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Electrical Innovations in Electrocoagulation: Designing and Testing Prototypes for Sustainable Water Treatment

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Abstract: Electrocoagulation is emerging as a sustainable solution for water treatment, despite higher energy consumption compared to traditional biological methods. Its advantages include shorter treatment times and the absence of chemical additives. Particularly suitable for arid regions facing water scarcity, this method promotes water conservation and reuse. Our research highlights an innovative prototype featuring an electrical generator designed to optimize the coagulation process and enhance overall treatment efficiency. Through comprehensive experimental testing, we demonstrate the reliability and effectiveness of this system for treating industrial wastewater, paving the way for broader adoption in industries committed to sustainability and responsible water resource management.

Keywords: Electrocoagulation, Water treatment, Prototype design, Chemical-free treatment, Industrial water reuse

Introduction

Electrocoagulation is a water treatment method that uses electrical currents to generate ions from metal electrodes, such as aluminum or iron, which neutralize and remove contaminants like heavy metals, oils, and suspended particles. It is recognized for its cost efficiency, environmental benefits, and adaptability, making it suitable for industrial wastewater, sewage, and drinking water treatment (Mollah, 2001; Vasudevan, 2014; Kobya, 2003).

Recent advancements have demonstrated its effectiveness against emerging pollutants like microplastics and pharmaceuticals, while innovations in electrode materials aim to enhance contaminant removal and reduce energy consumption (Rajala et al., 2020). Studies also highlight the potential of low-voltage systems to maintain efficiency while lowering energy use, a critical factor for sustainable, large-scale applications (Karimifard & Moghaddam, 2018; Xie et al., 2021). Additionally, adaptive power supply systems have proven beneficial in industrial applications, such as textile wastewater treatment (Chen, 2004; Kobya et al., 2018).

Efficient power systems allow immediate reuse of treated water, conserving resources and supporting operational efficiency. These systems also reduce energy costs while meeting water quality standards, making them valuable in industrial settings (Karimifard & Moghaddam, 2018; Xie, Zhang, & Ji, 2021). This paper examines the power supply system in electrocoagulation plants, detailing the system's design, implementation, and experimental results to optimize energy use and treatment efficiency.

Overview of the Electrocoagulation Plant

This section provides an overview of the critical components and operational principles of an electrocoagulation plant, a wastewater treatment technology that removes contaminants by applying electrical currents to metal electrodes, typically aluminum or iron. The electrocoagulation system's key components include the reaction chamber, where the treatment process takes place. The chamber's design—specifically its dimensions and hydraulic retention time—plays a pivotal role in treatment efficiency, as optimized flow patterns promote effective interactions between pollutants and charged ions (Xie et al., 2021). Furthermore, the selection and arrangement of electrode materials are vital, as they directly influence ion release and pollutant removal efficiency. Proper spacing and sufficient electrode surface area are essential to enhancing electrochemical reactions while minimizing energy consumption (Karimifard & Moghaddam, 2018).

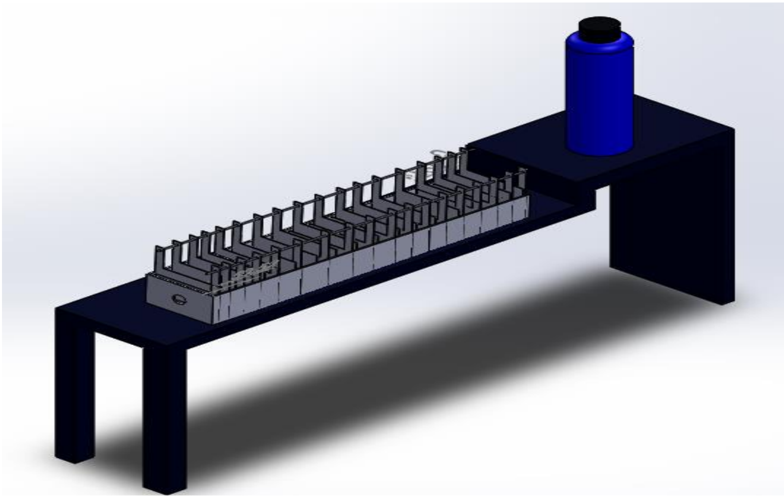


Figure 1. Water treatment using electrocoagulation process.

Generator Location in the Process, Chambers` Design

Figure 1 illustrates the key chambers and functions of the electrocoagulation plant in our prototype. The central reaction chamber treats unsuitable water through electrocoagulation, where a stack of 14 iron electrodes (7 anodes and 7 cathodes), each measuring 18 cm x 30 cm with a 2 mm thickness, is powered by a high-current supply. These electrodes, arranged with a 2 cm spacing in a single-phase parallel configuration, ensure uniform current distribution, reduced resistance, and energy-efficient operation.

Following the reaction chamber, a sludge removal chamber uses a conveyor belt with scrapers to collect floating sludge, directing it to a hopper for further treatment and preventing interference with sedimentation. The final sedimentation chamber separates clean water from heavier solids, which settle at the bottom and are directed to a basin with specialized filters. Filtered water is either pumped back for reuse or further disinfected via ozonation or chlorination before distribution or safe discharge into the environment. The prototype's design optimizes pollutant removal while minimizing energy consumption and ensuring water quality for reuse or environmental release.

Design of Power Supply for Electrocoagulation Water Treatment

The power supply is a critical component of the electrocoagulation (EC) system, requiring customization to meet the specific operational requirements of the electrocoagulation process. Below, we outline the key considerations and design features essential for creating an efficient power supply for electrocoagulation water treatment.

Voltage and Current Requirements

The electrocoagulation process relies on a specific voltage and current to create the electric field between electrodes. An adjustable voltage supply, typically ranging from 10 to 100 volts, is essential to optimize coagulation based on water quality and contaminants. Additionally, a constant current mode ensures operational stability and prevents electrode overheating, enhancing system efficiency and durability.

Power Supply Type

Electrocoagulation systems typically use DC power supplies, with some advanced designs employing pulsed power to enhance floc formation and reduce electrode fouling (Khan, 2016). An efficient control system is crucial for optimizing power supply parameters. Modern setups often feature microcontroller integration for real-time monitoring and adjustments of voltage, current, and temperature. User-friendly interfaces further enable operators to manage settings, monitor performance, and receive alerts for potential issues.

Safety Features

Safety is a critical consideration in the design of power supplies for electrocoagulation systems. To ensure reliability and protection, several key features should be incorporated. First, overcurrent protection is essential; the inclusion of circuit breakers or fuses can safeguard the system against excessive current, thereby preventing potential damage. Second, effective temperature monitoring is vital; thermal sensors can automatically shut down the power supply when critical temperature thresholds are exceeded, thus averting overheating incidents. Furthermore, galvanic isolation plays a crucial role in protecting human operators by preventing direct electrical connections. This can be achieved through the use of isolation devices such as transformers and optoisolators, which enhance safety by shielding equipment from voltage spikes and ensuring stable control signals. Typically, switching power supplies are employed to convert alternating current (AC) into direct current (DC) efficiently, thereby contributing to a reliable and secure operational environment for electrocoagulation systems.

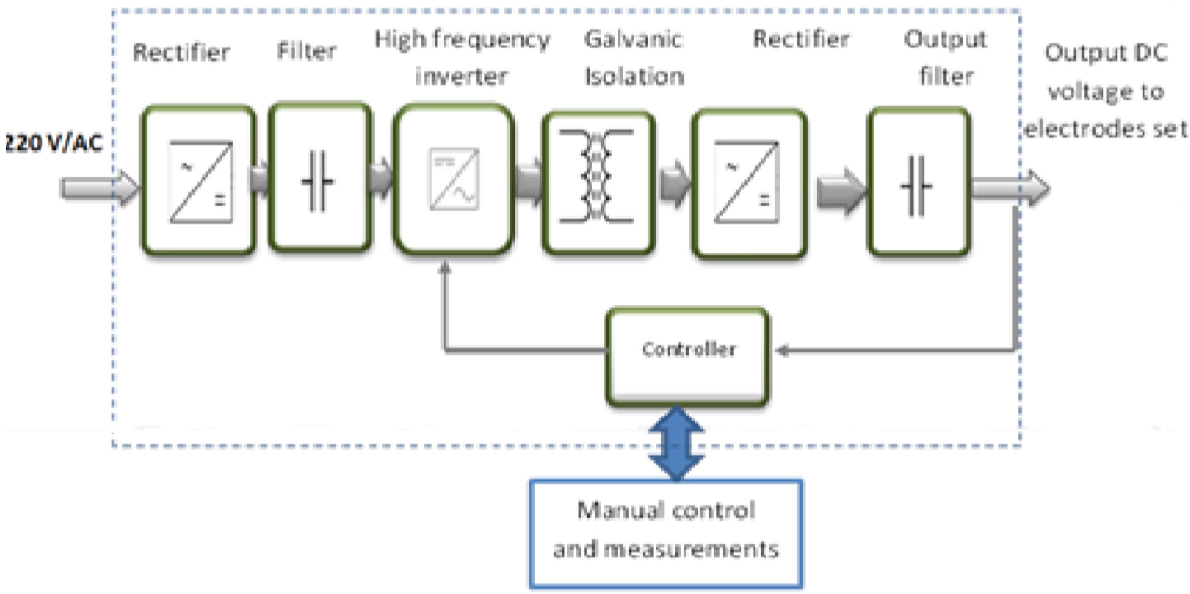


Figure 2. Main stages of the generator used in the electrocoagulation process

Figure 2 provides a detailed overview of the key stages involved in the power supply system discussed in this paper. At the initial stage, a rectifier is installed to convert the incoming alternating current (AC) into direct current (DC). Following the rectification process, a filter is employed to smooth out the DC output, significantly reducing voltage fluctuations and enhancing electromagnetic compatibility. This smoothing effect is crucial for maintaining stable operation in sensitive electronic systems and minimizing electromagnetic interference.

The next critical stage involves an inverter, which takes the smoothed DC output and converts it into high-frequency AC voltage. This conversion is achieved through pulse-width modulation (PWM), a technique that enables precise control over the output voltage level. The PWM signal is generated by a feedback controller, which plays a pivotal role in monitoring system performance. This controller continuously collects data on the output voltage and the current flowing to the electrodes, comparing these measurements to the desired values. By doing so, the controller regulates the power output, ensuring compliance with the optimal electrocoagulation requirements that have been established through prior studies. Once the high-frequency AC voltage is generated, it is transformed to a lower voltage level using a galvanic transformer. This step is vital not only for ensuring the output is suitable for further processing but also for enhancing safety. The transformer provides isolation on the output side, protecting users from electrical hazards while working with the system. Subsequently, the output rectifier converts the transformed AC voltage back into DC. This rectified output is then passed through an output filter, which further smooth and stabilizes the voltage and current. The filtered DC is then delivered to the electrodes that are submerged in the water to be treated. This final stage is crucial, as it allows for the effective electrocoagulation process to take place, utilizing the regulated DC current and voltage to achieve the desired treatment outcomes. Through these meticulously designed stages, the power supply system ensures reliable and efficient operation tailored to the specific requirements of electrocoagulation. (Smith, 2023).

In the following section, we will present the prototype developed as part of this study. This section will include a detailed description of the prototype's design and key features, highlighting its capabilities to meet the requirements of the electrocoagulation process. Additionally, we will discuss the results obtained from testing the prototype, including performance metrics, efficiency analyses, and any challenges encountered during the testing phase. This comprehensive examination will provide insights into how effectively the prototype meets the intended objectives and will lay the groundwork for further exploration and potential improvements in future work.

Prototype and Test Results

Implementation of the DC Generator

The switching power supply has been designed as a full bridge, following the schematic illustrated below. This design choice is based on the specific requirements outlined in our specifications.

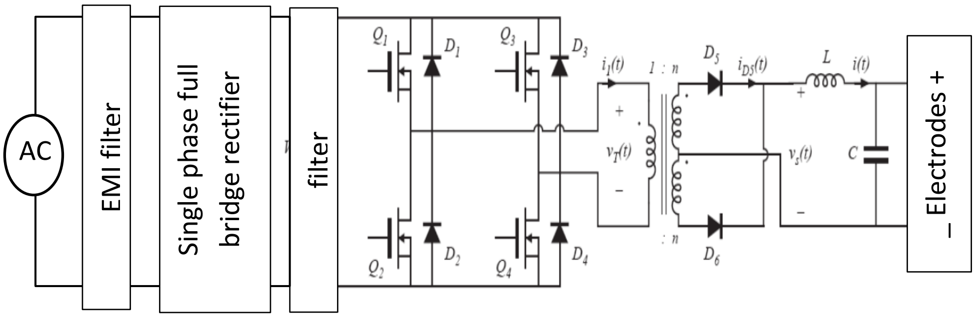


Figure 3. Switched-mode power supply (SMPS) specifically adapted for real-time electrocoagulation in water treatment applications used in the present prototype design.

Figure 3 shows the schematic of a switched-mode power supply (SMPS) specifically adapted for real-time electrocoagulation in large scale water treatment applications. The schematic begins with an EMI filter, designed to reduce electromagnetic interference, ensuring compliance with EMC standards critical in online systems. Next, a single-phase full-bridge rectifier converts the incoming AC to pulsating DC using four diodes configured in a bridge arrangement.

Following the rectifier, a DC filter smooths this pulsating DC through a capacitor, resulting in a stable DC voltage. This stable DC is then input to a high-frequency inverter, where it is rapidly switched using MOSFETS, producing a high-frequency AC waveform. This high-frequency switching enables the use of a more compact high-frequency transformer, which provides both galvanic isolation for user protection and the ability to adjust the voltage up or down as required for the electrocoagulation process.

On the secondary side of the transformer, a half-bridge rectifier converts the high-frequency AC back into DC using two fast diodes. Finally, a DC output filter, comprising capacitors and inductors, smooths the rectified signal to ensure a stable DC output for the electrocoagulation electrodes. Each stage in Figure 3 is essential for achieving efficient AC-to-DC conversion, delivering clean, stable power required for real-time electrocoagulation water treatment. The design of the power supply for electrocoagulation water treatment is critical to the effectiveness and efficiency of the process. As water treatment needs evolve, continued advancements in power supply technology will play a significant role in optimizing electrocoagulation processes for sustainable water management. The following specifications are required for sizing the generator operating in continuous conduction mode (CCM):

- Input Voltage Range: $Vemin = 180$ V, $Vemax = 265$ V,
- Nominal Output Voltage Range: $Vsmin = 6.2$, $Vemax = 26$ V.
- Output Current Adjustment Range: $Ismin = 0$ A, $I smax = 200$ A ;
- Switching Frequency: $f = 50$ KHz.

Figure 3 shows the experimental setup of the power supply, installed to test the prototype under real operating conditions. This setup allows us to monitor input voltage stability, output regulation, and efficiency at different load levels, verifying the power supply's performance and readiness for full-scale application. In this paper, the current power supply operates in open-loop control for the electrocoagulation treatment; only the desired current can be regulated in closed-loop control.

Test and Result

Experimental Procedure and Performance Evaluation of the Electrocoagulation System

Figure 4. Final prototype including the generator

Figure 4 shows the final prototype used in the experimental tests. Testing and verifying the performance of the electrocoagulation system is essential to assess the efficiency and reliability of the integrated generator. This section describes the tests conducted to validate the system's functionality. Three specific tests were performed:

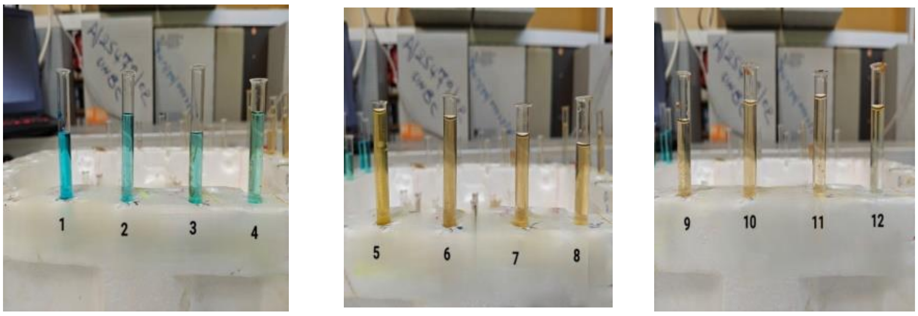
Electrocoagulation Test of Methylene Blue

The first test focused on the electrocoagulation of methylene blue using varying current values. Methylene blue was chosen as a model substance to assess the process's effectiveness, with the goal of determining the optimal current value for efficient coagulation. Key parameters such as methylene blue decolorization, coagulation time, and flocculation efficiency were evaluated to identify the most effective current setting in this specific context. Three trials were conducted under different conditions to assess the process's performance. The results for each trial are presented in the following figures 5.

The electrocoagulation wastewater treatment experiment, focusing on the removal of methyl blue dye, demonstrated promising results at a fixed water flow rate of 2 L/min from the inlet to the outlet. Across the tested samples at varying current levels of 5A, 10A, and 15A, an improvement in dye removal efficiency was observed with increasing current. The most significant enhancement occurred when increasing the current from 5A to 10A, indicating effective coagulation and flocculation processes at this level. However, the transition from 10A to 15A yielded only marginal improvements in dye removal efficiency, suggesting a potential point of diminishing returns at higher currents.

While the overall treatment performance continued to improve, raising the current to 15A resulted in a noticeable increase in water temperature. This thermal effect may impact the stability of the treatment process and the potential degradation of organic compounds. Additionally, the electrolysis process intensified with higher current, as evidenced by the increased formation of bubbles. This enhanced gas evolution can contribute to better mixing and stirring of the wastewater, potentially improving the coagulation process.

In summary, the electrocoagulation method shows effective potential for treating wastewater containing methyl blue dye, particularly at lower currents and under a fixed flow rate of 2 L/min. However, careful consideration must be given to operational parameters, as increasing current may lead to thermal concerns and diminishing returns in treatment efficiency beyond a certain point. Future studies should focus on optimizing current settings and flow rates to balance treatment effectiveness with operational efficiency and safety.



(a) (b) (c)

Figure 5. Electrocoagulation Treatment of Methylene Blue Solution at Varying Current Levels with a Fixed Flow Rate of 2 L/min

Note: a) Post treatment with supplying current I=5A b) Post treatment with supplying current I=10A c) Post treatment with supplying current I=15A

Conclusion

This paper explores the development and testing of a generator prototype aimed at supporting large-scale electrocoagulation for sustainable water treatment. The study highlights how electrical innovations can provide the power needed to enhance contaminant removal efficiency, showing promise for scaling electrocoagulation systems. The results emphasize the importance of design improvements in achieving both scalability and effectiveness in water treatment technologies. The findings suggest that electrical advancements can overcome limitations of traditional electrocoagulation, particularly for larger or more complex wastewater treatments. However, further research is needed to optimize the prototype under varying wastewater compositions and operational conditions for broader real-world applications.

In conclusion, this study demonstrates that scalable electrical innovations can play a critical role in advancing sustainable water treatment technologies, offering a strong foundation for future developments in improving global water quality and wastewater management.

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