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Voltage, Current, and Work Process Monitoring System on CNC Diode Lasers

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Abstract – The advancement of CNC laser diode technology has transformed manufacturing by enabling high precision cutting and engraving of various materials, yet ensuring reliable operation requires accurate monitoring of electrical and mechanical parameters. This research focused on designing and implementing a real-time monitoring system that integrates the PZEM-004T sensor for electrical measurements and limit switches for safety boundaries in CNC laser diode machines. The system was developed using NodeMCU ESP8266 as the main controller, with results displayed on an LCD 16x2 and alarms generated through a buzzer and relay. Experimental evaluation demonstrated that the system effectively measured voltage, current, power, and energy, with the PZEM-004T showing an average error below 5% compared to reference instruments. The integration of the limit switches functioned reliably, preventing mechanical failures and ensuring safe operation within defined limits. Monitoring data supported energy efficiency by identifying power usage patterns and reducing operational risks. Engraving tests confirmed stable performance, with improved detail observed during longer process durations. Overall, the implemented system provides a practical and reliable solution for operational monitoring and mechanical protection, making it particularly suitable for small-scale CNC laser diode applications in industrial, educational, and creative fields.

Keywords – CNC Laser Diode, NodeMCU, Sensor PZEM-004T, Limit Switch, Electrical Power Monitoring

1. INTRODUCTION

In contemporary manufacturing, the pursuit of precision, efficiency, and automation has driven continuous advancements in production technologies. A prominent development in this area is the extensive utilization of Computer Numerical Control (CNC) machines, which execute production tasks based on digital commands and provide substantial improvements over conventional manual methods [1]. CNC systems facilitate processes such as cutting, engraving, and shaping with high accuracy and consistency, making them essential across various domains, including creative industries, small workshops, educational institutions, and large-scale manufacturing. Among the different types of CNC machines, laser diode-based systems have gained particular recognition due to their capability to perform fine engraving and cutting with remarkable precision across diverse materials [2]. The laser’s inherent properties, monochromatic, coherent, and highly collimated, enable the production of intricate patterns, sharp details, and accurate replications of complex digital designs. Consequently, CNC laser diode machines are widely adopted in applications demanding detailed results, user-friendly operation, and adaptability to materials such as wood, plastics, acrylics, cartons, leather, and textiles [3].

Despite their numerous advantages, the operation of CNC laser diode machines presents several critical challenges, particularly in terms of electrical and mechanical reliability. The performance and durability of these machines are highly dependent on the stability of their power supply [4]. Issues such as voltage fluctuations, current surges, and sudden power losses are

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common and can lead to reduced laser performance, degraded engraving quality, or even damage to sensitive components, including the laser diode, stepper motors, and power modules [5]. Mechanical risks are also significant, where movements exceeding the designed limits may cause misalignments or collisions that compromise the frame or actuators. Traditionally, many CNC laser systems have not been equipped with integrated monitoring features for electrical and mechanical parameters. In the absence of real-time data such as voltage, current, or mechanical positioning, operators face difficulties identifying abnormal conditions before irreversible damage occurs [6] [7]. Undetected overcurrents or overvoltages can result in overheating and component failures, while unnoticed limit violations may cause mechanical crashes, leading to increased repair costs and equipment downtime. These risks, combined with safety concerns, highlight the urgent need for intelligent monitoring solutions that ensure both operational reliability and user protection.

To overcome these challenges, the implementation of a reliable monitoring system becomes indispensable. Such a system should be capable of continuously measuring critical electrical parameters namely voltage, current, power, and energy while simultaneously offering feedback on mechanical positioning through the use of limit switches [8]. A responsive and precise monitoring mechanism enables proactive intervention: abnormal electrical conditions can activate alarms or automatically shut down the system via relays, whereas breaches of mechanical limits can immediately stop machine movement, thus safeguarding both the equipment and the workpiece [9] [10]. Recent advancements in sensor technology and the availability of low-cost microcontrollers have made the development of comprehensive monitoring solutions increasingly feasible and economical. As an example, the PZEM-004T sensor module provides accurate AC measurements of electrical parameters, supported by digital communication features that seamlessly integrate with microcontrollers such as the NodeMCU equipped with the ESP8266 chipset [11]. This configuration facilitates real-time monitoring and display of operational data. At the same time, the application of standard limit switches ensures reliable detection of axis boundaries, thereby preventing mechanical components from operating beyond their designated safe ranges.

The rapid advancement of Internet of Things (IoT) technologies opens new possibilities for enhancing CNC laser diode systems [12]. Through appropriate networking, monitoring data can be transmitted and accessed remotely, allowing preventive maintenance, process optimization, and energy management to be conducted from virtually any location, in line with the objectives of Industry 4.0 [13] [14]. However, even without IoT connectivity, the integration of local displays (LCD), alarms (buzzers), and automatic shutdown mechanisms (relay switching) significantly enhances operational safety and reliability, especially in small enterprises or educational settings where financial and technical resources are often constrained[15] [16]. This study seeks to bridge the gap between cost-effective monitoring technologies and practical application requirements, while also serving as a reference for future research and deployments in industrial and academic contexts. The system's objectives, methodology, and validation are designed to demonstrate that an accessible, microcontroller-based solution can achieve industrial-grade reliability in safeguarding CNC laser systems. The development and implementation of such an integrated, real-time monitoring and protection system marks an important step toward safer and more efficient use of CNC laser diode machines. By ensuring equipment longevity, improving work quality, conserving resources, and boosting productivity, this approach addresses key priorities within modern production environments.

2. RESEARCH METHOD

2.1. Tool Planning

This study used engineering and experimental methods that included the design and implementation stages of a voltage, current, and work process monitoring system on a diode laser CNC machine. The initial stage began with tool planning by determining the main component

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requirements and designing the system based on the research objectives and problem formulation that had been established. At this stage, component selection was an important aspect, including NodeMCU as the control center, PZEM-004T sensors to measure electrical parameters such as voltage and current, and limit switch sensors as mechanical limit safety devices [17].

The system architecture in this study was deliberately designed to integrate the electrical and mechanical monitoring functions in real time, utilizing PZEM-004T for precise voltage and current measurements and reliable limit switch mechanisms for movement boundaries. This architectural improvement ensures immediate detection and intervention for both electrical and mechanical anomalies on the CNC diode laser.

2.2. Hardware Planning

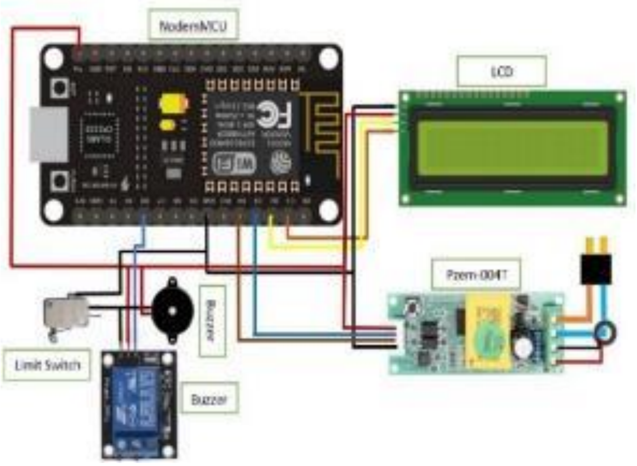

Figure 1 Design of a Tool

The next stage was the design of hardware and software. On the hardware side, block diagrams and schematic circuits were developed to integrate the NodeMCU, PZEM-004T sensor, limit switch, 16x2 LCD, relay, buzzer, and 5V DC adapter. After all components were assembled, initial testing was conducted to ensure that each part functioned as designed. On the software side, a programming algorithm on the NodeMCU is developed to read sensor data, process signals from the limit switch, display measurement results on the LCD, and activate the relay and buzzer when abnormal conditions are detected. In the event of an electrical overload or limit switch activation, the NodeMCU will automatically cut off the power supply and activate the buzzer as a warning system. Unlike conventional monitoring approaches that typically operate separately or reactively, the NodeMCU-based solution allows for seamless interaction between sensor readings and control signals. The control algorithm is developed to execute automatic actions such as activating alarms and shutting off power through relays and buzzers as soon as abnormal electrical or positional conditions are detected, thereby optimizing protection and data recording of operating parameters in an integrated manner

2.3. Tool Desain

The final stage consists of structured system testing on the diode laser CNC machine. Measurement data is obtained directly at specific points in the electrical system, then analyzed based on established standards and formulas. The test results are used to evaluate system performance and as a basis for further improvements, so that this monitoring system prototype can function effectively, safely, and efficiently in supporting CNC laser machine operations. This system's flowchart illustrates how improvements in architecture provide simultaneous monitoring, data logging, and automated safety responses. All sensor data are processed by NodeMCU, which ensures that critical events are addressed instantly and that operational records

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are kept accurately and efficiently, supporting proactive maintenance and long-term reliability for users.

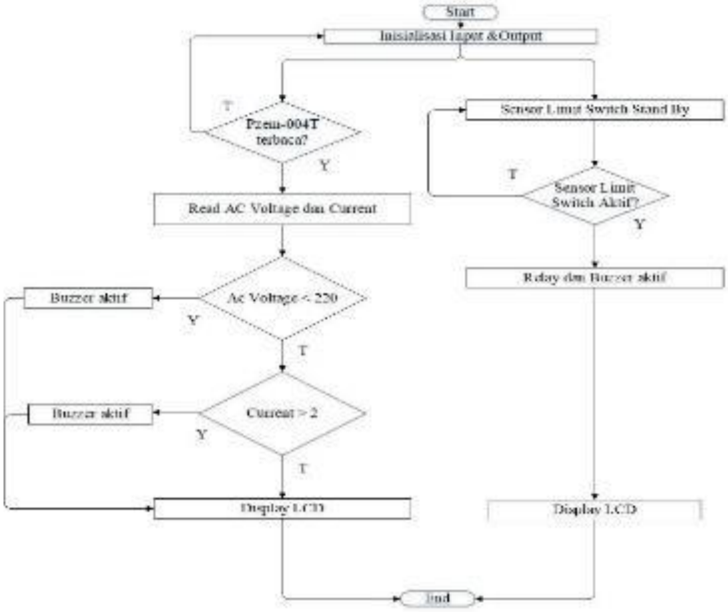

Figure 2 Flowchart

3. RESULTS AND DISCUSSION

This research resulted in a microcontroller-based monitoring system using NodeMCU ESP8266 integrated with a PZEM-004T sensor for monitoring electrical parameters and a limit switch sensor for mechanical protection on a diode laser CNC machine. Device testing and data analysis results show that the designed system can effectively detect, process, and display electrical information and operational status of the tool in real-time, thereby supporting machine safety and efficiency.

The process of measuring voltage and current at various points specified in the system block aims to ensure that all components receive power supply according to the expected specifications. The main measurement points include the PLN source input, transformer output, after the rectifier diode, after the capacitor, IC regulator output, NodeMCU input, and other sensor inputs such as limit switches, buzzers, and LCDs. The measurement data is displayed in the following table:

Table 1 Measurement Point Results

No	Titik Uji	Acuan Standart	Satuan	Hasil Uji					X	Description
				1	2	3	4	5		
1	TP 1	220 (*Volt*)	V (*Volt*) AC	223	223	223	223	223	223	*Input* Trafo (PLN)
2	TP 2	12 (*Volt*)	V (*Volt*) AC	12,65	12,59	12,61	12,41	12,20	12,49	*Output* Trafo
3	TP 3	15 (*Volt*)	V (*Volt*) DC	15,00	15,10	15,25	15,28	15,29	15,18	*Output* Dioda

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4	TP 4	15 (*Volt*)	V (*Volt*) DC	15,25	15,10	15.00	15,08	15.00	15,06	Kapasitor
5	TP 5	5 (*Volt*)	V (*Volt*) DC	5,02	5.04	5,03	5.05	5,01	5,03	*Input* IC
6	TP 6	5 (*Volt*)	V (*Volt*) DC	5,02	5,03	5,00	5,04	5,07	4,83	*Input* NodeMCU
7	TP 7	3 (*Volt*)	V (*Volt*) DC	3.1	3,3	3,5	3,7	3,4	3,4	*Limit switch*
8	TP 8	3 (*Volt*)	V (*Volt*) DC	3,3	3,4	3,2	3,7	3,8	3,48	*Input Buzzer*
9	TP 9	5 (*Volt*)	V (*Volt*) DC	5,02	5,04	5,03	5,05	5.06	5,04	*TX Pzem-004T*
10	TP 10	5 (*Volt*)	V (*Volt*) DC	4,92	4,98	5,03	5,00	5,01	4,98	*RX Input* Pzem-004T
11	TP 11	5 (*Volt*)	V (*Volt*) DC	5,02	5,01	5,03	4,98	5,04	5,02	*GND Input* Pzem-004T
12	TP 12	5 (*Volt*)	V (*Volt*) DC	5,02	5,01	4,98	5,00	5,03	5,01	SDA LCD 16X2
13	TP 13	5 (*Volt*)	V (*Volt*) DC	4,92	5,00	4,95	4,98	5,01	4,97	SCL LCD 16X2
14	TP 14	5 (*Volt*)	V (*Volt*) DC	4,92	4,98	5,00	4,99	5,01	4,98	VCC LCD 16X2

Based on the measurement results, the voltage values at each point show stability and are close to the standard reference values for the components. For example, at the PLN input point, the average value is 223 V, at the NodeMCU input it is 4.83 V, while at the PZEM sensor and LCD inputs it is in the range of 4.98–5.04 V, indicating that the power supply circuit is functioning optimally. Current measurements at the load point also show results that are proportional to the amount of power generated by the system. Further analysis was conducted by calculating the percentage error between the measured values and the theoretical values or data sheet values that had been calculated previously. The comparison results showed that the majority of the percentage errors were below 5%, so it can be concluded that the measurement deviation was relatively small and the main sensor had been calibrated properly. As for the limit switch and buzzer input measurements, the results were "out of range," which was caused by the basic nature of the on/off output signal, which is different from analog sensors. This is considered reasonable and in accordance with the system design characteristics.

Compared to legacy monitoring systems, the newly developed architecture provides significant advantages in integrated safety and operational efficiency. While traditional systems often lack real-time response and comprehensive data recording, the proposed solution enables immediate detection of electrical and mechanical irregularities, automatic intervention, and detailed logging of operational parameters. As a result, the system ensures enhanced machine protection, reduced downtime, and more reliable long-term performance. These improvements collectively address the key weaknesses found in older standalone or reactive monitoring designs.

The PZEM-004T sensor was tested by monitoring changes in electrical parameters sequentially while the device was operating under actual load conditions. Measurements were

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taken periodically to record voltage, current, and power data, with the aim of testing the reliability of the system under various operating conditions, ranging from idle, light load, to maximum load. The test results showed that the output voltage was stable in the range of 223.8–225 V. The recorded electric current was 0.18 A at the start of the test and then gradually decreased to 0.08 A as the load decreased. In line with this, the electrical power also decreased from 39.6 W to 18.37 W during the 70-minute observation period.

Table 2 PZEM-0047T Sensor Testing

Time (menit)	**Voltage (V)**	**Current (A)**	**Power (W)**	***Limit switch***	**Description**
19:00:00	225	0,18	39,6	*Non*-Aktif	*In range*
19:15:00	223,9	0,17	38,29	*Non*-Aktif	*In range*
19:20:00	224,7	0,17	39,1	*Non*-Aktif	*In range*
19:25:00	223,8	0,17	38,49	*Non*-Aktif	*In range*
19:30:00	223,9	0,17	38,51	*Non*-Aktif	*In range*
19:40:00	223,9	0,14	32,24	*Non*-Aktif	*In range*
19:45:00	223,9	0,12	25,75	*Non*-Aktif	*In range*
19:50:00	224,1	0,08	18,15	*Non*-Aktif	*In range*
20:00:00	223,9	0,08	18,14	*Non*-Aktif	*In range*
20:10:00	224	0,08	18,37	*Non*-Aktif	*In range*

The power fluctuations that occur indicate that the system can sensitively read changes in energy consumption due to changes in load or machine operating conditions. The sensor's performance has been verified to be highly responsive for early detection of electrical anomalies such as current surges or significant voltage drops. Testing also ensures that there is no significant noise interference in the transmission of sensor data to the microcontroller. The limit switch is integrated as the primary safety sensor responsible for detecting the maximum movement limits of the CNC machine along its axes. The test was conducted by pressing and releasing the limit switch to simulate the machine's conditions during normal operation and when a collision threat (hard stop) occurs. When the limit switch is in the active position (pressed), the output voltage is stable at 3.295 V, indicating that the circuit is connected and the system allows operation. When the switch is released (inactive), the voltage drops to 0 V, causing the program to automatically cut off the power supply to the stepper motor via a relay and sound a buzzer as a warning. This interlock mechanism has proven to be effective as an emergency safety feature.

Table 3 Limit Switch Testing

No.	**Waktu (menit)**	**Tegangan (V)**	***Limit switch***	**Keterangan**
1	19:40:00	3,295	Aktif	*In range*
2	19:50:00	3,294	Aktif	*In range*
3	19:55:00	0	*Non*-Aktif	*Tidak range*

The reliability of the limit switch sensor is reflected in the consistency of the test results, with two consecutive readings in active conditions showing a very small difference (only 0.001 V), indicating excellent connectivity and wiring of the device without any bouncing issues. This data proves that hardware-based protection works as expected and can prevent mechanical damage due to human error or operational disturbances.

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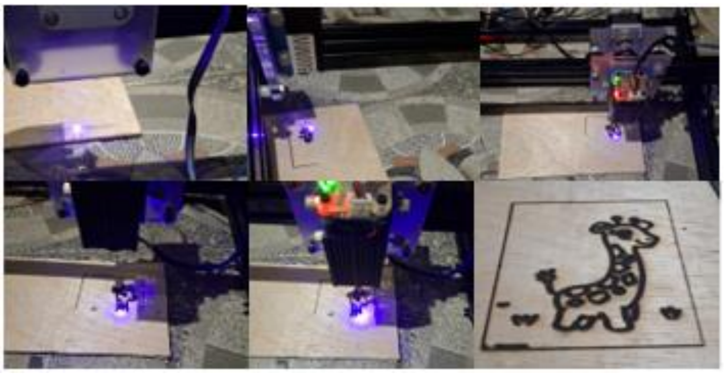

Figure 3 Work Time Process

Practical testing of machine performance was conducted by applying the engraving process to 3 mm thick plywood using varying exposure times and measuring operating parameters. During testing, the voltage was recorded as stable at around 225 V with a current of approximately 0.04 A, resulting in an effective power of around 9 W per engraving cycle. At durations of 20 to 240 minutes, the engraving quality improved with increasing exposure time, marked by neater lines, sharper details, and more significant engraving depth, although the side effect of darkening edges (burn marks) was also increasingly visible. Visual documentation during the process also shows that the system runs stably without any detected voltage drops, buzzer sound changes, or other warnings from NodeMCU, proving that the monitoring system integration is able to work in harmony with the security mechanism. Thus, operators can monitor directly through the engraving results while also monitoring real-time sensor data displayed on the LCD.

Based on comprehensive testing results, the monitoring system based on NodeMCU and PZEM-004T sensors and limit switches is able to work according to its functional design. The measurement error percentage is very small and within the tolerance limits set by the industry, making the system very suitable for energy monitoring and CNC machine protection applications on a small to medium scale.

4. CONCLUSION

This research concludes that the voltage, current, and work process monitoring system on a NodeMCU ESP8266-based diode laser CNC machine with PZEM-004T sensor and limit switch support has been successfully implemented effectively. This system is capable of monitoring electrical parameters in real-time with a good level of accuracy, as indicated by a measurement error percentage of less than 5%. In addition, the integration of a limit switch provides reliable mechanical protection, thereby supporting the safety and operational efficiency of the machine. Thus, this design not only extends the life of the device, but also minimizes potential damage from both electrical and mechanical aspects.

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