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DEVELOPMENT PROCESS OF A FREQUENCY CONVERTER FOR INDUCTION HEATING OF OIL PIPELINE

Abstract

The article provides a detailed overview of the history, development and applications of frequency converters, with particular emphasis on their use in the oil and gas industry. It traces the evolution of frequency converters from their inception in the late 19th and early 20th centuries to their modern applications, which use microprocessors and digital signal processing to precisely control the output frequency. In the oil and gas industry, frequency converters are critical to efficient and accurate induction heating of pipelines. They convert a fixed frequency and voltage power supply into a variable frequency and variable voltage output, controlling the speed of the induction motors used in the heating process. The article also covers the design and modeling of frequency converters, discussing the process of characterizing them, creating mathematical models, and using modeling software tools such as MatLab. It presents equations for inductive energy, capacitor energy, resonance conditions and power factor, which are necessary in the mathematical modeling of frequency converters. The article concludes by highlighting the impact of frequency converters on the efficiency and economics of induction heating systems. It emphasizes the need for careful design and modeling to ensure optimal performance and safety.

Key words: frequency converters, induction heating, oil pipeline, design and modeling, technological temperature maintenance.

Introduction

At the present stage of development, the rapid development of science and technology has brought great changes to various industries, and the oil and gas industry is no exception. One of the technological advancements that has had a major impact on the industry is the development of frequency converters. This article examines the history, development, and applications of frequency converters, especially as they relate to induction heating used to maintain process temperatures in petroleum pipelines.

The research conducted in this article is highly relevant for the oil and gas industry, where efficient and accurate induction heating of pipelines is very important. Research focuses on the evolution, development and application of frequency converters, which play an important role in this process. The purpose of this study is to provide a comprehensive understanding of frequency converters, their evolution and application in induction heating. It also aims to explain the technical aspects of frequency converters, including the mathematical equations that govern their design, modeling and operation.

The study uses a multifaceted approach combining historical analysis, technical expertise, applied research and statistical modeling. It begins with a comprehensive review of the existing literature on the history and development of frequency converters. This study also includes in-depth technical analysis of frequency converters, detailed study of the electronic components used in these devices, and the application of mathematical equations to describe energy exchange in LC circuits.

This study has practical implications as it provides insight into the design and modeling of frequency converters for heating oil pipelines. The simulation results are suitable for practical application in oil refineries.

New research focuses on a holistic approach to understanding current frequency converter applications in the oil and gas industry. It also provides a detailed mathematical model of the frequency converter, which is a new addition in this field.

This research provides new insight into the role of frequency converters, particularly in the oil and gas industry where induction heating is used to maintain process temperatures in oil pipelines. This highlights the need for careful design and modeling to ensure optimal performance and safety and opens up new prospects for improving the efficiency and economics of induction heating systems.

Literature review

The history of frequency converters dates back to the late 19th and early 20th centuries, when power systems were just in their infancy.

As alternating current (AC) systems began to dominate direct current (DC) systems, the need for frequency conversion arose. The first frequency converters (late 1800s to early 1900s) were mechanical devices such as motor-generator sets, in which an AC motor drove a DC generator and the output frequency was controlled by the speed of the motor.

Electronic frequency converters began to emerge (mid-1900s) with the invention of electronic components such as vacuum tubes and later transistors. These devices use electronic circuits to convert the frequency of electrical signals, providing greater efficiency and control than mechanical devices.

The development of semiconductor devices such as diodes and thyristors led to the advent of solid-state frequency converters (late 1900s – early 2000s). These devices greatly improve efficiency, reliability, and controllability and have become the standard for most applications [1].

Thanks to advances in digital technology, modern frequency converters now use microprocessors and convert digital signals into frequency converters. These devices are used in a variety of applications, from electronics to communications.

Throughout history, the need for efficient and precise control of electronic systems has driven the development of frequency converters.

Induction heating is now widely used in the oil and gas industry for heating or heating oil pipelines. Frequency converters play an important role in providing sufficient and accurate heating in oil pipelines.

Water heaters have two main purposes: to compensate for heat loss during oil transportation and to satisfy other industrial needs, for example, active heating of oil. Induction heating has many advantages over traditional pipe heating methods. This is a very good way. About 90% of the energy used is converted into heat. In comparison, the energy conversion rate is 30-50%, which is more efficient in traditional processes such as heating hot water or oil. Induction heating also provides a precise and consistent heating system, ensuring the entire pipe is reheated [2].

The frequency converter plays an important role in induction heating of oil pipelines. It is responsible for converting fixed voltages and currents into AC and AC currents and controlling the speed of the induction motor used in the heating system. By controlling frequency and voltage, the frequency converter can precisely control the induction heating system, ensuring heating efficiency and uniformity [3, 4].

Research method

The research conducted in this article used an interdisciplinary approach combining historical analysis, technical research, applied research and mathematical modeling. This study begins with a thorough review of the existing literature on the history and development of frequency converters.

This review examines the evolution of these devices from their mechanical origins to the modern use of microprocessors and digital signal processors. An in-depth technical analysis of frequency converters was carried out. This includes a detailed study of the electronic components used in these devices. Also, the study includes an analysis of the use of frequency converters in the oil and gas industry, in particular for induction heating of pipelines. This analysis examines the importance of frequency conversion, the benefits of induction heating, and the role of frequency converters in this process. Shown are the mathematical equations used to describe power transfer, resonance conditions, and power conditions in LC circuits. The study provides equations to calculate the energy stored in inductors and capacitors. The operation of the frequency converter was simulated using software – Matlab.

The research methods used in this article provide an in-depth understanding of frequency converters, their development, technical aspects, applications and design specifically in the oil and gas industry.

Results and discussions

Taking the example of oil pipelines, frequency converters are used to power induction heating equipment for various purposes such as pre-weld heat treatment, post-weld heat treatment, pipe coating, carbide brazing of drill bits, etc. The use of frequency converters in induction heating systems allows flexible and efficient heating even in places where water sources are located far away and difficult to access [5].

Over time, advances in inverter technology have made oil pipeline induction heating systems more efficient and economical. For example, the development of full-phase inverters using Vienna rectifiers improves energy conversion efficiency and works in high-frequency induction heating systems.

The oil and gas industry widely uses induction heating equipment in a variety of processes, including drilling, pipeline installation and repair, and biofuel processing. Induction heating has replaced gas welding in many industries due to its reliability, safety, and ability to accurately control heat [6].

The development of frequency converters plays an important role in efficient and accurate heating of oil pipelines. The converter, currently under development, converts direct wave energy into alternating waves to provide better control and uniform heating throughout the pipe. Advances in frequency control technology have led to efficient and economical heating systems, making them the number one choice in the oil and gas industry [7].

In this article we will consider a new frequency converter for induction heating of oil pipelines, manufactured by the authors and colleagues (Fig. 1). The first stage of the development process is the design stage. This includes determining the characteristics of the frequency converter such as input and output power, power rating and efficiency. Design also includes component selection and circuit design.

Figure 1 – Experimental setup

The design process begins with the understanding that maximum power dissipation occurs when the inductor power is uniform. This can be achieved by connecting a set of compensation capacitors in parallel with the inductor. A compensating group of capacitors and chokes forms an oscillatory load circuit, in which the active energy stored in the magnetic field of the inductor is transferred to the capacitor and converted into electrical energy [8].

Mathematically, this process can be described as follows: In an oscillatory load circuit consisting of an inductor (L) and a capacitor (C), a force circulates between the magnetic field of the inductor and the electric field of the capacitor [9]. This can be expressed using the following equation:

Inductor power (W_L). The energy stored in the magnetic field of the inductor is determined by the inductor is determined by formula 1:

$$W_L = 1/2 \cdot L \cdot I^2 \qquad (1)$$

where L – inductance in henry (H),

I – current through the inductor in amperes (A).

Capacitor Energy (W_C). The energy stored in the electric field of the capacitor is determined by formula 2:

$$W_C = 1/2 \cdot C \cdot V^2 \qquad (2)$$

where C – capacity in farads (F),

V – voltage across the capacitor in volts (V).

In an oscillatory circuit, the energy stored in the inductor (W_L), transferred to the capacitor (W_C) and vice versa. This transfer of energy continues back and forth, creating vibrations.

Resonance. The resonance condition in an LC circuit (where the circuit oscillates at its natural frequency) is given by Formula 3:

$$f = \frac{1}{2 \cdot \pi \cdot sqrt(L \cdot C)} \qquad (3)$$

where f – oscillation frequency in hertz (Hz),

L – inductance in henry (H),

C – capacity in farads (F).

Power factor. The power factor (PF) of an AC circuit is determined by formula 4:

$$PF = (\theta) \qquad (4)$$

where θ – phase angle between current and voltage.

In a DC circuit (such as an LC circuit), the power factor is zero. However, if the inductor's power factor is 1 (1), this means that the circuit is operating in resonance with the voltage and current being in phase.

The purpose of this design is to achieve unity of power by tuning the LC circuit to air flow. This ensures high energy transfer between the inductor and capacitor, resulting in efficient use of electromagnetic energy in the system.

Load oscillatory circuit with inductor and capacitor.

An oscillating load circuit consisting of an inductor and a capacitor is often called an LC circuit (Fig. 2). The circuit can circulate without a source of electromotive force (EMF) by transferring the energy stored in the circuit between the electric and magnetic fields.

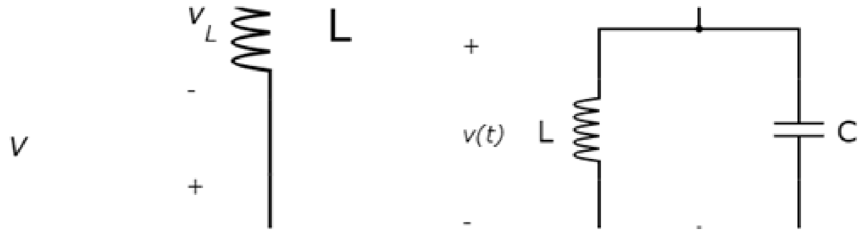

Figure 2 – Diagram of an oscillating load with an inductor and a capacitor

In an LC circuit, an inductor (L) and a capacitor (C) are connected in series or parallel. In a series configuration, the total voltage across the open terminals is the sum of the inductor voltage and the capacitor voltage. The current flowing through the active terminal of the circuit is equal to the current flowing through the capacitor and inductor. In a parallel configuration, the voltage across the open terminal is equal to the voltage across the inductor and the voltage across the capacitor. The total current flowing through the positive terminal of the circuit is equal to the sum of the current flowing through the inductor and the current flowing through the capacitor.

The oscillatory behavior of LC circuits is caused by the transfer of energy between capacitors and inductors. When the switch closes, the capacitor begins to discharge, creating a current in the circuit. This current creates a magnetic field in the inductor. The energy is transferred to the capacitor, where the electric field decreases, to the inductor, where the magnetic field increases. This process continues, causing a cycle between electricity and magnetism.

It is worth noting that energy loss occurs within the circuit, which reduces fluctuations over time. These losses can be caused by factors such as the DC resistance of the inductor, the dielectric of the capacitor, and radiation in the circuit.

LC oscillators are widely used for generating high frequencies and are often used in radio generators, superheaters, radio and television receivers, etc.

The use of an oscillating load circuit (usually with an inductor and capacitor or LC circuit) allows energy to be exchanged between electricity and magnetism, creating oscillations without the need for an external emf source.

High frequency generators, such as transistor frequency converters, are used as power sources in oscillating load circuits. High frequency induction heaters have an output frequency range of 10 to 40 or 30 to 100 kHz. In this frequency range, the depth of the induction field is 2–5 mm. If additional heating is required along the depth of the part, the heating time will be increased [10].

When designing an oscillating transformer and considering an oscillating load circuit containing inductors and capacitors, several factors must be considered:

1. List of repetitions. High frequency induction heaters, including those used in frequency converters, typically operate in the frequency range of 10 to 40 kHz or 30 to 100 kHz. The specific frequency range depends on the application and required heating characteristics.

2. Penetration depth. The penetration depth of the guided field in this wavelength range is typically between 2 and 5 mm. This means that the induced current and heating occur predominantly in the surface layer of the heated material.

3. Time and depth of heating. If additional heating is required along the depth of the part, the heating time should be increased. This allows more energy to be transferred to deeper layers of the material, thereby increasing the depth of heating. However, it is worth noting that increasing the heating time may increase the overall processing time.

4. Impedance and resonant frequency. The impedance of the load oscillating circuit (including inductors and capacitors) plays an important role in the frequency converter. Impedance depends on the operating frequency and the size of the inductor and capacitor. When the impedance is low, a resonant frequency occurs in the circuit, allowing more energy to be transferred between the inductor

and the capacitor. The resonant frequency can be calculated using equations and the values of the inductors and capacitors in the circuit.

For example, as shown in Figure 3, the Hartley oscillator, an oscillator used in electronic products, is currently in use. It is known for its simple and lightweight design. It produces sine waves and is used to generate signals. and Colpitts oscillators, which are widely used in wireless communications to generate high-frequency sinusoidal signals. Known for stability and low harmonic distortion.

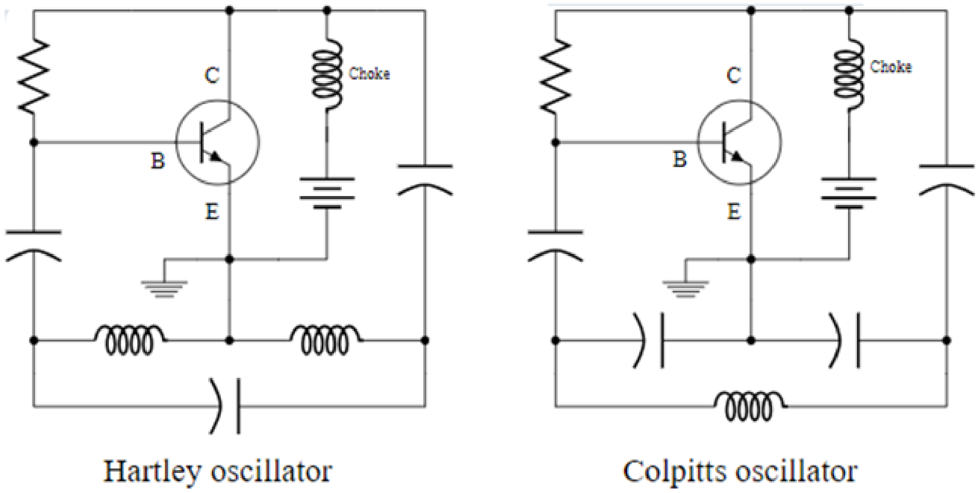

Figure 3 – Hartley Oscillator and Colpitts Oscillator

It is worth noting that the specific design and load parameters of the frequency converter generator circuit may vary depending on the application requirements and the required heating characteristics.

Next we will look at modern high-frequency transistor transformers for induction installers. Today's transistor high-frequency sensing modules, especially those integrated into gate bipolar transistor (IGBT) modules, are widely used in mid- and high-power applications. IGBTs are three types of power semiconductor devices that combine the power characteristics of MOSFETs and bipolar transistors. They provide high current density, low power consumption and high performance, allowing for smaller heatsink size and lower system cost. These devices can drive loads of hundreds of kilowatts, handle currents up to hundreds of amperes, and withstand voltages in the thousands of volts range. Their low forward energy loss and impedance make them suitable for power applications such as converters, transformers and power supplies [11].

The current flow diagram of the oil pipeline heating process is as follows: In the induction heating oil pipe, the induction wire is wound on the outside of the oil pipe to form a cylindrical inductor. The inductor is closed by a compensation capacitor bank and connected to the high-frequency generator through a damping (shunt) transformer [12].

The inductor is a metal coil surrounded by a tube. It has a cylindrical shape and is designed to create a strong magnetic field when high frequency alternating current (AC) flows. The inductor induces eddy currents in the tube conductor, causing resistive heating.

The capacitor compensation section is connected in parallel with the inductor. Capacitors are used to compensate reactive power in the circuit and increase voltage. This helps improve energy distribution and increase the efficiency of induction heating systems [13].

A damping transformer is connected between the high-frequency generator and the inductor. It performs two important functions [14].

- Appropriate harmony. The shunt transformer ensures that the parameters of the high-frequency generator precisely match the parameters of the load circuit. Controls voltage and current levels for efficient power transfer between generator and inductor. This helps improve energy transfer and heating efficiency.

- Galvanic isolation. The shunt transformer provides galvanic isolation between the inductor and the high-frequency generator. Galvanic isolation is important for safety reasons because it helps prevent electrical shock and protect equipment and personnel. Electrically isolates the inductor from the generator to ensure safe operation.

Induction. The process mode of induction technology is controlled by the controller. The controller monitors and controls various parameters such as temperature, power output, heating time, etc. The heating process is precisely controlled to ensure uniform and stable heating of the oil pipes. Therefore, frequency converters designed for induction heating of oil pipelines require careful consideration of the power supply, inductor design, and use of matching transformer to ensure proper performance and safety.

After completing the design process, we begin executing the model. After completing the design of the frequency converter for the oil pipe heating device, measurements of the system are carried out using software [16]. Calibration allows you to periodically predict the performance of your transmitter and make necessary design adjustments. In this study, simulations were carried out using the MatLab software package.

In this work, system modeling can be used to understand and optimize system performance and reliability. This will help you evaluate different design options, predict system behavior, and identify potential problems before implementing your design in the real world.

The first modeling step is to create a mathematical model of the installed inverter. This includes identifying components, their properties and interactions. The model shows the behavior of the system and allows engineers to simulate its operation under various conditions [17, 18].

Creating a mathematical model of a frequency converter requires a mathematical representation of the converter components and their interactions [19].

Input voltage source (Vin) is the power source of the inverter. In the model we consider it as a constant voltage source.

The switching element (S) is the main component of the inverter. You can think of it as a switch model that turns on and off at a certain frequency. The switching frequency can be expressed as a model parameter.

The output load (L) is the component that uses the power provided by the inverter. In the model, this can be expressed as resistance.

Filter (C) is used to smooth the output voltage. In the model, this can be represented as a capacitor.

The mathematical model of the frequency converter can be expressed by Formula 5:

$$V_{out} = V_m \cdot D \tag{5}$$

where V_{out} – output voltage,

V_m – input voltage,

D – switching element duty cycle.

Duty cycle D is defined as the ratio of the switch closing time (T_{on}) to the total switching cycle period (T_T), i.e., according to formula 6:

$$D = T_{on}/T_T \tag{6}$$

The simulation result is presented in Figures 4 and 5.

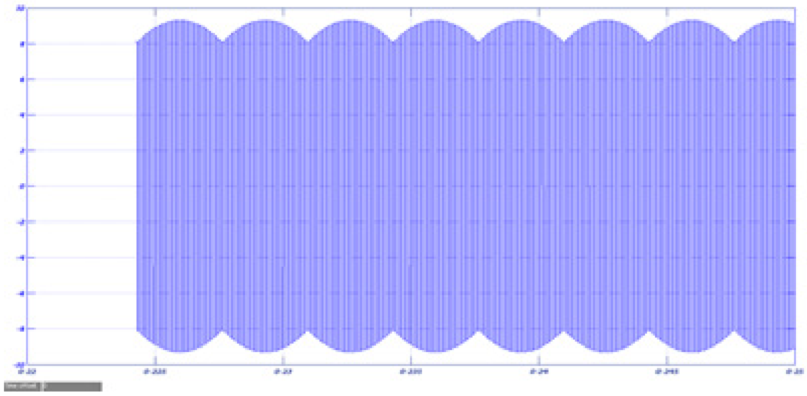

Figure 4 – Simulation results in the MatLab software package

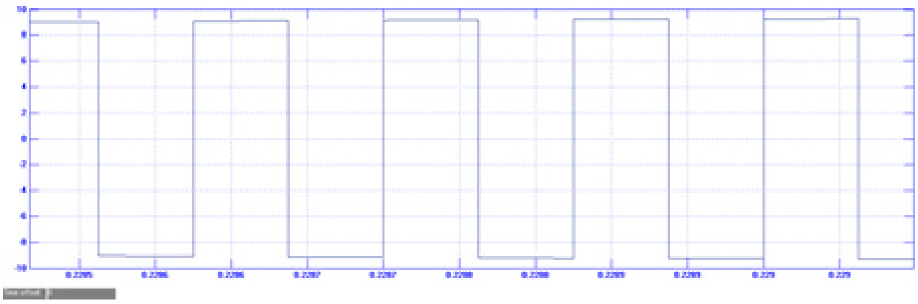

Figure 5 – Simulation results in the MatLab software package

The simulation results show that as the frequency of the inductive converter increases, the number of parts, cost, and weight of the device and control system also increase. Unlike most devices that heat only the surface of the pipe, the transformer heats the entire surface of the pipe.

If the inductor power is 1, the electromagnetic force can be increased. This can be achieved by connecting a capacitor bank in parallel with the inductor. The compensation capacitor bank and the inductor form an oscillatory load circuit, and the active energy collected in the magnetic field of the inductor is transferred to the capacitor and converted into electrical energy [20].

A mathematical model was built in the Simulink environment to visually display the logarithm of the amplitude-phase frequency response. The simulation results are shown in Figure 6.

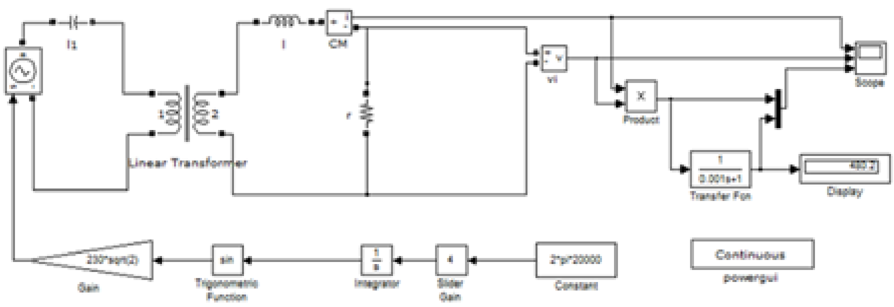

Figure 6 – Simulation results in Simulink environment

The simulation results of this frequency converter can be used for efficient implementation in existing refineries. This means that theoretical designs and models can be implemented in real physical heating systems for oil pipelines. This will also help you understand the working of the inverter. This understanding can be used to improve the efficiency and effectiveness of induction heating systems.

The simulation results can be used to develop inverter control strategies. This ensures precise heating by precisely controlling the output frequency.

Therefore, the obtained simulation results are not only of theoretical significance, but also have practical application value and can contribute to the development of efficient, safe and effective heating systems in the oil and gas industry.

Conclusions

This article provides a comprehensive overview of the evolution, design and application of multiphase conversions, especially in the context of the oil and gas industry.

This article traces the development of the Time-Turner from its origins in the late 19th and early 20th centuries to the present day. Modern inverters use advanced technologies such as microprocessors and digital signal processing to provide precise control of the output frequency.

In the oil and gas industry, frequency converters play an important role in heating pipelines efficiently and accurately. Converts a fixed frequency and voltage source to a variable frequency and voltage output to control the speed of induction motors used in heating systems.

This article describes in detail the design and simulation of frequency converters. We describe the process of characterizing these devices, creating mathematical models, and using software modeling tools such as MatLab. This article presents the equations of inductor power, capacitor power, resonance conditions and power factor required for the mathematical model of a frequency converter.

The article concludes by highlighting the impact of frequency converters on the efficiency and economics of induction heating systems. It emphasizes the importance of careful design and modeling to ensure optimal performance and safety. The simulation results are applicable for practical use at operating oil refineries.

To summarize, the evolution of variable speed drives has paved the way for more efficient and cost-effective induction heating systems, making them the preferred choice in the oil and gas industry. However, the design and modeling of frequency converters requires careful consideration to ensure optimal performance and safety.

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МҰНАЙ ҚҰБЫРЫН ИНДУКЦИЯЛЫҚ ҚЫЗДЫРУҒА АРНАЛҒАН ЖИІЛІК ТҮРЛЕНДІРГІШІН ӘЗІРЛЕУ ҮРДІСІ

Аңдатпа

Мақалада жиілік түрлендіргіштерінің тарихы, дамуы және қолданылуы туралы егжей-тегжейлі шолу ұсынылып, ерекше назар олардың мұнай-газ саласында қолданылуына аударылған. Жиілік түрлендіргіштерінің 19 ғасырдың соңы мен 20 ғасырдың басында жасалуынан бастап, қазіргі кезде микропроцессорлар мен сигналдарды цифрлық өңдеу арқылы шығу жиілігін дәл басқаруға дейінгі эволюциясы қарастырылады. Мұнай-газ саласында жиілік түрлендіргіштері құбырларды тиімді және дәл индукциялық жылыту үшін маңызды рөл атқарады. Олар тұрақты жиілік пен кернеу көзін айнымалы жиілік пен айнымалы кернеу сигналдарына түрлендіріп, жылыту үрдісінде қолданылатын асинхронды қозғалтқыштардың жылдамдығын басқарады. Мақалада сонымен қатар жиілік түрлендіргіштерін жобалау және модельдеу мәселелері қарастырылады, олардың сипаттамаларын анықтау үрдісі, математикалық модельдерді жасау және MatLab сияқты бағдарламалық құралдарды пайдалану талқыланады. Жиілік түрлендіргіштерін математикалық модельдеу кезінде қажет болатын индуктивтілік энергиясы, конденсатор энергиясы, резонанс шарттары және қуат коэффициентіне қатысты теңдеулер ұсынылған. Мақала соңында жиілік түрлендіргіштерінің индукциялық жылыту жүйелерінің тиімділігі мен экономикасына әсері аталды. Сонымен қатар, оңтайлы өнімділік пен қауіпсіздікті қамтамасыз ету үшін мұқият жобалау мен модельдеудің қажеттілігіне ерекше мән берілген.

Тірек сөздер: жиілікті түрлендіргіштер, индукциялық қыздыру, мұнай құбыры, жобалау және модельдеу, технологиялық температураны ұстау.

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ПРОЦЕСС РАЗРАБОТКИ ПРЕОБРАЗОВАТЕЛЯ ЧАСТОТЫ ИНДУКЦИОННОГО НАГРЕВА НЕФТЕПРОВОДА

Аннотация

В статье представлен подробный обзор истории, развития и применения преобразователей частоты с особым акцентом на их использование в нефтегазовой отрасли. Прослеживается эволюция преобразователей частоты от их создания в конце 19 – начале 20 вв. до их современного применения, когда используются микропроцессоры и цифровая обработка сигналов для точного управления выходной частотой. В нефтегазовой отрасли преобразователи частоты имеют решающее значение для эффективного и точного индукционного нагрева трубопроводов. Они преобразуют источник питания с фиксированной частотой и напряжением в выходной сигнал переменной частоты и переменного напряжения, управляя скоростью асинхронных двигателей, используемых в процессе нагрева. В статье также рассматриваются вопросы проектирования и моделирования преобразователей частоты, обсуждается процесс их определения характеристик, создания математических моделей и использования программных инструментов моделирования, таких как MatLab. В нем представлены уравнения для энергии индуктивности, энергии конденсатора, условий резонанса и коэффициента мощности, которые необходимы при математическом моделировании преобразователей частоты. В заключение статьи подчеркивается влияние преобразователей частоты на эффективность и экономику систем индукционного нагрева. В нем подчеркивается необходимость тщательного проектирования и моделирования для обеспечения оптимальной производительности и безопасности.

Ключевые слова: преобразователи частоты, индукционный нагрев, нефтепровод, проектирование и моделирование, технологическое поддержание температуры.

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