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Performance analysis of pulsed direct current electrocoagulation for chemical oxygen demand removal from wastewater: energy savings and cost minimization

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ABSTRACT

This study primarily focusses on an electrocoagulation module designed for wastewater treatment, which operates on pulsed direct current (PDC) as a power source, thereby ensuring a reliable and efficacious treatment solution. The system's overall specific energy consumption (SEC) underwent a notable reduction while concurrently maintaining its efficacy in reducing chemical oxygen demand (COD). This improvement in reducing COD and the notable reduction in the system's SEC can be attributed to the development of advanced control algorithms for PDC. To facilitate the operation of the PDC system, a buck converter is employed and the optimization of power to electrocoagulation is achieved using an improved proportional - integral control of pulse width modulation (PWM) pulses. Furthermore, it was observed that compared to conventional controlled rectifier-based DC (CR-DC) powered electrocoagulation units, the PWM - controlled buck converter achieved a substantial 48.5% reduction in specific energy consumption at its maximum voltage of 275 V over CR-DC. The performance characteristics of the uncertainty behavior of the developed system were assessed through a combination of simulation and experimental methodologies, confirming its suitability across a wide spectrum of operating voltages. The specific energy consumption for COD removal was determined to be 11.99 and 5.81 kWh/m^3 for CR-DC and PDC, respectively, over a 60-min timespan. Additionally, it was established that the PDC module represents a cost-effective alternative, being 48.5% less expensive than CR-DC. The findings from the study prove that the PDC module has commendable efficiency in conserving energy and its economic viability in the electrocoagulation process.

Keywords: Sustainable water treatment; Reactor; Pollutants; Iron electrodes; Pulse width modulation

1. Introduction

Availability of clean water to mankind has become a global issue due to rapid industrialization and use of various raw materials for different processes during manufacturing process [1]. The surge in population, demands extensively processed industrial products to a greater extent and ends up in municipal solid waste that contaminates the water resources. The demand has created increased disposal of industrial effluents loaded with diverse pollutants which

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causes severe environmental and ecological repercussions [2]. Industrial effluents with high chemical oxygen demand in the form of biodegradable and non-biodegradable contaminants have serious negative impacts on aquatic life [3]. High chemical oxygen demand (COD) can significantly bring down the dissolved oxygen (DO) of water that can lead to anaerobic conditions which are deleterious to life of aquatic ecosystem [4,5]. Hence there is an urgent need to remediate the wastewater since water is the base of life.

Various treatment techniques are widely used around the world for the effective mitigation and remediation of wastewater from industrial sources [6]. Techniques such as biological process and physio-chemical process are employed, and physio-chemical processes dominate the biological process in terms of time of treatment [7–10]. Physio-chemical processes such as adsorption [11], flocculation [12], membrane filtration [13] and coagulation [14,15] are used. However, coagulation in combination with electricity provides a synergy to effectively reduce the COD in the wastewater. The combined technique is called electrocoagulation. The fact that it does not require any coagulant makes it more attractive for treatment process [16].

Electrocoagulation process has been practiced since the 20th century with limited success due to various influential factors such as pH, electrodes characteristics, inter-electrode distance and operational time and cost [17,18]. The influential parameters are optimized by several researchers to obtain significant efficiencies and to overcome the limitations. However, the cost of the electrocoagulation process is still a challenging technique due to the energy requirements. COD removal from leachate by monopolar electrodes was proposed [19] and estimated a value of 1.41 US $/kg incurred for treating 1 kg of COD and energy consumed was estimated to be 0.055 kWh/kg. In general, direct current is usually employed in electrocoagulation process to achieve the desired outputs and there will be energy losses during the operational process [20–23]. To minimize energy consumption and reduce the cost of electro-coagulation process, a pulsed direct current (PDC) approach was proposed for the treatment of COD by electro-coagulation process [24].

2. Materials and methods

2.1. Raw effluent characteristics

The raw effluent was procured from Zero Discharge Technologies Private Limited, Coimbatore, India and the physio-chemical characteristics of the effluents are represented in Table 1.

Table 1 indicates physio-chemical characteristics of raw effluent. Biochemical oxygen demand (BOD) is one of the most important and widely used parameters for characterizing the organic pollution of water and wastewater, which is estimated by determining the amount of oxygen required by aerobic microorganisms for degrading organic matters in wastewater. Most pristine rivers will have BOD below 1 mg/L. Moderately polluted rivers may have a BOD value in the range of 2–8 mg/L [25]. The values specified in Table 1 indicate that it is unsuitable for consumption. COD also indicates the level of pollution in wastewater. Influent COD in normal domestic sewage is generally around 600–900 mg/L and it is then treated to at least 75–100 mg/L before discharge to minimize pollution potential [26]. DO is the amount of oxygen dissolved in water, that is, the amount of oxygen available for aquatic organisms. As pollution increases the BOD level rises, leading to depletion in dissolved oxygen level, making it hard for aquatic life to thrive. Oxygen is also required for the breakdown of organic matter [27]. When the water body does not support life form due to reduced DO levels, it indicates pollution of the water body.

Untreated water can have significant negative impacts on society across various categories, including health, environment and infrastructure. The imbalance caused by the physical and chemical properties can cause enormous damage to the environment. Untreated water can contain pathogenic microorganisms like *Escherichia coli* and *Cryptosporidium*. Physical properties like turbidity, pH, dissolved oxygen, total suspended solids and total dissolved solids indicate water quality. Turbidity, a measure of water cloudiness due to suspended particles, can indicate the presence of contaminants in water. High turbidity can reduce water quality, block sunlight penetration, harm aquatic organisms and hinder effective disinfection [28]. The acidity or alkalinity of water, with a neutral value of 7 and extreme values can corrode pipes [29] this can harm aquatic ecosystems, disrupt the balance of aquatic life. Acidic water (low pH) can harm fish and aquatic insects. Alkaline water (high pH) can affect the solubility of metals like lead, increasing the risk of contamination [30–32]. High total dissolved solids (TDS) levels can affect the taste of water, harm aquatic life and indicate contamination from sources like industrial discharge or agricultural runoff. Low DO levels can harm aquatic organisms and promote the growth of anaerobic bacteria [33]. Insufficient oxygen in water can cause fish to suffocate, disrupting aquatic food chains.

Table 1
Physico-chemical characteristics of raw effluent

Parameters	Raw effluent	Permissible values as per IS 10500-2012
pH	9–10	7.5–8.5
Suspended solids, mg/L	500	30
COD, mg/L	2,000	200
BOD, mg/L	700	5
Dissolved oxygen, mg/L	–	6.5–8
Colour, Pt.Co.	3,000	25
Conductivity, µS/cm	8,000 max.	2,500
TDS, mg/L	4,000	2,000
Iron, mg/L	Less than 0.5	1–3
Oil and grease, mg/L	20	0.2
Sodium, mg/L	2,500 max.	30–60
Sulfate, mg/L	800 max.	200
Chloride, mg/L	1,500 max.	250
Silica, mg/L	20	50
Total hardness, mg/L	200	120–170
Turbidity, NTU	500	5
Silt density index	More than 6.5	Less than 3

Untreated water often contains harmful bacteria, viruses and parasites, leading to waterborne diseases such as cholera, dysentery and giardiasis. Polluted untreated water can harm aquatic life and disrupt entire ecosystems [34]. Nutrient pollution from untreated water can cause excessive algal growth, leading to oxygen depletion in water bodies. High levels of dissolved salts and corrosive ions in untreated water can damage pipes, plumbing systems and industrial equipment, which leads to costly repairs [35,36]. Untreated water with suspended solids can cause sediment build up in reservoirs and water treatment facilities. Using untreated water for irrigation can lead to soil salinity and reduced crop yields. Contaminated water can harm livestock, impacting agricultural production. Treating waterborne diseases strains healthcare systems and can lead to substantial medical costs. As seen from the comparison shown in Table 1, the sample collected is unfit to be discharged in the water bodies [37]. Discharge of untreated water in the society might cause various effects including eutrophication and cholera.

2.2. Pulsed direct current system

A new system configuration was developed for the conversion of AC-DC with a 3-phase diode bridge rectifier and the DC input to buck converter is smoothened with capacitor filter as shown in Fig. 1. Output power optimization as well as voltage control is obtained through the pulse width modulation (PWM) pulses that are generated in the control module consisting of digital signal processor - dsPIC 4011. PWM pulses are driven through the driver module and fed to IGBT module. Hardware protection system is provided to reset the PWM pulses once the operating temperature of IGBT module reaches 85°C (as designed based on the safe operating region from the electrical characteristics of the device). Output current is limited to a maximum of 40A from the design requirement of the coagulator to protect the system for overcurrent and short circuit.

2.3. System and operation

Electrocoagulation is performed in the designed miniscule reactor [38] with a capacity of 24 L having dimensions 400 mm × 200 mm × 300 mm (L × B × H) as per industry requirement, as shown in Fig. 2. A total of 23 iron electrode plates (3 mm) with an inter electrode distance of 12 mm were arranged in the reactor. Depending on the operational requirement of electrocoagulator, the continuous running time and operating voltage are varied suitably. This PDC module is designed to operate on full load for a fixed time schedule. By varying the duty cycle, the output voltage can be raised or lowered, with the manual push button switches connected to increment/decrement part of dsPIC program interface. The system runs normally until the output current reaches the set value or the temperature reaches the set value, above that the PWM pulses are disconnected by the hardware protection unit. The output pulsed current is smoothened by the designed Inductor filter. Additionally, the capacitor bank is supposed to absorb the DC link voltage ripple, thereby improving the system power factor.

2.4. Design of proposed system

This pulsed DC module with dsPIC is properly designed to operate at various operating voltages to deliver the intended results. The IGBT's rating is formulated to meet the peak output requirement of the electrocoagulation module of 16 kW which is adequate to maintain the unit's maximum performance. The following subsections provide the design of various system components.

2.4.1. Power switch selection

A SKM200GB12T4 dual switch IGBT module forms the switching component in the buck converter module with voltage and current (V_{CES}, I_C) of 1200V and of 313 A, at standard test conditions (STC), respectively, and 316J IGBT gate

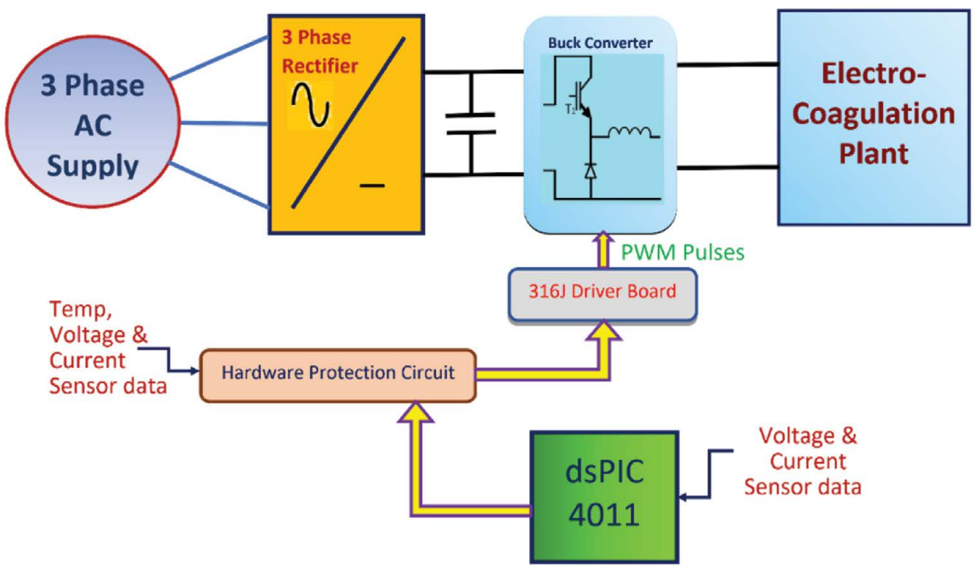

Fig. 1. Block diagram of pulsed direct current system to electrocoagulation plant.

drive optocoupler is selected for driving power IGBTs. The output stage's high operating voltage range provides the drive voltages required by gate-controlled devices. This optocoupler's voltage and current output makes it ideal for directly driving the selected dual switch IGBT module in the designed system.

2.4.2. Modeling of buck converter

Buck converters are also referred as step-down converters that offers a typical output voltage that is lower than the input voltage. Fig. 3 depicts a non-isolated buck converter circuit diagram. IGBT is used as the power semiconductor device here. Only one of the two switches of the module is activated to work in the first quadrant, while the diode of the second switch is employed for operation in the freewheeling mode [39]. The output filter containing inductor L and capacitor C is utilized to reduce the amount of ripple content. The ON/OFF state of switch SW1 gets controlled by the PWM signal. When the PWM pulse signal is high, SW1 is ON, and low, SW1 is OFF. The state of conduction of diode is just out of phase with that of SW1. Thus, as the conduction duty ratio of the PWM signal varies during a PWM cycle, the converter's output voltage will also vary. As a result, depending on the converter's condition, the output voltage given in Eqs. (1) and (2) can be changed in real-time by modifying the PWM signal's conduction duty ratio, which is accomplished via PI control [40] in the dsPIC.

The buck converter's average output voltage is:

$$V_O = \frac{R / \left(\frac{1}{sC}\right)}{sL + R / \left(\frac{1}{sC}\right)} \cdot \frac{t_{\mathrm{ON}}}{T} \cdot V_{\mathrm{dc}} \tag{1}$$

where t_{ON} is the ON state time duration and T is the total time and R, L and C are circuit parameters, and V_{dc} and V_O are the input and output voltages, respectively. The output transfer function:

$$G(s) = V_O = \frac{1}{s^2 LC + s\frac{L}{R} + 1} \cdot D \cdot V_{\mathrm{dc}} \tag{2}$$

where D is the duty cycle.

The magnitude of duty cycle D for a DC constant voltage of around 200 V with switching frequency of 18 kHz can be estimated [41] as $D = 0.45$.

For the buck converter's design, the input voltage V_{dc} is taken as 440 V DC, the output voltage requirement is variable DC voltage in the range of 100 to 400 V, with an optimal switching frequency of 18 kHz, the inductor and capacitor values are computed as $L = 1{\cdot}e^{-3}$ H and $C = 0.22{\cdot}e^{-6}$ F from the design equations [41]. The duty cycle of the switch can be varied in between 0.227 to 0.909, to achieve the change in average output voltage [42].

According to the optimum values of duty cycle, Inductor was designed to provide continuous and smooth DC current to the load. During buck mode of operation, when the switch is turned ON, the source powers the load as well as stores energy in the inductor L. Inductor L discharges its stored energy and feeds the load while the switch is in the OFF position. The Volt-Sec balance equation estimates that the inductor L should be minimum 1 mH for continuous current conduction.

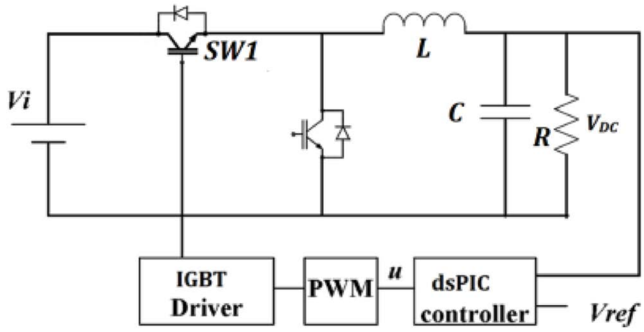

Fig. 3. Non-isolated buck converter circuit.

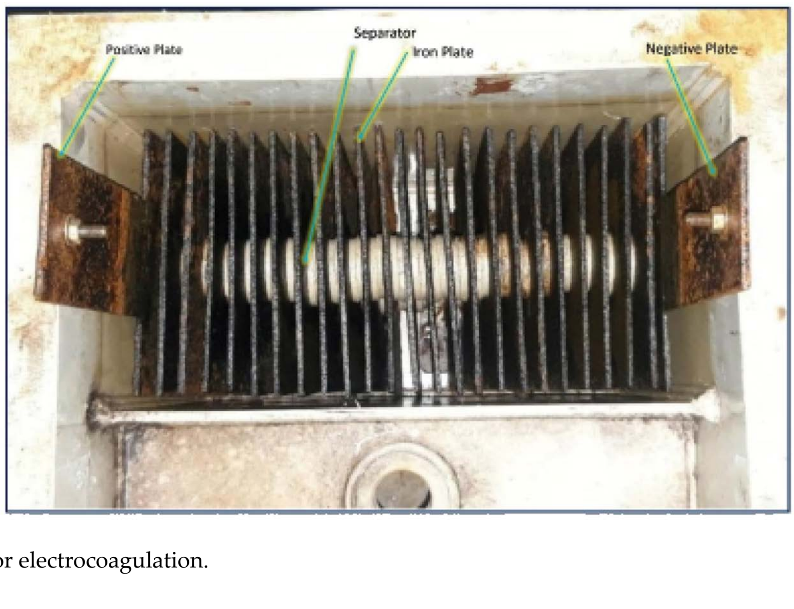

Fig. 2. Miniscule reactor for electrocoagulation.

2.5. Control scheme

A crucial component of the PDC that enables stable voltage transformation is the control circuit. The basic block diagram of overall system as shown in Fig. 1, has some of the control logics that are designed for a developed system to operate it efficiently under all working situations. Buck converter output should be resistant to changes in load and reference voltages and it should be controlled and adhered to design specifications. The buck converter needs to conform to the desired range of requirements. Designers frequently have trouble obtaining the required phase margin for a buck converter when using a conventional PID controller. In accordance with this, a pulse modulator and DSP implementation are required. The switching efficiency of IGBT switches was improved by variable pulse width and output voltage ripples were eliminated by selecting the proper inductance and capacitance values. As a result, the switching process was free from EMI interference [43]. Traditional PI controllers rely on exact mathematical models that are guaranteed to be reliable, stable and controllable. They perform well and have a straightforward structure. The controller receives the error and uses it to calculate the proportional and integral gain values k_p and k_I, respectively. The correct values are fed to the PI controller along with the error signal to control the duty ratio.

The output voltage is controlled by a PI controller using the IGBT module in the buck converter. Here, the switch permits current to flow so that the capacitor (C) and inductance (L) can be fully charged. Diode used to freewheel the energy that has built up in L during the charged state to pass and energise the load [44]. After fine-tuning the PI controller, the following proportional gain (k_p) and integral gain (k_I) values were obtained to control the desired output voltage k_p = 2.1 and k_I = 285. The frequency for switching between ON and OFF states is generated by a triangle wave generator. The switching frequency is 18 kHz. Ramp voltage referencing is taken into consideration to prevent overshooting at the very start of circuit operation. As a result, voltage rises at a rate of 17.3 V/ms this way, without overshoots. The reference switcher also enables instantaneous voltage switching.

3. Results and discussion

3.1. Simulated performance

A simulated performance of controlled rectifier-based DC (CR-DC) and PDC was performed in MATLAB Simulink® and the results are displayed in Fig. 4. Fig. 5 depicts the high overshoot and ripples in the existing converter than the proposed PDC converter. The DC voltage levels required in a typical electrocoagulation was taken as reference and the buck converter was controlled to provide output voltage at various steps from 100, 150, 200 and 275 V in the same manner that was realized and validated in experimental stage, respectively, to demonstrate the improvement in specific energy consumption of the developed system. Initially, the three-phase AC supply is converted into DC with 3 phase bridge rectifier and fed to a highly efficient DC-DC buck converter [45–47] to supply the resistive load at different DC levels from 100, 150, 200 and 275 V. The DC obtained is smooth compared to that from thyristor-based control. A sample of the three-phase AC input and the DC output voltage for 275 V is shown in Fig. 4.

Now for controlled rectifier-based DC supply (CR-DC) obtained from the three-phase AC, is rectified with thyristor-based controlled rectifier [48–50], at different DC voltage levels from 100, 150, 200 and 275 V, by adjusting the firing angle "α". The ripple in CR-DC is high when compared to that from PDC. The three-phase AC input, PWM pulses and the DC output voltage and current corresponding to

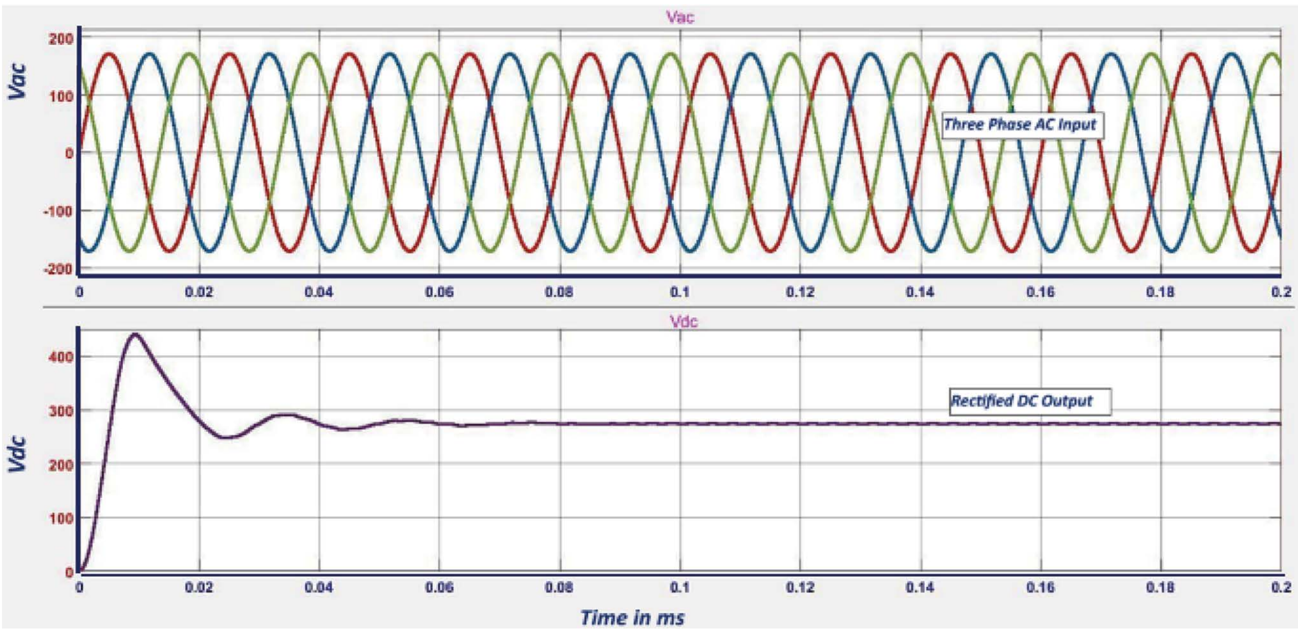

Fig. 4. Three-phase input and rectified DC output of 3 phase thyristor-based control rectifier.

275 V is shown in Fig. 5, the ripples in the waveform shows the amount of AC in DC the amount of pure DC is limited in traditional CR-DC whereas in PDC the ripple content is very low due to high operating frequency that also results in lower amount of filter components, which consumes less energy compared to the low frequency operation of thyristorized controlled rectifier CR-DC that produces high ripple and requires large amount of Inductor and capacitor to filter the ripple as well as consume more energy in them, thereby reducing the efficiency.

3.2. Energy consumption investigations on COD removal

Initially the whole process of electrocoagulation was performed with CR-DC power supply at various voltages and COD is analyzed. The specific energy consumption (SEC) for the process was also measured for a fixed duration of 1 h. The results are tabulated in Table 2. Similarly, the electrocoagulation experiments with buck converter based PDC power supply at various voltages were performed towards COD removal and the energy efficiency [49] results are presented in Table 3.

Under the same operating conditions, it was observed that the output current I_{dc} and output power P_{dc} values of the electrocoagulation unit powered by the buck converter-based PDC were reduced, and the efficiency increased to 95.5% in comparison to the CR-DC module. This finding defends the assertion that the converter is highly efficient due to the fact it operates at a high frequency and has smaller filtering components than an SCR-based rectifier, leading to lower I_{dc} and P_{dc} as obtained in Table 2. As well as the consumption of electrode plate is higher due to action of unipolar current, whereas in PDC supply due to the pulsing nature of the supply the consumption of electrode plate is reasonably lower, this fact is proved [20].

The COD removal efficiency for CR-DC and PDC modules were investigated and the results are represented in Fig. 6 and other parameters are summarized in Table 4. It can be observed that the removal efficiency remains unchanged at various DC voltages suggesting that the PDC can be an energy efficient method to remediate the COD in wastewaters [51,52]. It is also observed that in addition to COD other parameters such as BOD, total hardness and turbidity decreased as well for CR-DC and PDC methods. These results suggest that the PDC based electrocoagulation technique is equivalent to CR-DC based process with additional energy savings.

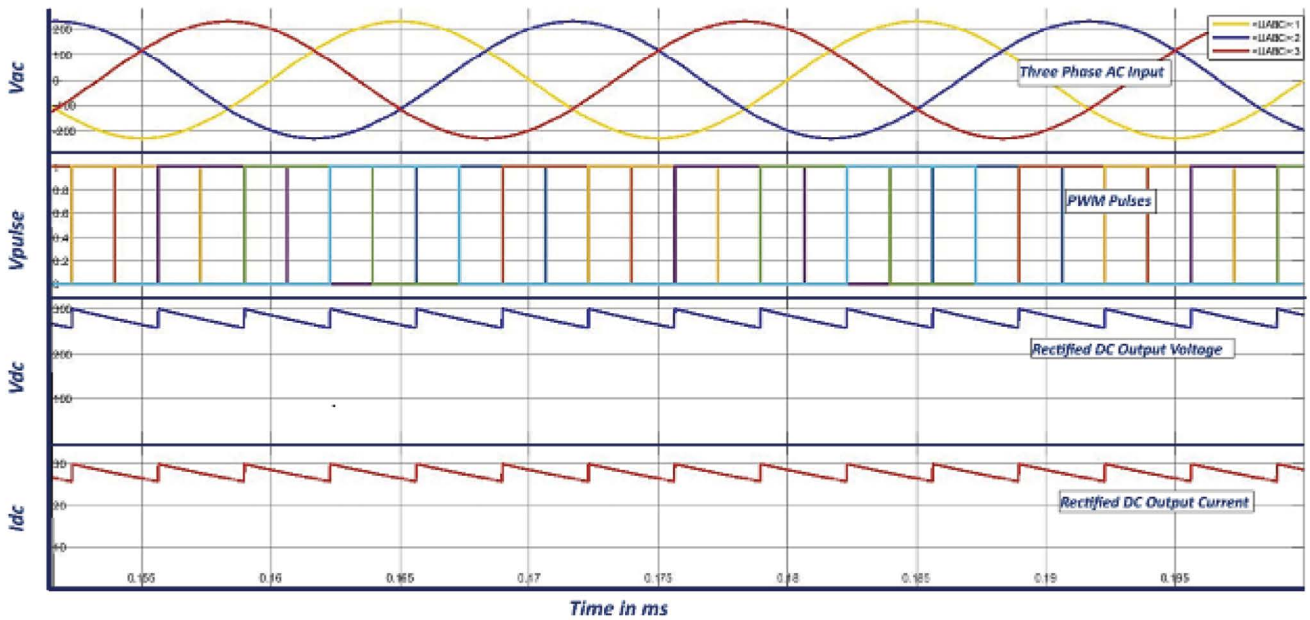

Fig. 5. Three-phase input, pulse width modulation and rectified DC output of PDC converter.

Table 2
Three-phase thyristor-controlled rectifier (CR-DC) module efficiency

Voltage (V)	Current (A)	Cos (pi)	Operating time (h)	Power (kW)	Energy (kWh)	Output DC voltage (V_{dc})	Output DC current (I_{dc})	Output power (P_{dc})	Efficiency (%)
440	6.4	0.276	1	1.346	1.35	105	8.31	0.872	64.8
440	24.4	0.507	1	9.433	9.43	193	32	6.176	65.5
440	27.3	0.538	1	11.211	11.21	205	36	7.380	65.8
440	31	0.757	1	17.885	17.89	288	42.1	12.124	67.8

Table 3
Bridge rectifier - buck converter based pulsed - DC (PDC) module efficiency

Voltage (V)	Current (A)	Cos (pi)	Operating time (h)	Power (kW)	Energy (kWh)	Output DC voltage (V_{dc})	Output DC current (I_{dc})	Output power (P_{dc})	Efficiency (%)
440	2.1	0.754	1	1.206	1.21	105	8.31	0.872	72.3
440	7.5	0.867	1	4.955	4.96	193	21.27	4.105	82.8
440	8.3	0.891	1	5.635	5.64	205	23.6	4.838	85.8
440	15.6	0.954	1	11.341	11.34	288	37.6	10.828	95.5

Table 4
Physio-chemical characteristics of effluent after treatment with DC and PDC

Parameters	Raw effluent	CR-DC	PDC
pH	9–10	6–7	6–7
Suspended solids, mg/L	500	50	50
COD, mg/L	2,000	500	550
BOD, mg/L	700	100	100
Colour, Pt.Co.	3,000	300	300
Conductivity, µS/cm	8,000 max.	8,000 max.	8,000 max.
TDS, mg/L	4,000	4,000 max.	4,000 max.
Iron, mg/L	Less than 0.5	Less than 0.5	Less than 0.5
Oil and grease, mg/L	20	1	1
Sodium, mg/L	2,500 max.	2,500 max.	2,400 max.
Sulfate, mg/L	800 max.	800 max.	800 max.
Chloride, mg/L	1,500 max.	1,500 max.	1,500 max.
Silica, mg/L	20	5	5
Total hardness, mg/L	200	100 mg/L	<100
Turbidity, NTU	500	50	<50
Silt density index	More than 6.5	5	5

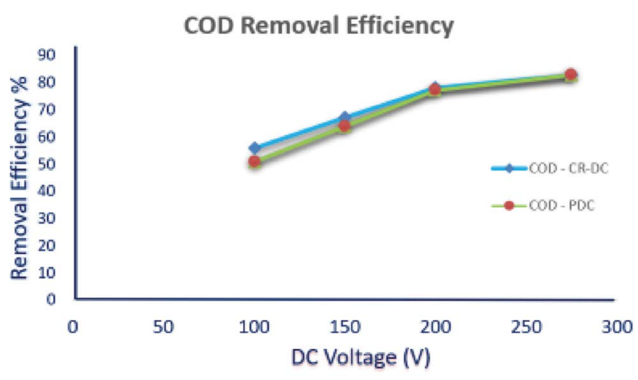

Fig. 6. Chemical oxygen demand removal efficiency of CR-DC and PDC modules.

3.3. Cost assessments

In general, the viability of any treatment technique depends on the cost of the process, and it is highly desirable to evaluate the operating cost of the energy consumption (EC) process. In this study, a comparative investigation on CR-DC and PDC process were investigated towards removal of COD from industrial wastewater. Specific energy consumption (SEC) analysis was carried out and the results are represented in Fig. 7. It is clearly visible that the specific energy consumption for PDC is less than CR-DC at various voltages. The SEC of PDC at 275 V is closer to 6 kWh/m³ compared to 12 kWh/m³ of DC and the SEC is 50% lesser than the CR-DC. The operating cost of the present process arrived with Eqs. (3)–(5).

$$\text{Operating Cost} = aC_{\text{energy}} + bC_{\text{electrode}} \tag{3}$$

where a and b are coefficients of electricity and electrodes and C_{energy} and $C_{\text{electrodes}}$ were calculated based on Eqs. (4) and (5):

$$C_{\text{energy}} = \frac{U \times I \times t_{\text{EC}}}{V \times C_i \times R_e} \tag{4}$$

$$C_{\text{electrode}} = \frac{I \times t_{\text{EC}} \times M_w \times \varnothing_{\text{Fe}}}{z \times F \times V \times C_i \times R_e} \tag{5}$$

where V is volume (m³) of the effluent, C_i (kg/m³) t_{EC} is COD concentration of effluent, and R_e is COD removal efficiency.

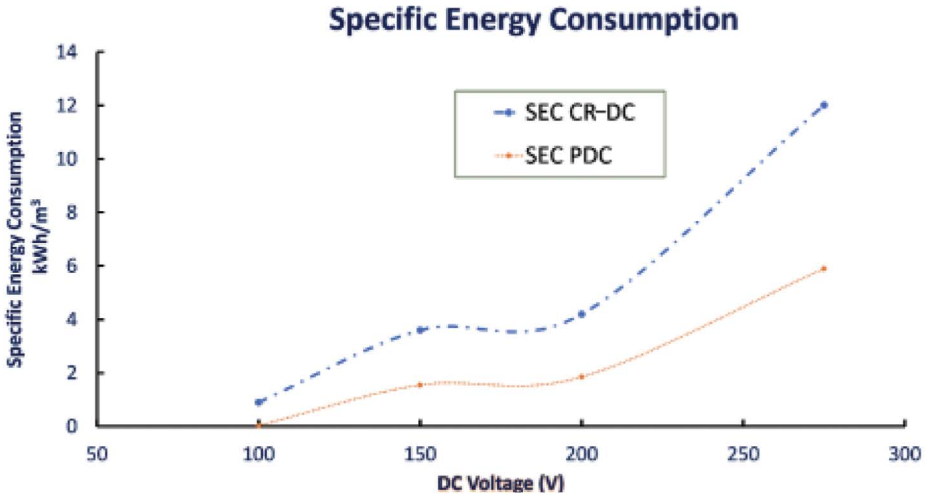

Fig. 7. Specific energy consumption comparison between the CR-DC and PDC converters.

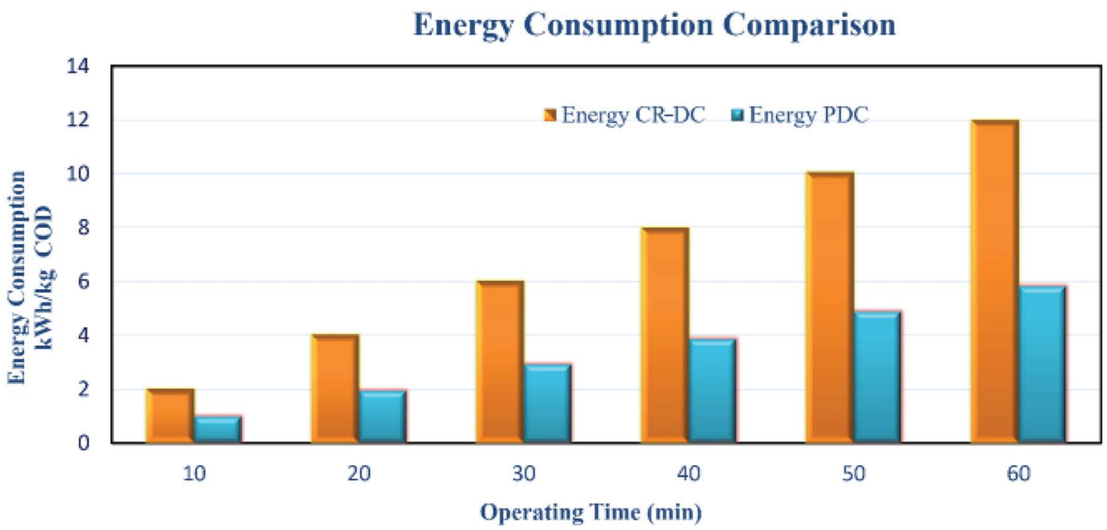

Fig. 8. Energy consumption comparison between the CR-DC and PDC converters.

From Fig. 7 it was noticed that for PDC, the voltage change from 100 to 150 V; 90% increase in SEC was observed and for change in voltage from 200 to 275, 68.5% was observed and for DC 80% and 64.63%, respectively. In comparison with CR-DC and PDC electrocoagulation, overall, 50%–60% improvement in SEC is observed for high operating voltage and 79% improvement was observed when operated at low voltage due to high power loss in DC. The specific energy consumption at various voltages for DC and PDC are represented in Fig. 7. Fig. 8 represents the energy consumption between CR-DC and PDC with respect to operating time.

The specific energy consumption for DC is in the range of 2 to 11.99 kWh/kg for the operating time from 10 to 60 min and for PDC it is observed to be 0.97 to 5.81 kWh/kg. It is noticed that the specific energy consumption is 50% less for PDC suggesting that PDC has prolific applications in electrocoagulation treatments of wastewater. The operating cost for different operating time were calculated with an assumption of Rs. 15 per unit for industry and it is summarised in Table 5 and it is observed that the operating cost increases with respect to the energy consumption;

Table 5
Operating cost of energy consumption at various time intervals for CR-DC and PDC

Operating time (min)	Energy CR-DC (kWh)	Cost CR-DC (₹)	Energy PDC (kWh)	Cost PDC (₹)
10	2.00	29.98	0.97	14.62
20	4.02	60.33	1.92	28.87
30	6.01	90.22	2.91	43.58
40	7.99	119.92	3.85	57.74
50	10.05	150.82	4.87	73.10
60	11.99	179.88	5.81	87.16

in comparison to DC, the PDC electrocoagulation cost less which makes it a viable technique. When the system operated for 1 h, the operating cost for CR-DC is Rs. 179.8 for PDC it is Rs. 87.1 therefore operating cost was reduced by 52% and similar trend was observed for all operating time, thus PDC method is more economical and less energy intensive. Electrocoagulation removes only the colloidal/suspended particles in the wastewater, while dissolved impurities like chloride and sulfate can be removed with the subsequent process of either evaporation or reverse osmosis.

4. Conclusion

This comprehensive study evaluates the performance of both CR-DC and PDC in the electrocoagulation treatment of COD present in industrial effluent. An innovative control logic for PDC was developed to enhance its efficiency and extensive simulations were conducted using MATLAB to compare the performance of these two systems. A key focus of this research was to investigate the energy consumption of both modules in relation to operating voltage and operating time. The results of this investigation revealed compelling insights into the energy consumption patterns of these systems. When the operation time was increased from 10 to 60 min, it was observed that the energy consumption for the CR-DC module exhibited a noteworthy variation, ranging from 2 to 11.99 kWh/kg. In contrast, the PDC module showcased remarkable energy efficiency, with energy consumption ranging from 1.01 to 5.81 kWh/kg over the same operating time frame. This substantiates the superiority of the PDC system in terms of energy efficiency, regardless of the operating voltage or operating duration. Furthermore, this study identified specific operational conditions that yielded optimal results. Notably, the maximum removal efficiency of COD was achieved when the EC unit operated at 275 V. In the case of PDC, the maximum gain in energy consumption occurred at 100 V, further emphasizing the advantages of PDC over CR-DC, particularly in mitigating power loss at low voltage levels.

To assess the economic viability of these methods an in-depth analysis of operational costs for both the CR-DC and PDC systems was performed. The findings revealed that PDC exhibited a remarkable cost advantage, being 50% more cost-effective across all modes of operation. These cost savings, combined with the superior energy efficiency and COD removal efficiency demonstrated by the PDC-based electrocoagulation, underscore the potential of this technique as a highly effective and economically favorable solution for the treatment of COD in industrial wastewater. To conclude, the results of this study provide evidence that pulsed direct current-based electrocoagulation represents a promising and cost-effective approach for the efficient removal of COD from industrial wastewater, contributing significantly to environmental sustainability and resource optimization in industrial processes.

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Declaration

Authors declare no conflicts of interest.

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