the pump, which is indistinguishable from pressure sensor faults.

In the second case with a leak in the riser, the clogging, the leak flow, and the flow sensor fault indicators light up. It is expected that the leak flow indicator lights up as the leak in the riser leads to water flowing back into the borehole. The leak flow adds to the amount of pumped water but is not measured by the flow sensor. Therefore, a flow sensor fault and a leak fault are hard to distinguish. Finally, the clogging indicator lights up. This is due to the operating point of the pump, which leads to a residual behavior looking a bit like clogging.

Better fault indication can be obtained by changing the operating conditions of the pump, by either changing the pump speed or by using the short off valve at the pump head as a throttle valve.

References

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Mahalik, N., Dastidar, S.G., Mohanty, A. R., and Pradhan, P.K. 2012 Fault detection in a centrifugal pump using vibration and motor current signature analysis. *International Journal of Automation and Control.* **6**(3-4), 261-276.

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