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We consider a new notion of controllability for distributed parameter systems. It is formulated as the correctness in sense of A. Tikhonov for inverse reflection of the state space into the space of controls. An algorithm is proposed for implementing such controllability by optimization methods with regularization. There are considered an example of implementation of controllability for a quasilinear hyperbolic system relative to a given objective functional.

Key words: *controllability, DPS, regularization.*

Отримано: 16.02.2012

UDC 519.6

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SEARCH FOR ADAPTIVE METHODS IMMUNIZING FROM HIGH-NOISE, APPLICATION ON OIL INDUSTRY POWER COMPLEXES CONTROL TELEMETRY MODEL

Here in the paper, an analog signal processing implementation was searched for the detection the most efficient adaptive noise cancellation filters among dozens of recognized ones for telemetry control systems of oil industry electrical submersible pump under severe noisily conditions.

Key words: *signal, noise, adaptive methods, oil industry, submersible pump, communication-telemetry channels.*

1. INTRODUCTION

More than thousand switchboards of Electrosubmersible Pump (ESP) under different trademarks are running on the oil fields of Russia and CIS (USSR), representing a wide spectrum of varied equipment, which are working on the problems of the oil production and its optimization. Not only simple devices of ESP motor control, but complicated electronic complex for

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putting into an oil well for operating duty. The main problem is to preset supporting parameters during oil production at several well clusters simultaneously. At the same time the ESP operating information can be read out to any computer, to data transfer and storage micro-unit; it can be transferred to a telemetric system by a special port or by radio channel to a dispatcher control board for further analysis of pump unit and database supporting. Ideology of the equipments consists in integrated approach towards automation and optimization of the oil production and in intension to produce oil production equipment to compare the well data with the samples in the world. Submersible telemetry system which usually allows getting information on pump unit's intake pressure, temperature and most important for submersible motor stator coil — its insulation resistance for the successful exploitation of the oil complexes, in neighborhood of different type of heavy electromagnetic noise: random, pulsing, harmonic and so on [1—3].

The change from analogue to digital communication techniques is going fast in almost all technical fields. The emission limits for radiated and conducted disturbances as prescribed in international standards are based on their possible impact on analogue telemetry. When the existing analogue telemetry technologies are substituted with digital technologies, interference could occur even though all equipment complies.

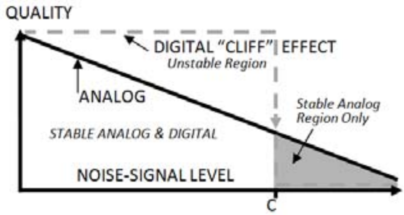


Fig. 1. *Digital cliff unlike analogue transmissions, which experience gradual degradation; digital transmissions can experience sudden degradation*

Increasing disturbance levels with corrupted the analog telemetry result in an increasing noise level, but often still "audible" or control still reliable. Digital telemetry technology is much better in suppressing disturbances up to a certain level. With increasing disturbances level, the analogue signal will be remain low, but audible. However beyond a certain disturbance level, the digital telemetry and control stops abruptly. This, the so called "digital cliff" at point *C*, shown in Fig. 1, makes it more complicated with digital telemetry to know the "headroom", the disturbance critical level, before the digital telemetry and control unexpectedly stops. The analogue signal after point *C* will be lower, but still audible and control system still reliable.

Here, a signal processing implementation is studding for the detection the most efficient adaptive noise cancellation filters among dozens of well known ones for telemetry control of oil industry power complexes under severe noisily conditions. A useful approach to this filter-optimization problem is to minimize the mean square value of the error that defines as the difference between some desired signal and the filter actual output.

There are many noise cancellation methods and their applications in industrial, civil, military, power systems telemetry and control equipments apparatus. But success of these noise cancellation methods and filters extremely depends on the noise factor (signal/noise ratio) and also on the control signal character under consideration: close to random, exponential, voice, sinusoidal, and so on.

Most of the publication in the field of noise cancellation methods and their applications deal with rather big signal/noise ratio (that is — noise $<<$ signal) and show good achievements for cell phones, radio/TV technique, tape recorders, apparatus for people with hearing loss, concert hall equipments.

There are some cases when the signal/noise ratio is around 1 (noise $\approx$ signal) — command-and-control telemetry systems between centers and operators of winches, tractors, lorries, textile factory workshops, compressors workshops, metro, railways, controlled AC/DC drivers, as in the submersible pump telemetry case, and so on. Not all the noise cancellation methods show good results especially in the real-time noise filtering and need a special study to find the best filtering method for the engine particular noise case.

The special cases are some severe ones, which deals with the signal/noise ratios $\approx 0.2 \div 0.1$ (noise $>\approx 5 \div 10$ higher than useful signal) — military command-and-control telemetry between centers, jet pilots and jets service teams of aircraft carriers battleships; in different metallurgical and especially arc furnaces telemetry between dispatcher and operators team, and so on. There is understandable shortage and vacuum of any information and publications not only in military fields, but in the modern technological companies, too.

A similar situation of low signal/noise ratio is presented in the field of the power systems, powerful controlled electrical machines and high voltage power electronics control-feedback signals. Any wrong interpretation of the signals due to high noise can bring to unexpected accidents or malefaction of big power system or heave duty electromechanical installation.

Due to mentioned the "digital cliff", powerful electric machines control fundamental manufactures still have preferences to work with analog equipments and signals. The paper deals with the oil industry ESP motor, in particularly with its control, which is working close to, or neighborhood to different heavy "jam" of electromagnetic noises: random, pulsing, harmonic and so on, that overwhelm (engulf) the useful signals.

As it will be shown, for the case of ESP only a few of the *MATLAB* noise cancellation methods — *Adaptive Filtering Methods* — present real-time noise filtering good results for the mentioned ESP severe noise cases. Every other apparatus case needs a special study to find the best filtering method for the particular equipment [4—6].

2. THE OIL INDUSTRY Electrical Submersible PUMPS (ESP)

Electrical Submersible Pump (ESP) induction motors are applied as a drive for electrical centrifugal oil deep-well pumps. They are usually putted on the market in diameters dimensional groups: 103, 117, 130 and 180 mm, and power from 12 to 500 kW, even more. There are more than 60 different modern types of the ESP of various capacities, which allow picking up the optimal motor-pump to get maximum possible efficiency for the particular oil field [7].

The techniques manufactures have to keep the highest quality and performance reliability of the ESP motors because of:

1. Equipment often has to work in inaccessible places or faraway from their technical service centers (the Arctic tundra locations, hot or cold deserts, the sea jack-up platforms, real or artificial islands on the surface of swamps or lakes, and so on). In some cases there are high requirements for dependability and survivability of the machines, since the equipment often may be serviced only once a year by a mobile team of technicians (using helicopters, ships or all-terrain track-type vehicles, and so on).
2. Any unexpected temporary equipment outage even for 10-20 minutes because of any reason (mechanical, electrical, electronic, and so on.) can lead to an array of problems for extended periods, especially during the winter season – frozen well liquid in output pipes, lubricating oil, and so on.
3. In the so-called reach of sand (or clay) wells scenario can be even worse — any stoppage can be dramatic — sand may settle gradually down by gravity and block the ESP subterranean reverse valve at the bottom of the well. It makes automatic “self-start” of the pump more difficult and longer or even impossible, which in the Winter may lead to a forced outage up to the next service team visit (up to next Spring or even Summer in Siberia, Canada, Alaska, and so on.). And again it requires an expensive and complicated lift of the pump exploitation column, cleaning the ESP pipes and reverse valve from the sand and so on.

To raise working survivability and to keep the highest quality, some ESP manufactures apply new techniques and measures, for example:

1. Stator is made of with the closed groove that raises cleanliness of the motor internal room of the engine, allows to apply successfully in the winding grooves firm isolation in the tube form.
2. The electric motor rotor has got original bearings, having mechanical fixing from any cranking.
3. Application of special modern electro-technical materials allows maintaining ESP motors at temperature strata liquids to 120°C, with super-heat-resistant materials — up to 160°C.
4. 100% of ESP’s have to be disassembled up to all elements to be checked, and, after all these, the ESP parts are thoroughly assembled

back and ESP must be carefully tested in the conditions closed to real, including with heating ESP up to working temperatures as in a well.

After 1-hour the mentioned check up, the motor winding isolation normal resistance should be not less than 10 MOhm. The control of the normally working motor resistance of the system “transformer-cable-ESP” isolation must be not less ~350 kOhm. This isolation resistance usually decay very slowly during months (as a rule — exponentially) from ~350 kOm to ~30 kOhm — not less. The decaying process can take several months (even years), but the resistance less than ~30 kOhm is potentially risky and can be a provocateur of any heavy internal short circuit in the stator winding and destroy some its section. That means — it will be an expensive and complicated lift of the exploitation column, removal of the burned motor, cleaning from the burned section on the test bench and rewiring it. Then again: after disassembling each component, quality of each must be supervised, the electrical motor must be tested at workshop station and so on. Thus ESP motor is the most sensitive and very expensive element of the ESP and control of its working motor insulation resistance must be very strong and effective [8; 9].

2.1. Structure Cart of the ESP Unit Equipment Complex

The electrical submersible oil pump (ESP) is usually fed from 400 V network and consume current is in-between 160 — 1200 A. The ESP consist of the following main parts: switchboard, step-up transformer, variable speed driver (VSD) convertor with build-in electronic active filter (FSA) and electrical submersible oil pump (ESP).

ESP is spanned by very omnibus telemetry. Among other ESP parameters, only the special ESP electric motor telemetry controls the following motors main parameters: R-insulation (resistance) and t_o — temperature (^oC) of the ESP motor cooling oil; the ESP motor axial and radial vibrations**:** and also some oil pump technological parameters like formation liquid t_p — temperature (^oC) on the pump discharge, P-pressure on the pump discharge and formation of the pumping liquid flow and so on.

As it was mention, the ESP electric motors are very sensitive to their regime parameters. It is the cooling oil filled motor (seldom distill water), separated by strong gasket from pumping liquid, which is row oil mixed with salty underground water. But the mentioned above sand or clay in the underground water very slowly destroy the gasket, so this salty aggressive water may gradually enter into the motor cooling oil and to spoil slowly its electrical insulation (resistance) from normal at the beginning — more than 500 kOhm, — to risky one less than 30 kOhm (in bad case — exponentially throughout one-three or more months).

ESP electrical motors are the extremely expensive parts of any ESP. To run the ESP under risky conditions is dangerous. Therefore down-hole submersible telemetry unit (system) must control its electrical resistance in real time very cautionly. It should be mentioned here, that usually telemetry input/output signals of down-hole unit are around standards: 0 — 10 V or 4 — 20 mA.

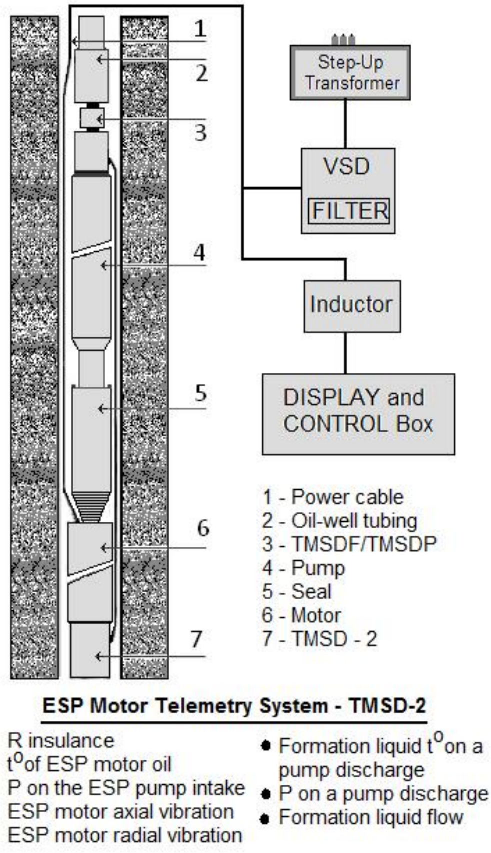


Fig. 2. *Structure cart of the ESP unit equipment complex: step-up transformer, display/control and inductor boxes, VSD convertor with build-in FSA, down-hole unit submersible telemetry system (TMSD Flow/TMSD Pressure or TMSD-2)*

Telemetry signals are sent up from down-hole unit to display/control box by means of the same powerful motors supply cable between the ESP motor and the variable speed driver PWM convertor with a build-in electronic active filter (as it is shown in Fig. 2). The PWM convertor waveform distortion factors of output voltage and current correspondingly are: without filter — $K_{UOutput} = 43.73\%$, $K_{IOutput} = 6.75\%$, and after filter applied — $K_{UOutput} = 2.55\%$, $K_{IOutput} = 0.58\%$ [3].

Theoretically, harmonics may affect such equipment in several ways, mainly:

- Notches in the sinusoidal voltage cause malfunction due to misfiring thyristor;
- Voltage harmonics may cause ignition beyond the required time;
- A resonance in the presence of different types of equipment can lead to overstrain and machines shacking.

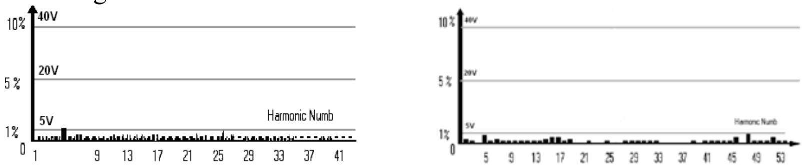
For ESP motors these waveform distortion factors of the output voltage and current are not affect the ESP motor-pump performance activity. But voltage and current residual harmonics may be higher than some of the telemetry signals during some regimes and may confuse the display/control system and bring to malfunction the equipment of the ESP (data errors, failures, even short circuits in the motor and so on). Interference induction and stray pick-up may be found comparable or even higher, than the useful telemetry system signals at the moment. The harmonics in power circuits make noises in the chain of the telemetry and control lines. The small noise leads to a certain discomfort, but with its increase the transmitted information misinterpretation may appear, or it will lose and in the limiting case the telemetry becomes impossible in total. In the case of any technological changes in electrical and telemetry there should be considered the impact on telemetry lines and, as an importance, on the controlled equipment.

All these regime parameters controlled by ESP telemetry (R-resistance, t_o — temperature of the motor cooling oil, motor vibrations, and pump technological parameters) are very important for the ESP normal exploitation, but from the very sensitive ESP electrical motor viewpoint, — the most important parameter of ESP motor is the resistance R of the its cooling oil, which depending on the sand factor which may provocative the pumping salty underground liquid leak throw the casket into the motor. So, the resistance R of the cooling oil start slowly decrease exponentially throughout three-five months or even more, from normal one — more than 500 kOhm, — to risky one — fewer than 30 kOhm, — and its telemetry voltage signal proportionally slowly decrease from 10 V to 0.6 V. This signal too, as all ESP telemetry signals, is transmitted from the down-hole unit upward to the display/control box of the ESP using also the same motor feeding powerful cable, which full up by interference induction from currents, internal and external network commutations stray pick-up, VSD convertor powerful PWM pulse interference and residual after filter harmonics, random, casual or incidental noise [10; 11].

So, the paper deals with an attempt to elevate the accuracy in the continuous interpretating of the R-signal from just mentioned above corrupted by jam of interferences, harmonics and noises by the help of modern adaptive methods. Any error in the interpretations of the R-signal may bring to the wrong early prediction of the critically low the R-signal and the unreasonable expensive lift of the ESP for the motor cooling oil removal and its renewal service, or in the worse case of late prediction — to short circuit inside the motor, emergency lift of the ESP for service and more expensive restoration of the motor.

2.2. Interferences and Noises in ESP Telemetry

So, the jam of interferences and noises in all ESP telemetry, which accompanying the useful telemetry signals consist of: electromagnetic interference induction from cable currents, internal and external network commutations stray pick-up, VSD converter powerful pulse intervention, residual after filter harmonics, random, casual or incidental noise and so on. It was analyzed several typical for VSD with PWM converters harmonics spectra for study state regime of ESP and the typical share and fraction of harmonics values after FSA filter are presented for this case [3] as noted below figure:



a) 10-20th and 40-50th current harmonics of ~0.5-1.0% (~2-4A) of I_{Peak} value (374A) of the motor current

b) 10-20th and 40-50th voltage harmonics of ~0.5-1.0% (~3-5V) of the motor voltage V_{Peak} value (496V)

Fig. 3. *The typical share of current (a) and voltage (b) harmonics values of the VSD PWM converter after build-in FSA*

Usually to assess the impact of the various harmonics, it will be used here the coefficient representing harmonics taken with certain weights. Most common are two factors: photometric weighting and C-transfer [12; 13; 14].

3. OBJECTIVE COMPARATIVE EVALUATION OF MATLAB NOISE CANCELLATION ADAPTIVE METHODS

For comparative evaluation of MATLAB noise cancellation (filtering) adaptive methods here applies twice heaver case for the study — voltages of the jam of accompanying harmonics V_H =10 V each (not 3 — 5 V) and random noise V_{RN} = 1V (not 0.1 — 0.5 V). As have mentioned above the controlled useful exponential variable — parameter of the ESP motor cooling oil R-resistance signal is decaying from 10 V to 0.6 V. All presented below MATLAB Adaptive Filtering Methods were one-by-one tested under the mentioned above conditions for R-resistance decreasing exponentially signal, corrupted by the jam of accompanying the useful signal harmonics and noise. Then R-resistance signal is recognized and analyzed [15—18].

3.1. Analyses of Results

Thus, signals types are: exponential, sinusoidal and random. The adaptive filter algorithms were applied to observed value of exponential variable parameter of the ESP motor cooling oil $R(t)$ — resistance signal, corrupted by the jam of accompanying interferences and noises. All methods were tested under mixture of random noise and dominated harmonics for f = 1; 2.5; 5 kHz.

There are two main zones in the presented below result curves:

1. The first zone — filter output signal at the beginning of the filter adoptation time T_{AD} = 3 — 30 days (not very important) wich converge towards to desired exponential $R(t)$ — signal and then continuously controls it till critical point.
2. The second zone — filter output signal at the end of the observing time — three and more monthes (up a years), — till very important critical point, when signal $R(t) \leq 0.6$V, which means that the ESP motor cooling oil resistance less than 30 kOhм — it is extremely risky moment and the ESP must be switched off (from the maintenance instruction). It should be remaind here again that any error in interpretation of the R(t)-signal critical point may bring to wrong unreasonable early expensive lift of the ESP for the motor cooling oil removal and renewal service, or in the worse case of the R(t)-signal critical point late prediction — to short circuit inside the motor, emergency lift of the ESP for service and very expensive restoration of the motor.

Unfortunately characteristic some of the adaptive filter algorithms have shown their very low frequency ripple oscillation (like Sign-error, Sign-data and Sign-sign filters), which may bring additional error in the late or early interpretation of the critical point issue. The less amplitude of this oscillation, the better the adaptive filter algorithm (method). It was recognized as the best — The Normalized LMS FIR filter algorithm adaptfilt.nlms. One of the best approaches to avoid this very low frequency ripple oscillation is to add block of Wavelet filter algorithm into the just mentioned the best adaptive filters algorithms, too. And it was done at the end of study and improved results, too [19—21].

3.2. Matlab Adaptive Filtering Methods And Their Results Analyses

Table 1

Matlab Adaptive Filtering Methods and their results analyses

Type of Adaptive Filter Methods	Harmonics Frequency (kHz)	Remarks
1. The Normalized LMS FIR filter algorithm (adaptfilt.nlms)	1 ; 2.5 ; 5	The Best
2. The Sign-data LMS FIR filter algorithm (adaptfilt.sd)	2.5	Good

Continued table 1

3. The Sign-error LMS FIR filter algorithm (adaptfilt.se)	2.5	Good
4. The Sign-sign LMS FIR filter algorithm (adaptfilt.ss)	2.5	Good
5. The Traditional LMS FIR filter algorithm (adaptfilt.lms)	2.5	Fair
6. The Delayed LMS FIR filter algorithm (adaptfilt.dlms)	2.5	Fair
7. The Adjoint LMS FIR filter algorithm (adaptfilt.adjlms)	2.5	Very Bad
8. The FFT-based Block LMS FIR filter algorithm (adaptfilt.blmsfft)	2.5	Very Bad
9. The Filtered-x LMS FIR filter algorithm (adaptfilt.filtxlms)	2.5	Very Bad
10. The Block LMS FIR adaptive filter algorithm (adaptfilt.blms)	2.5	Very Bad

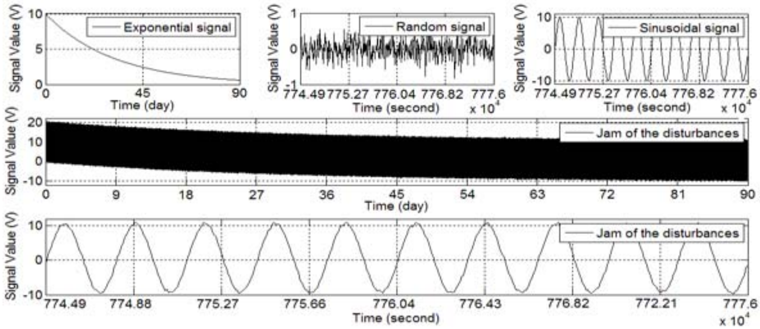


Fig. 4. *Signals: useful exponential, which corrupted by jam of sinusoidal harmonics and random noise*

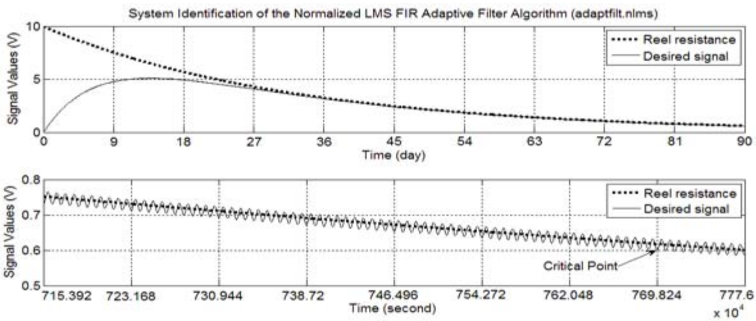


Fig. 5. *The Normalized LMS FIR adaptive filter algorithm adaptfilt.nlms (1 kHz) (The Best)*

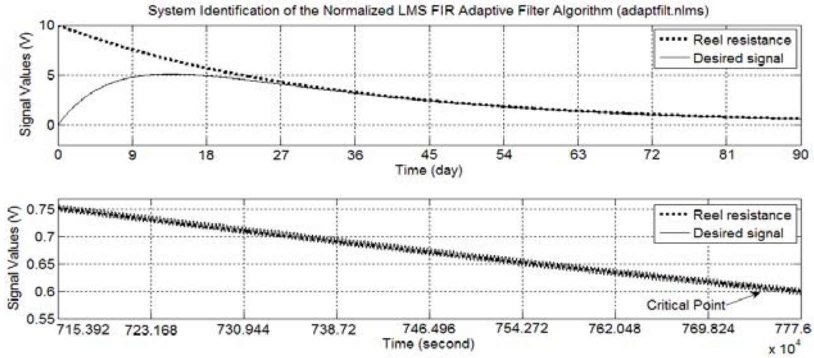


Fig. 6. *The Normalized LMS FIR adaptive filter algorithm adaptfilt.nlms (2.5 kHz) (The Best)*

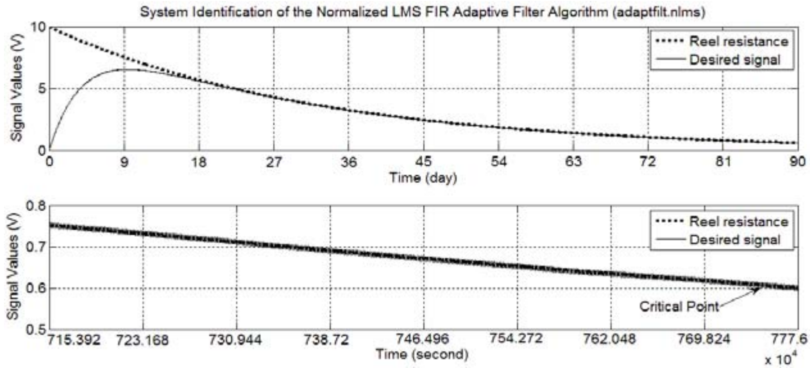


Fig. 7. *The Normalized LMS FIR adaptive filter algorithm adaptfilt.nlms (5 kHz) (The Best)*

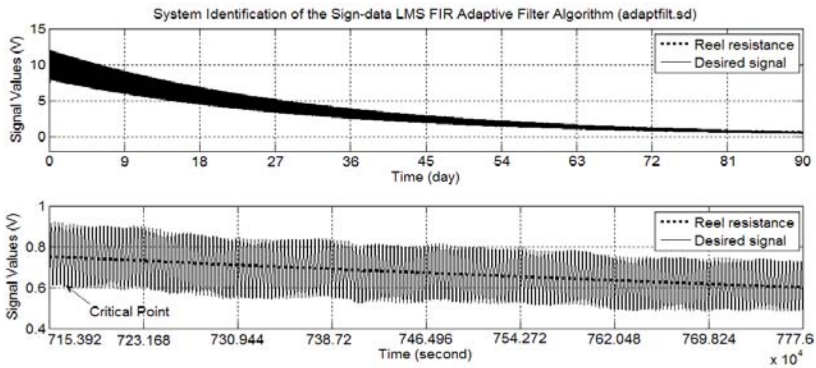


Fig. 8. *The Sign-data LMS FIR adaptive filter algorithm adaptfilt.sd (2.5 kHz) (Very good)*

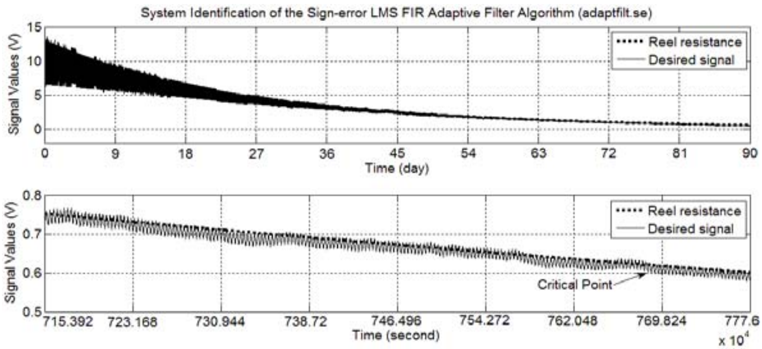


Fig. 9. *The Sign-error LMS FIR adaptive filter algorithm adaptfilt.se (2.5 kHz) (Very good)*

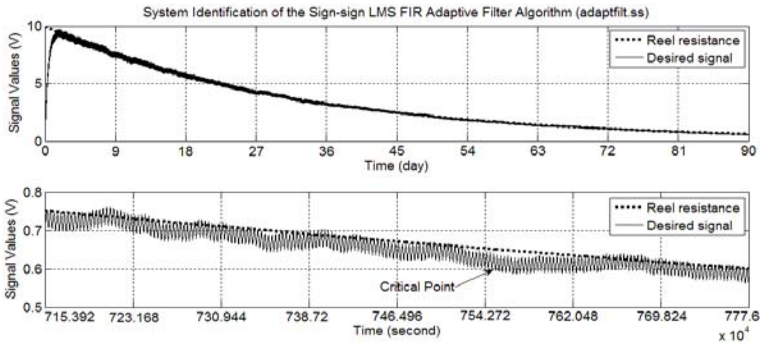


Fig. 10. *The Sign-sign LMS FIR adaptive filter algorithm adaptfilt.ss (2.5 kHz) (Very good)*

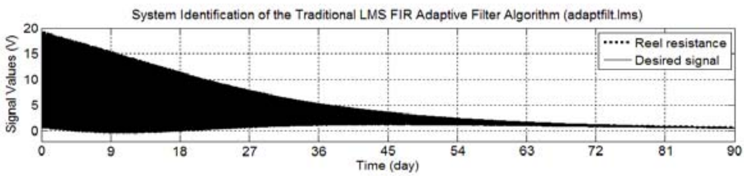


Fig. 11. *The Traditional LMS FIR adaptive filter algorithm adaptfilt.lms (2.5 kHz) (Fair)*

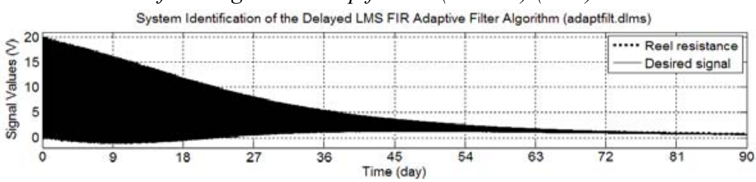


Fig. 12. *The Delayed LMS FIR adaptive filter algorithm adaptfilt.dlms (2.5 kHz) (Fair)*

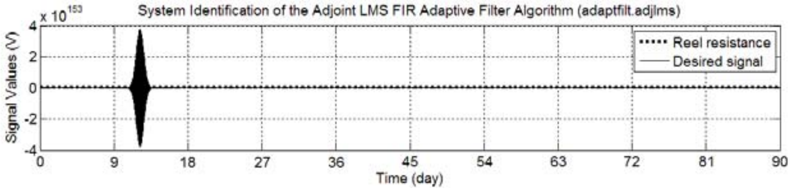


Fig. 13. *The Adjoint LMS FIR adaptive filter algorithm adaptfilt.adjlms (2.5 kHz) (Very Bad)*

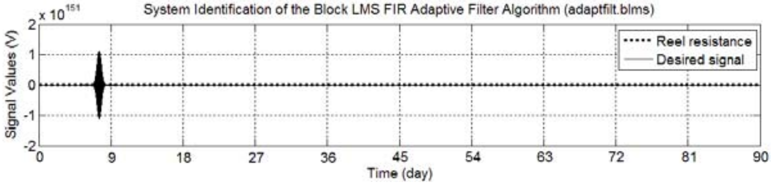


Fig. 14. *The Block LMS FIR adaptive filter algorithm adaptfilt.blms (2.5 kHz) (Very Bad)*

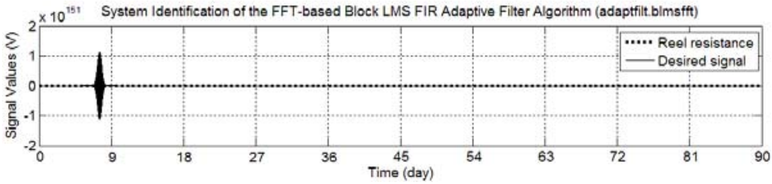


Fig. 15. *The FFT-based Block LMS FIR adaptive filter algorithm adaptfilt.blmsfft (2.5 kHz) (Very Bad)*

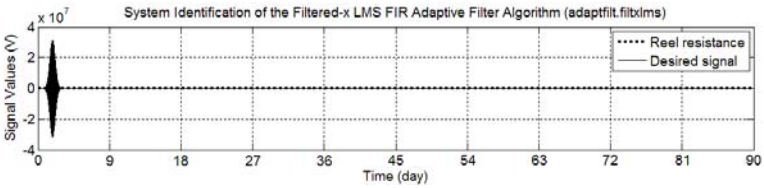


Fig. 16. *The Filtered-x LMS FIR adaptive filter algorithm adaptfilt.filtxlms (2.5 kHz) (Very Bad)*

4. CONCLUSION

In this paper, several Adaptive Filters algorithms from MATLAB have been applied to solve in real time the problem of early prediction of disruption in the oil industry Electro Submersible Pump (ESP) motor. From the analysis of the results, it is possible to claim that the start of a trouble is predictable within a very long time interval of the practical interest. Unfortunately some of the adaptive filter algorithms have shown bad (4) and some fair (2) results, which may bring additional error in the late or false early interpretation of the critical point of the ESP motor insulation disruption issue. Some of the adaptive filter algorithms have shown successfully very good results of the early prediction of the ESP motor real insulation disruption (like Sign-error, Sign-data and Sign-sign filters) The best among ten of the analyzed adaptive filter algorithms (methods) for application in ESP telemetry was recognized as the best — The Normalized LMS FIR filter algorithm — adaptfilt.nlms.

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В предлагаемой статье для выполнения обработки аналогового сигнала погружаемых электрических насосов с высоким уровнем шумов был проведен поиск и найдены среди десятков известных наиболее эффективные адаптивные фильтры подавления помех для систем управления и телеметрии.

Ключевые слова: *сигнал, шум, адаптивные методы, нефтяная промышленность, погружные насосы, коммуникации телеметрических каналов.*

Отримано: 27.04.2011

УДК 519.216

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ВЛАСТИВОСТІ УМОВНИХ ЛІНІЙНИХ ПРОЦЕСІВ ТА ЇХ ЗАСТОСУВАННЯ В ПРИКЛАДНИХ ЗАДАЧАХ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ СТОХАСТИЧНИХ СИГНАЛІВ

Охарактеризовано умовний лінійний випадковий процес, зображуваний як стохастичний інтеграл від випадкової функції за процесом із незалежними приростами. Отримано вирази для моментних функцій процесу, показано умови, за яких він буде стаціонарним у широкому розумінні, а також періодично корельованим випадковим процесом.

Ключові слова: *лінійний, умовний, стохастичний інтеграл, характеристична функція, моментні функції, стаціонарний процес, період, періодично корельований процес.*

Постановка проблеми. Розробка та впровадження комп'ютеризованих інформаційних систем обробки стохастичних сигналів та полів є актуальною науково-технічною проблемою при вирішенні завдань технічної та медичної діагностики, автоматизованого керування

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