Creation of Surface Dynamometer Cards of Sucker Rod Pump Using Frequency Converter Estimates and Process Identification Run

Tuomo Lindh, Jan-Henri Montonen, Maxim Grachev, Markku Niemelä
Lappeenranta University of Technology (Finland)
tuomo.lindh@lut.fi

Abstract—This paper presents a novel method for the creation of surface dynamometer cards of sucker rod pump using a torque and rotational speed estimates of variable speed induction motor drive and pumping process identification run.

1. INTRODUCTION

According to the history of pumping system development, the sucker-rod pumping is very frequently used for artificial lifting of fluids and it covers nearly two thirds of the oil wells in operation around the world [1]. Nearly 70% of all the wells operate on sucker-rod pumps [2,3]. Fig. 1 describes a sucker rod pumping system.

Sucker rod pumping system consists of five basic parts: Prime mover, Gear reducer, Pumping unit, Sucker rod string and Subsurface pump. The prime mover is in our case a rotational speed controlled induction motor drive. The gear reducer increases the torque in order to adopt these values to the needs of pumping system. Pumping unit transforms the rotating motion provided by the motor drive and the gear reducer into a reciprocating motion of a sucker rod string. Sucker rod string passes the reciprocating motion of pumping unit to the downhole pump, mounted in the well. The subsurface pump sucks fluid (e.g. oil or etc.) from the well for further transmission into the surface. The block diagram of rod pumping system is presented in Fig. 2.

The surface dynamometer card plots the force in the top of rod string as function of rod displacement. The cards are the main tool used to analyze pumping performance, oil well conditions and different abnormal operation conditions.

To create a surface plot the normal procedure is to install a dynamometer equipment that is comprised of force and position sensors and a program that plots the force against rod position. Another way to produce a plot is to use motor torque signal and then calculate the polished rod force. The calculation can be done using a kinematic analysis of a pumping unit as proposed by Liu et. al. [4]. The proposed procedure has two main drawbacks: Firstly, in order to calculate the kinematics, a very detailed model of geometry is required, and secondly, the geometry varies between pumps and between different settings of pump such as the rod stroke length or the gear ratio. We propose that an identification procedure can reveal the kinematic connection and forces affecting to pump in such accuracy that the surface dynamometer card can be formed without geometry information, only by using the estimates created by the frequency converter and with one additional limit switch. The system forms an intelligent drive.

Concept of intelligent drive refers to a system where drive adapts to process, does condition monitoring or identifies the process that it is driving [5,6,7]. Sometimes, the intelligent drive refers a system, in which, the motor parameters are automatically obtained during an identification run in a
commissioning phase. In this paper, the term identification run means a system, in which, the required pumping process parameters are identified.

II. TEST SETUP

In order to be able to test the identification based estimation of surface dynamometer cards, a simulation model of whole rod pump system was created [8]. The model consists of A) a detailed frequency converter model containing actual converter control code and two axis induction motor model, B) a pumping geometry presented in [1, 4] including a gearbox, rodstrings as a lumped flexible system, a downhole pump and a simple well model as a RC-circuit [8] where capacitance reserves the inflowing oil that is flowing to well through a resistance. The simulations in different operating conditions with different wells were executed and results were compared to actual measurements. One of the results is plotted in Fig. 3.

![Fig. 3. Surface dynamometer card of a real plant and a simulated version.](image)

III. IDENTIFICATION PROCEDURE

The basic idea is to find a correspondence between motor torque and a rod string force. The torque as a function of time or as a function of measured rod position does not directly correspond to polished rod force. The main difference is due to a counter balance torque. The counter balance torque itself is comprised of two components: static moment and dynamic component due to inertia. These two components can be isolated from each other in identification because the latter is a function of rotational speed. The identification procedure does not and does not have to ensure the source “no load” torque components. Later we refer all these as counterbalance torque because it is supposed to be the biggest of all torque components that are not influenced by polished rod force.

Neglecting the losses in gearbox and in joints it can be stated that produced power must equal to used rod and in counter balance, which leads to equations

\[
(\hat{T}_e + T_{CB}) \cdot \frac{\omega_{\text{rank}}}{v_{\text{rod}}} = P_{\text{rod}}
\]

(1)

\[
(\hat{T}_e + T'_{CB}) \cdot \frac{\omega_{\text{rotor}}}{v_{\text{rod}}} = P_{\text{rod}}
\]

where \(T_e\) is electrical torque estimate on secondary side (crank side), \(T_{CB}\) is a counterbalance torque, \(T_e\) is electrical torque estimate on primary side (motor side), \(T'_{CB}\) is a counterbalance torque reduced to primary side (motor side), \(\omega_{\text{rank}}\) is crank angular speed ; \(v_{\text{rod}}\) is a rod speed and \(\omega_{\text{rotor}}\) is the rotor angular speed. It is necessary to know all the values from this equation to estimate rod load. The electrical torque component can be estimated from the frequency converter, while the counterbalance torque component can be measured during the identification run of the pumping system with zero rod load value. The rotational speed of the crank is not measured and in addition cannot be assessed by utilization of gearbox ratio, because in the case of the real system this values is not known and gearbox might have multiple values of ratio. The last value needed for calculation of the rod load is rod speed, which can be calculated. Rod speed is a derivative of rod position, therefore it is essential to have information about rod position in order to obtain values of rod speed.

Identification. The correspondence between rod position and motor angle incremental during one rod cycle can be achieved by identification run. The limit switch is used to get information of one position during cycle. The relation between rotor angle and polished the measured or estimated rod position is recorded in a lookup table. This table will be utilized in operational run of the system. In the real life application the ID-run procedure can be expressed with following steps:

![Fig. 4. Torque-position curve from the simulation model.](image)
1) Obtaining the polished rod position signal during one operating cycle of the system, including the upstroke and the downstroke of the rod.

2) Measuring rotor speed (obtaining rotor speed from estimates of frequency converter).

3) Integration of rotor speed signal in order to obtain the rotor angle signal for creation of lookup values table.

4) Application of a limit switch, which resets the estimates of rotor angle to zero every time when the polished reaches its zero position (when it finishes its upstroke).

5) The measured polished rod position is put to accordance with estimated values of rotor angle position to form a lookup table of values.

6) On the output of identification run procedure the set of angle-position values is obtained and further utilized in operational run of the pumping system.

7) Measuring of “no-load” torque $T'_c$ by running the pump with low velocity and with normal operational velocity when polished rod is dismantled from supporting string.

One of the purposes of the identification run is to measure the ratio between rod speed and crank rotational speed, or simply between rod position and crank angle. When the ratio is known, the force applied to rod can be estimated:

$$ F_{rod} = \frac{\omega_{rotor}}{\chi_{rod}(t) - \chi_{rod}(t-\tau)} (T_c - T'_c) $$ \tag{2}

The integration of the rotational speed estimate allows obtaining estimate of rotor angle. In addition it can be mentioned that the angle values of rotor are different from the crank angle values by gearbox ratio. Which gives us

$$ \begin{align*}
\int_{t_0}^{t_1} w_{crank} dt &= \theta_{crank}(t_1) - \theta_{crank}(t_0) \\
\int_{t_0}^{t_1} w_{rotor} dt &= \theta_{rotor}(t_1) - \theta_{rotor}(t_0)
\end{align*} $$ \tag{3}

where $\theta_{crank}$ is an absolute angle of crank from the limit switch; $\theta_{rotor}$ is an absolute angle of rotor from the limit switch. $t = 0$ refers to the time of the limit switch triggering.

Rod position information in the identification run can be obtained in two ways: it can be provided by the measurement or it can be generated based on known stroke length of the pumping system, a limit switch information and a sinusoidal fitting. If sinusoidal fitting is used, no extra measurement hardware is needed in identification phase but a same limit switch used during operational run triggers a one phase in fitting. Due to known angle value when the limit switch takes place every round it is possible to derive a formula for obtaining sinusoidal signal of amplitude that equals rod movement length $A_{stroke}$. The position of rod can be calculated using

$$ x = \frac{A_{stroke}}{2} \left( 1 + \sin \left( \frac{w_{rotor} dt}{\theta_{2\pi}} \cdot 2\pi - \frac{\pi}{2} \right) \right) $$ \tag{4}

where $\theta_{2\pi}$ is the integral of rotational speed of rotor of motor during one cycle or in other words between two occurrences of the limit switch triggering. Of course, if the geometry does not guarantee sinusoidal speed of rod with constant crank rotational velocity, then position measurement is needed during identification run.

The block diagrams of identification run and operational run are presented in Fig.5

Operational run. The procedure of the operational run can be expressed in next steps:

1) Measuring the rotor speed (obtaining the rotor speed from the frequency converter) and application of a limit switch, which resets the values of rotor angle to zero, when the rod reaches the zero position.

2) Integration of obtained rotor speed in order to get the rotor angle value at any moment.

3) Comparing current value of rotor angle to the corresponding value in lookup table, which was produced during the ID run.

4) After rotor angle and corresponding position of the polished rod at certain point in time are known calculate rotational speed of a crank and polished rod, using eg. direct Euler model of derivative as presented in (2). It is made this way to avoid accumulation of errors from using direct derivatives.

5) Creation of ratio between the rotational speed of crank and rod velocity for further calculation of load;

6) Obtaining overall torque estimates, which includes counter-balance torque component from ID-run and electrical torque component from frequency converter estimates.

7) Multiplication of ratio and overall torque gives resulting load, that polished rod undergoes during operation.

8) Creation of surface force plots by means of estimated rod load and obtained position values.

---

Fig. 5. Scheme of identification run and operational run.
IV. TEST RESULTS

The identification run based surface dynamometer card formation was tested by executing identification runs and operational runs with a simulation model and estimated surface plots using (2) and (3) were compared with the force as a function plot directly produced by a simulation model. One of the results is illustrated in Fig. 6.

![Dynamometer card comparison](image)

Fig. 6. Dynamometer card comparison.

The resulting curve from operational run fits the original one in terms of covered area (work) with accuracy of 99%, and negligible error of less than 2% in force. However these values were obtained suggesting that frequency converter estimates are accurate. The accuracy of frequency converter estimates of induction-motor-driven systems were measured by Ahonen [9]. He concluded that relative errors of the estimates are quite low for all three investigated parameters: 0,2% for rotational speed, 2,1% for shaft torque and 2,1% for shaft power. This error directly increases the uncertainty of the surface plot. However, if the estimation errors are expected to be non-correlating, not more than 3%. The gearbox and joint friction, on the other hand are taken into account already in identification run as a part of “no-load” torque and the error to the force estimate is only due to variation of these friction forces.

V. CONCLUSIONS

There are few possible options for creation of dynamometer cards nowadays. Most of these methods employ quite complicated instrumentations and devices for recording load values applied to the polished rod and obtaining the rod position signal. In this paper, a novel method of surface dynamometer card plotting was presented. This method utilizes torque and rotor rotational speed estimates obtained from the frequency converter and the identified correspondence between torque and load for calculation of load, which polished rod undergoes. The only measurement device that has to be added to pump control is a limit switch. A calculation of polished rod force can be executed in frequency converter or in automation device such as high performance PLC.

REFERENCES