University of Miskolc

Sucker Rod Pumping Analysis Based on Measured Electrical Parameters

New scientific achievements of PhD Thesis

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1   INTRODUCTION

Sucker rod pumping is the leading artificial lifting method in the world. More than 75% of the world's artificial lifted wells are operated using beam pump units (SPE, 2015.). The popularity of the system is not new because ever since artificial lift exists the sucker rod pumping system has been the most widely used method in the history (Beckwith, 2014.). Rod pumping is a mature and well-known production method and the long history of rod pumping provided enough time for petroleum (and other mechanical) engineers to invent and optimize the technology. However, there are always new ways to improve the existing system. This Thesis is about a new approach to improve rod pumping supervision techniques. The research conducted combines electrical and petroleum engineering aspects to develop new methods for rod pump analysis.

1.1   RESEARCH GOAL AND RESEARCH CONDUCTED

Previous authors (Gibbs & Miller, 1997.) suggested to perform research in the electrical motor – sucker rod pumping system. The research direction was clear from the beginning based on the author's previous experience: to investigate the sucker rod pumping system from the motor's view.

The work has started in 2012 with literature research. The aims and goals were determined in that period of the investigation. It was clear from the beginning that there is no measurement system available on the market that could fit the research budget and the needed functions. So, the measurement system hardware development was started in the early stages of the scientific work parallel to the basic theoretical research.

The electrical motors used in sucker rod pumping service were analyzed first and the available solutions for motor modeling were exposed. The special motors used in the petroleum industry and the lack of information about the motors resulted in the improvement of flexible motor equivalent circuit parameter determination solutions. The flexibility of the optimization procedures played an important role because the data on the motors available in existing oil fields is greatly limited. New parameter determination software was coded and tested by the author based on the CPSO-S optimization algorithm. The improved flexible system can be used to produce the

motor's appropriate characteristics. Surprisingly, the research gave a new, simple motor efficiency correlation for NEMA D or high-slip motors. Such findings were not expected before, but the developed empirical correlation gives a good opportunity to extend the sucker rod pumping efficiency calculations into new dimensions.

The efficiency of the sucker rod pumping system is normally described using dynamometer cards. The input data is normally the measured polished rod load and any needed information should be determined using the pumping unit geometry and manufacturer data. The torque analysis is a crucial task of the analysis because it gives information about the counterbalancing efficiency in the system. The available solutions were tested to check if they remained a good selection as well when the torque calculation direction is inversed i.e. the different torque components are inferred from motor torque.

The self-developed measurement system with the software development was a definite section of the research; the system can be seen in Figure 1. The data processing software had to be fitted to the given problem and finally a system was developed which was able to make the necessary measurements and calculation.

Figure 1. The measurement system's hardware

The final results the inferred dynamometer data were checked with real dynamometer measurements recorded at the same time. The research techniques included all the conventional scientific solutions like:

- literature research to identify the opportunities, then
- theory development and measurement system development to prove the assumptions, and finally
- data validation using conventional techniques.

The scientific achievements were continuously published throughout the life of the research work. The results include:

- newly developed measurement system (hardware selection, Voltage sensor development);
- a new data acquisition and processing algorithm coded by the author and fitted for the given purposes;
- several field measurements that resulted in over 1.5 Gb of raw data;
- a new empirical correlation for high-slip motor's efficiency determination;
- several Matlab programs for existing motor parameter optimization algorithm development;
- new algorithms which are about 1500 lines long.

Finally, the pursued goal, inferring the dynamometer diagram based only on electrical measurements was realized. The research can be followed up in more general to use the methods developed as a daily routine in everyday engineering practice.

2 NEW SCIENTIFIC ACHIEVEMENTS

The new scientific results concentrate on the motor-pumping unit cooperative system.

2.1 THESIS 1.

I developed a new empirical correlation for high-slip motor efficiency determination. The empirical correlation is based on the analysis of 28 different high-slip motor's characteristic curves.

The conventional parameter estimation procedures do not create sufficient results for efficiency determination (Pedra, 2008.). The speed-efficiency characteristics is the most complicated one to achieve because in the speed-efficiency characteristic all losses (including friction losses etc.) should be included which were generally neglected by the equivalent circuit development. So an empirical correlation can work better on speed-efficiency characteristics determination.

The NEMA standard clarifies as a general rule-of-thumb that the higher power induction motors have normally higher efficiency than the smaller ones (NEMA, 2017.). It seems to be straightforward to find a correlation between the efficiency and the motor power. Such a correlation could help generate the full speed-efficiency characteristics based only on the motor's nameplate power and efficiency. The direct comparison of motors having different nominal speed can be misleading. The induction motor's speed-efficiency curve is steep in the nominal range (or between the nominal and synchronous speeds) and a small change in the speed could cause big differences in the efficiency and power as well. So as the nominal slip differs for the different size NEMA D motors the motor's power should be analyzed at a reference speed for all motors. Thus the research methodology was to find a reference speed and reference power for each asynchronous motor at which the correlation can be developed. The speed-power curve of an induction motor is steep and almost linear between the nominal speed and synchronous speed, so it can be approximated using a linear function. If the reference speed is forced to be in that speed range the needed power value can be calculated using simple rational calculation. Experience has shown that in case of 3-pole pair motors and 60 Hz network frequency the reference speed can be set for n=1,150 1/min (so a slip of 0.0417).

The maximal efficiency of high-slip motors can be approximated using the following empirical equation developed in this Thesis:

$$\eta_{max} = 2.6141 \cdot ln(P_{ref}) + 60.567$$

Where:

η_{max}	motor's maximal efficiency
P_{ref}	motor power at the reference speed [W]

Where P_{ref} is the mechanical power of the given motor referenced to a special speed between the nominal speed and the synchronous speed. The average absolute error of the equation was found to be 1.86% on the investigated motors. Table 1. contains the statistical data of the invented correlation.

Table 1. Statistical data of the developed correlation for NEMA D motors' maximal efficiency in case of the investigated 28 motors

Average absolute error [efficiency %]	1.86
Standard deviation [efficiency %]	2.26
Median [efficiency %]	-0.01

2.2 THESIS 2.

I developed a new method to determine the full speed-efficiency characteristics of electric motors. The method is based on using of the empirical correlation presented in Chapter 2.1. Efficiency approximation using empirical correlation is important because the widely used parameter estimation algorithms (Pedra, 2008.) unfortunately cannot create a reliable one especially not for high slip motors.

The maximal efficiency value can be used to develop the full speed-efficiency characteristics approximating the first section (for lower speeds than the nominal speed) of the performance curve with a linear line crossing the nameplate data and determining the maximal efficiency speed

The maximal efficiency point-synchronous speed-efficiency region was divided into two subsections. The data analysis has shown that the speed-efficiency characteristics can be reconstructed using a given efficiency reduction. 16% reduction in efficiency was found at a speed of 1164 rpm for the investigated motors and a 50%

reduction at a speed of 1187. The efficiency conditions of high-slip motors used in sucker rod pumping can be approximated using my empirical correlation. Previously only the measurements of those characteristics were available. Table 2. contains the statistical data of the developed method, and Figure 2. shows an example speed-efficiency characteristics.

Table 2. Statistical data of the developed correlation for NEMA D motors' efficiency reduction

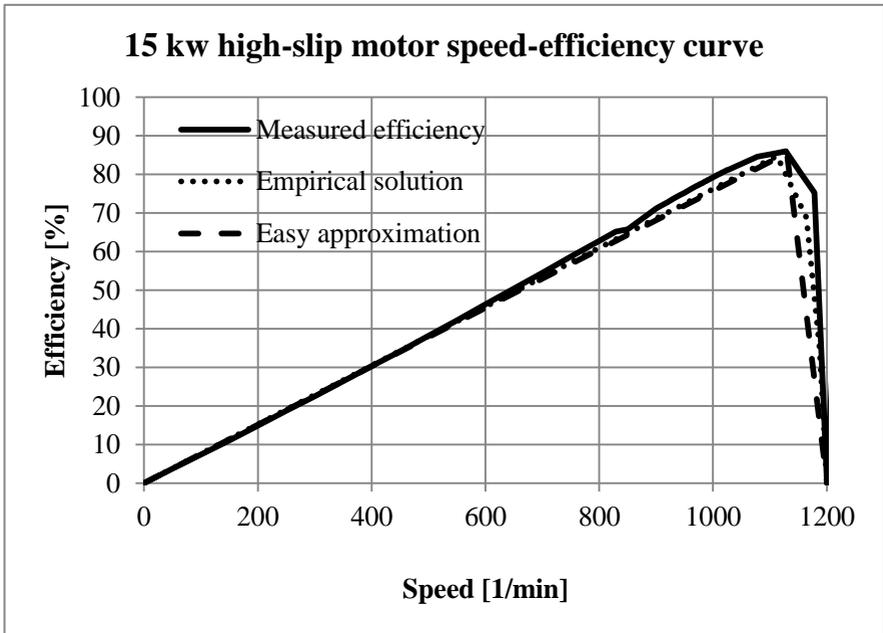| Parameter	16% efficiency reduction point	50% efficiency reduction point
Average absolute error [in RPM]	8.18	3.75
Standard deviation [in RPM]	11.4	4.67
Median [RPM]	1164.37	1187.83

Figure 2. 15 kW high-slip induction motor speed-efficiency characteristics

2.3 THESIS 3.

A new method was developed for the determination of the partial efficiencies of sucker rod pumping system that is more accurate than previous models (Echometer, 2017.). The method is based on the newly developed speed-efficiency motor characteristics. The speed-torque characteristics are presented using the motor model and parameter estimation described in the Thesis, in Chapter 2.4.1. Then an efficiency value is assigned to all available measured results over the pumping cycle and the motor's average overall efficiency in one pumping cycle can be determined. Using my new method, all partial efficiencies can be accurately computed when the motor's efficiency is calculated for a full period. The flowchart of the method can be seen in Figure 3.

The method produces accurate information about the motor behavior that is normally not analyzed. The importance of proper motor sizing was firstly recognized only by (Kilgore & Tripp, 1991.) based on their system efficiency measurements. The method presented is easier to use – there is no need to measure the induction motors characteristics – and faster as well.
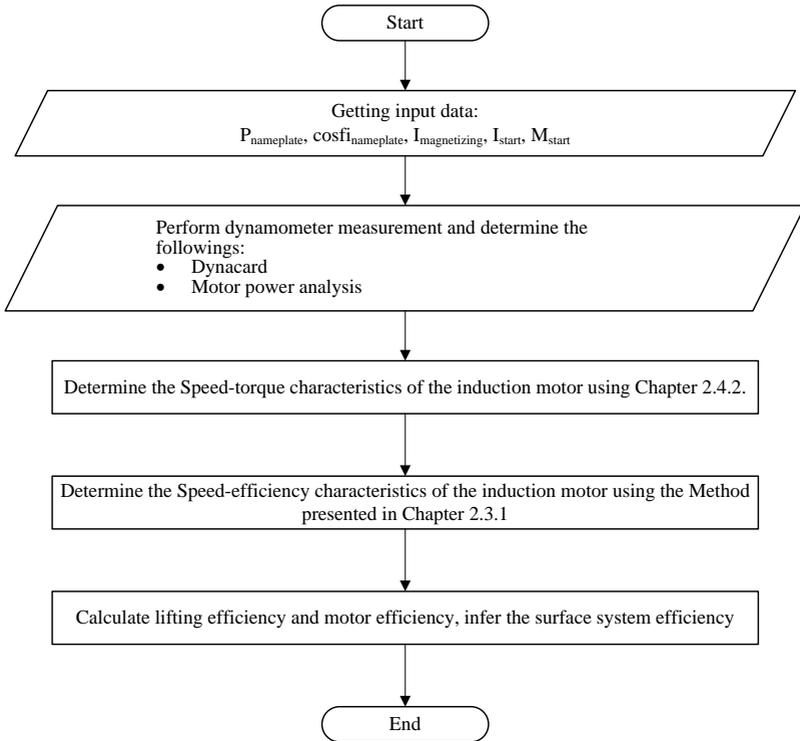
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                    │    Start     │
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    │            Getting input data:                        │
    │  P_nameplate, cosfi_nameplate, I_magnetizing,         │
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    │  Perform dynamometer measurement and determine the   │
    │  followings:                                          │
    │    • Dynacard                                         │
    │    • Motor power analysis                             │
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    ┌─────────────────────────────────────────────────────┐
    │ Determine the Speed-torque characteristics of the    │
    │ induction motor using Chapter 2.4.2.                  │
    └──────────────────────┬──────────────────────────────┘
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    ┌─────────────────────────────────────────────────────┐
    │ Determine the Speed-efficiency characteristics of    │
    │ the induction motor using the Method presented in    │
    │ Chapter 2.3.1                                         │
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    │ Calculate lifting efficiency and motor efficiency,   │
    │ infer the surface system efficiency                  │
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Figure 3 Flowchart of partial efficiency determination of sucker rod pumping system

2.4   THESIS 4.

I proved that similar parameter estimation methods which are conventionally used for NEMA-B motor parameter estimations can be modified to model the high-slip or NEMA-D motors. I proved that the magnetizing current can be used as a strong constraint instead of the breakdown torque in such calculations.

The parameter estimation procedure for NEMA D or high slip motors is different than for conventional industry-standard NEMA B motors. The equivalent circuit parameter estimators use different input parameters to identify the physical values of the given basic electric elements (Lindenmeyer, et al., 2001.). The breakdown torque plays an important role in those parameter determination procedures (Pedra, 2008.) however NEMA D or high-slip motors do not always have breakdown torque. The breakdown torque – as an important optimization limit - can

be replaced by magnetizing current for conventional numerical optimization methods. The use of magnetizing current makes it possible to build a well-defined numerical problem for the parameter estimation optimization procedure for the double cage motor model. Figure 4. shows the double cage motor model of asynchronous machines.
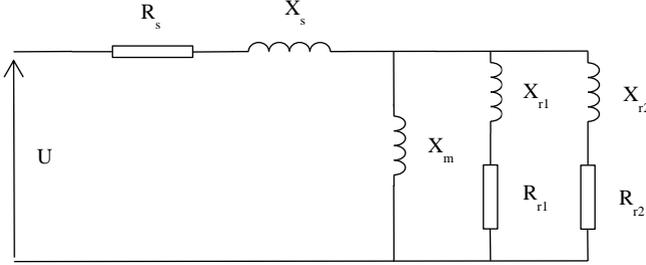

Figure 4. Double-cage equivalent circuit of induction motors (Pedra, 2008.)

The following objective function minimized by the Matlab fsolve algorithm can produce reliable speed-torque characteristics:

$$F(R_{r1}, R_{r2}, X_m, X_s, X_{r1}, s) = \left\{ \begin{array}{c} \dfrac{P_{nameplate} - P_{calculated_{sfl}}}{P_{nameplate}} \\ \dfrac{Q_{nameplate} - Q_{calculated_{sfl}}}{Q_{nameplate}} \\ \dfrac{I_{magnetizing} - I_{calculated_{magnetizing}}}{I_{magnetizing}} \\ \dfrac{I_{start} - I_{calculated_{start}}}{I_{magnetizing}} \\ \dfrac{M_{start} - M_{calculated_{start}}}{M_{start}} \end{array} \right\} = 0$$

2.5 THESIS 5.

I created a new, CPSO-S-based algorithm for high-slip or NEMA-D motor parameter estimation. The optimization algorithm is based on the CPSO-S solution of (van den Bergh, 2001.). The algorithm is strong and robust, and I proved that it can

successfully be used for general prediction of the asynchronous motor's speed-torque and speed-current characteristics. The flowchart of the method is shown in Figure 5. The algorithm uses the same induction motor equivalent circuit shown in the previous thesis.
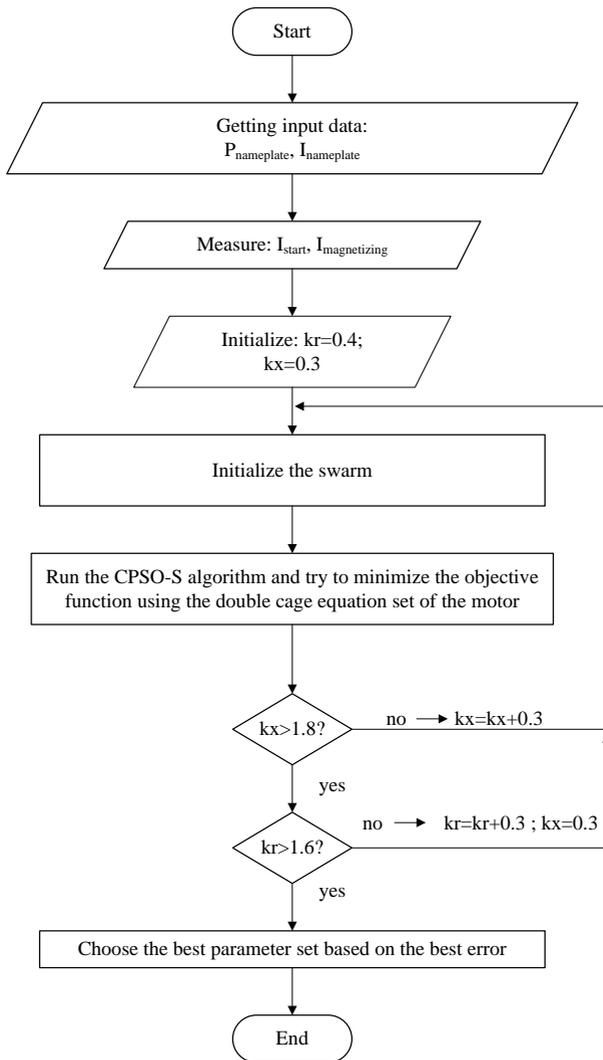

Figure 5. CPSO-S based high-slip motor parameter estimation flowchart

2.6 THESIS 6.

I implemented the available torque calculation methods (Takács, et al., 2016.) for reverse torque calculation. The torque conditions in the sucker rod pumping system are calculated normally from the polished rod and the different gearbox-torque components are determined for system analysis. I proved that the calculation's direction can be changed, and the polished rod torque can be determined. The previous attempts to calculate into the inverse direction neglected the last 30-35° crankshaft rotation angles at the end and start of strokes causing only ~240° useful information. The reason behind this phenomenon is the torque factor: it is a denominator in the calculation thus the accuracy is limited at the end of the strokes. My procedures can calculate over 330-340°crankshaft angles so the accuracy is highly increased.

2.7 THESIS 7.

I proved that the dynamometer diagram can be inferred using my newly invented accurate motor model, the reversed torque calculation procedure and numerical calculations presented in this thesis. The inferred dynamometer cards are ready for further applications like evaluation and pumping system failure detection.
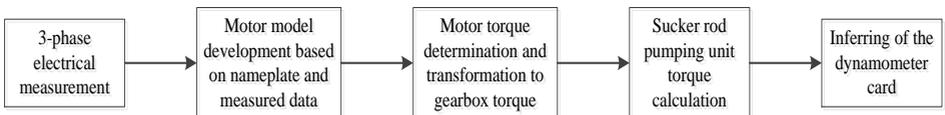

Figure 6. Proposed model milestones

The inferred dynamometer diagram is shown in Figure 7. The diagram's shape is identical to the conventionally measured one and the magnitudes of loads tend to the measured values as well. However, the magnitudes are not as accurate as the shape.
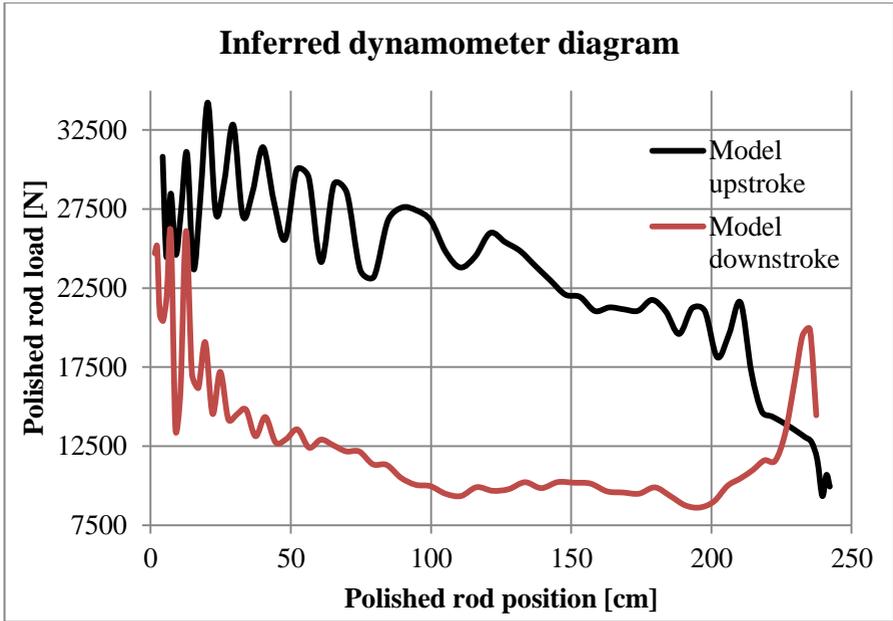
Figure 7. Inferred dynamometer diagram

2.8   THESIS 8.

The dynamometer diagram based on basic electrical measurements has fluctuating curves which makes their evaluation complicated. I suggested to use a filtering algorithm (Fourier-series) to smooth the curves and the result is a much better understandable dynamometer diagram. All new scientific achievements and methods presented in this thesis make it possible to build dynamometer measurement systems based only on electrical measurements. The use of this approach opens new opportunities in stripper well supervision.
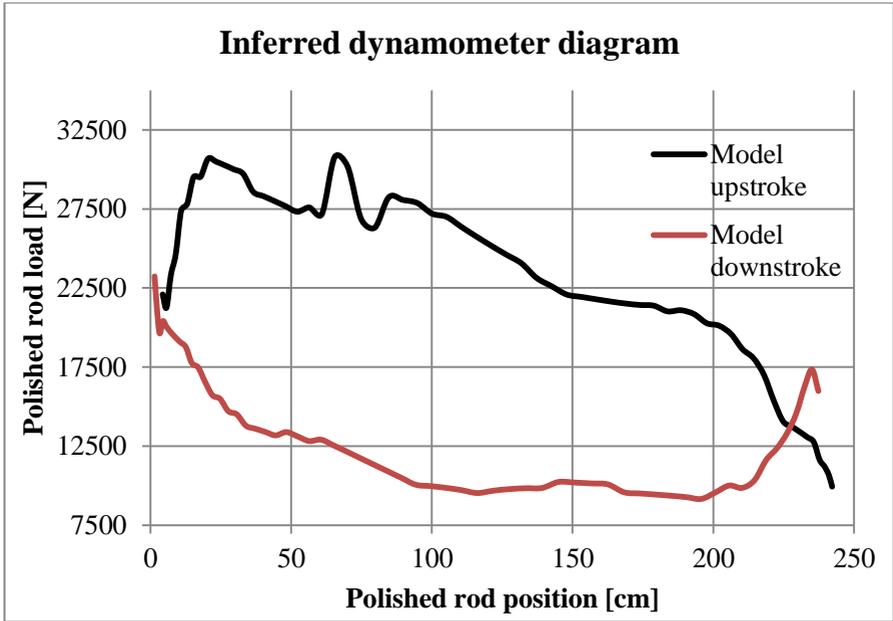
Figure 8. Inferred, smoothed dynamometer diagram

3   SUMMARY AND POTENTIAL FURTHER RESEARCH DIRECTIONS

Rod pumping is a mature and well-known production method and the long history of rod pumping provided enough time for petroleum (and other mechanical) engineers to invent and optimize the technology. However, there are always new ways to improve the existing system. In this Thesis, the sucker rod pumping system was analyzed from a quite new point of view: from the motor's side. The energy flow in the system flows from the motor hence it is straightforward to find methods for describing the system from that direction. The conventional methods use dynamometer measurements and the system analysis is based on dynamometer card analysis. This Thesis presents solutions to describe the pumping unit's actual loads started from the motor's power source.

The research was done to prove that the system can be analyzed based only on electrical measurements. A comprehensive literature review in the field of asynchronous modeling was done first and new scientific achievements were presented. I invented a new empirical method for NEMA-D or high-slip motor efficiency prediction over the full speed range. I implemented the conventional induction motor parameter estimation methods for high-slip motors and showed that the conventional limiting factor, the breakdown torque can be replaced using a better limiting factor which fits to sucker rod pumping system measurements. I coded a new, robust algorithm for high slip motors and showed how to apply the algorithm for parameter estimation procedures.

The research's main goal was achieved, and dynamometer diagrams were developed based on electrical measurements only. The dynamometer diagram's shape is identical to the conventionally measured ones and the amplitude of the loads follows the measurements.

The presented solutions can be improved to produce the dynamometer cards without conventional measurements. The next steps are to build a user-friendly software system which allows the user to easily produce the needed data. All methods presented in the Thesis can be included in only one software and the method can be implemented in the everyday engineering practice.

The number of tested wells should be increased and a uniform pumping unit database should be created where all pumping units – used in Hungary – all necessary data should be summarized. So the real field application should start.

4   PUBLICATIONS PRESENTED IN THE THESIS' TOPIC

4.1   WRITTEN PUBLICATIONS

Á. Koncz: Simple calculation model for performance curves of electric motors used in sucker rod pumping service Doktoranduszok Fóruma: Műszaki Földtudományi Kar section edition. Miskolc, Hungary, 07.10.2013., pp. 51-56.

Á. Koncz: An Improved Prime Mover Parameter Estimation Process For Sucker Rod Pumping Units microCAD 2014, A1 section ENVIRONMENTAL Science: SUSTAINABLE NATIONAL RESOURCES MANAGEMENT SYMPOSIUM. Miskolc, Hungary, 10-11st 10.2014. University of Miskolc, 2014. Paper A/2-9. 8 p. ISBN: 978-963-358-051-6

Á. Koncz: A himbás-rudazatos mélyszivattyús berendezés részhatásfokainak vizsgálata Doktoranduszok Fóruma: Műszaki Földtudományi Kar section edition Miskolc, Hungary, 19-21st 10.2014. pp. 22-27.

G. Takács, L. Kis, Á. Koncz: The calculation of gearbox torque components on sucker-rod pumping units using dynamometer card data JOURNAL OF PETROLEUM EXPLORATION AND PRODUCTION TECHNOLOGIES 172: Paper 10.1007/s13202-015-0172-z. 10 p. (2015)

G. Takács, L. Kis, Á. Koncz: The Use of Dynamometer Data for Calculating the Torsional Load on Sucker-Rod Pumping Units Proceedings of the 62nd Southwestern Petroleum Short Course. Lubbock, USA, 20-23rd 04. 2015.pp. 176-183.

Á. Koncz: Innovative developments in sucker rod pumped well analysis The Publications of the MultiScience - XXIX. microCAD International Multidisciplinary Scientific Conference. Miskolc, Hungary, 09-10th 04.2015. University of Miskolc, 2015. Paper A7. ISBN:978-963-358-061-5

Á. Koncz: Difficulties of a low cost measurement system development for sucker rod pumped well analysis MŰSZAKI FÖLDTUDOMÁNYI KÖZLEMÉNYEK 85:(1) University of Miskolc, 2016.

4.2 CONFERENCE PRESENTATIONS, POSTERS

Á. Koncz: Efficiency analysis of sucker rod pumping unit using new techniques East Meets West International Student Petroleum Congress & Career Expo. Kraków, Poland, 22-24th 04.2015. poster

Á. Koncz: Instrument development for sucker rod pumped well analysis, SPE European Regional Student Paper Contest, 2nd of June 2015. Budapest

Á. Koncz: Improvements in stripper well supervision, 31st International Oil and Gas Conference and Exhibition, 5-6th October 2017, Siófok

Á. Koncz: Simple calculation model for performance curves of electric motors used in sucker rod pumping service Doktoranduszok Fóruma Miskolc, Hungary, 07.10.2013.

Á. Koncz: An Improved Prime Mover Parameter Estimation Process For Sucker Rod Pumping Units microCAD 2014, A1 section ENVIRONMENTAL Science: SUSTAINABLE NATIONAL RESOURCES MANAGEMENT SYMPOSIUM. Miskolc, Hungary, 10-11st 10.2014.

Á. Koncz: A himbás-rudazatos mélyszivattyús berendezés részhatásfokainak vizsgálata Doktoranduszok Fóruma Miskolc, Hungary, 19-21st 10.2014.

Á. Koncz: Innovative developments in sucker rod pumped well analysis The Publications of the MultiScience - XXIX. microCAD International Multidisciplinary Scientific Conference. Miskolc, Hungary, 09-10th 04.2015.

Á. Koncz: Difficulties of a low cost measurement system development for sucker rod pumped well analysis Innovative technologies in the fluid production conference, 17th 06. 2015. Miskolc, Hungary

5 MOST IMPORTANT REFERENCES RELATED TO THE THESIS

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