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Full Length Article

Analysis of Electrical Systems In CNC Machines At Bharat Dynamics Limited

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Abstract
Computer Numerical Control (CNC) machines rely heavily on robust electrical systems to ensure precision, reliability, and productivity in advanced manufacturing environments. This paper presents a detailed examination of the electrical architecture of CNC machines installed at Bharat Dynamics Limited (BDL), a major defence manufacturing organization. The study investigates key components including power distribution networks, control circuits, drive mechanisms, and safety interlock systems, with particular focus on operational performance, energy utilization, and fault detection capabilities.An in-depth analysis of power quality parameters such as voltage regulation, harmonic distortion, and transient behavior identifies opportunities for improving equipment reliability and extending component life. The work further evaluates the role of Programmable Logic Controllers (PLCs), Human–Machine Interfaces (HMIs), and closed-loop feedback mechanisms, demonstrating their influence on machining accuracy and process consistency.The research also reviews protective arrangements including overload protection, grounding schemes, earth-fault monitoring, and surge suppression to ensure safe and stable operation within an industrial defence production environment. Using system modelling, on-site observations, and comparative analysis, the study proposes recommendations for optimized electrical configuration, enhanced grounding practices, and implementation of advanced monitoring solutions.
The findings indicate that systematic evaluation and improvement of CNC electrical systems can significantly enhance operational efficiency, minimize downtime, and support compliance with stringent defence manufacturing requirements.

Keywords—*Computer Numerical Control (CNC), Electrical Systems, Power Quality, Programmable Logic Controller (PLC), Human–Machine Interface (HMI), Harmonic Distortion, Voltage Regulation, Fault Detection, Industrial Automation, Operational Efficiency.*

INTRODUCTION

Computer Numerical Control (CNC) machines play a vital role in modern precision manufacturing by enabling automated machining with high accuracy and repeatability. These machines rely on sophisticated electrical systems that combine power supply networks, control units, drive systems, feedback devices, and protection circuits into a coordinated operational structure. Proper electrical design ensures accurate motion control, stable machining performance, reduced downtime, and efficient energy utilization, all of which are essential for maintaining productivity in industrial environments.This study examines the electrical systems employed in CNC machines at Bharat Dynamics Limited (BDL), a leading public sector defence manufacturing organization in India. CNC machines at BDL are used for the fabrication of critical and high-precision components, where even minor electrical disturbances may lead to dimensional errors and affect product quality. Therefore, analyzing the electrical configuration and operational characteristics of these machines is important for ensuring reliable and continuous manufacturing processes.The electrical architecture of CNC machines typically consists of industrial power distribution units, servo drives, spindle motor control systems, Programmable Logic Controllers (PLCs), encoders, sensors, and Human–Machine Interfaces (HMIs). These elements operate through closed-loop control strategies to maintain positioning accuracy, speed regulation, and synchronized multi-axis motion. In addition, protective features such as overload protection, grounding arrangements, and emergency interlock systems are incorporated to ensure safe operation and safeguard both equipment and personnel.

LITERATURE SURVEY

Several researchers have investigated the design and performance of CNC machine electrical systems. Ekengwu and Emeruwa (2024) provided an overview of CNC technology and emphasized the integration of controllers, drives, and feedback devices for achieving high precision and automation in manufacturing applications. Their work highlighted the importance of electrical subsystems in enhancing machining flexibility and accuracy.

Elser, Lechler, and Verl (2024) studied process-integrated CNC systems and discussed the interaction between machining processes and control architectures. Their research showed that interpolation, multi-axis coordination, and real-time processing are heavily dependent on reliable electrical control systems for accurate machine operation.Ali, Razak, and Hayima (2020) reviewed AC servo motor control in industrial environments and explained how servo drives provide precise regulation of position, speed, and torque. Their study demonstrated that improved control techniques can enhance dynamic performance, making servo systems essential for CNC applications.

Han (2017) focused on PLC-based electrical control system design for CNC machines. The study examined power distribution, wiring configurations, and control of spindle and feed axes, highlighting the role of PLCs in coordinating auxiliary operations and ensuring operational safety.Hermana, Aza, and Setyoadi (2022) analyzed advanced CNC control systems and reported that closed-loop control improves machining precision and automation capability, although it increases system complexity. Their work emphasized the significance of electrical control integration in modern CNC systems.

OVERVIEW OF BHARAT DYNAMICS LIMITED (BDL)

Bharat Dynamics Limited (BDL) is a Government of India enterprise functioning under the Ministry of Defence. The organization plays a significant role in the development and production of guided missile systems and related defence equipment for the Indian Armed Forces. With its headquarters located in Hyderabad, BDL operates multiple manufacturing units across the country to support large-scale production and supply of defence systems.

BDL is recognized for its contribution to strengthening national defence capabilities through indigenous manufacturing and technological advancement. The organization focuses on precision engineering, quality assurance, and strict adherence to defence manufacturing standards.

Fig 1 Overview of BDL

Infrastructure

BDL is equipped with advanced manufacturing facilities that include precision machining units, assembly lines, testing laboratories, and quality control departments. The company also operates integration facilities and specialized production divisions to ensure efficient workflow and product reliability. The presence of multiple production units enhances operational flexibility and improves supply chain efficiency.

Operational Capacity

The manufacturing infrastructure at BDL supports high-volume production of defence components while maintaining strict dimensional accuracy. The organization utilizes modern CNC machines, automated inspection systems, and specialized tooling to achieve consistent product quality.

Environmental Considerations

BDL follows established environmental and safety guidelines in its manufacturing processes. The organization implements pollution control systems, proper waste disposal methods, and energy-efficient practices. These measures help reduce environmental impact while maintaining safe working conditions within industrial facilities.

Definition of CNC Machines

A Computer Numerical Control (CNC) machine is an automated machine tool that performs machining operations based on computer-programmed instructions. These machines execute operations such as turning, milling, drilling, cutting, and shaping using coded commands known as G-codes and M-codes. The coded instructions control the movement of the cutting tool and workpiece along multiple axes, enabling high precision and repeatability.

Fig 2 CNC Machine

CNC machines combine mechanical components with electrical and electronic control systems, including motors, drives, controllers, and sensors. This integration allows complex machining operations to be performed with minimal human intervention. Due to their accuracy and efficiency, CNC machines are widely used in aerospace, automotive, and defence manufacturing industries.

Basic Working Principle of CNC Machines

CNC machines operate based on programmed instructions that control tool movement and machining operations. The system converts coded commands into precise mechanical motion using coordinated electrical, electronic, and mechanical subsystems.

Block Diagram of CNC Machine

The functional block diagram of a CNC machine represents the flow of information and power within the system. Each block performs a specific function to ensure accurate machining.

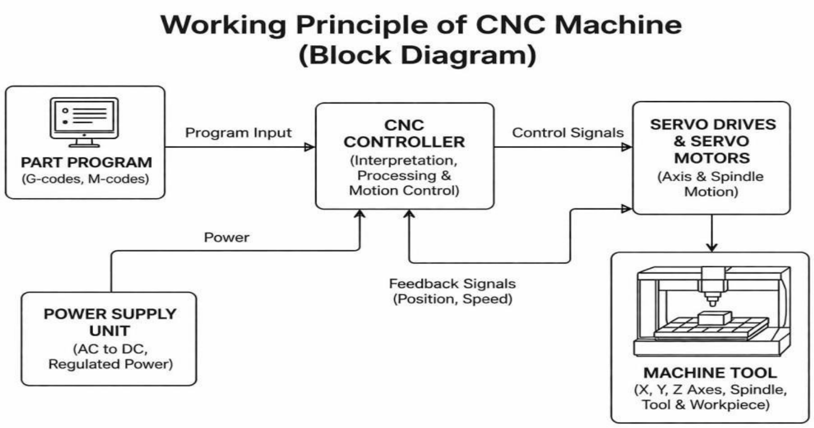

Fig. 3 Block Diagram of CNC Machine

1. Part Program (Program Input Unit)
The process begins with the part program, which contains machining instructions written in G-codes and M-codes. The program defines tool paths, feed rates, spindle speeds, and operation sequences. These instructions are entered through a computer or control panel.

2. CNC Controller (Machine Control Unit)
The CNC controller acts as the central processing unit of the machine. It interprets the program, performs interpolation, and generates control signals. The controller manages axis movement, machine logic, and operational sequencing.

3. Servo Drives and Servo Motors
Servo drives amplify control signals and regulate electrical power supplied to the motors. Servo motors convert electrical energy into mechanical motion and control movement along the X, Y, and Z axes, as well as spindle rotation.

4. Machine Tool
The machine tool is the mechanical section where machining takes place. It includes the spindle, cutting tool, worktable, and structural components. Controlled movement of axes enables material removal according to programmed dimensions.

5. Encoders and Feedback System
Encoders and sensors monitor position and speed of machine axes. These devices generate feedback signals representing actual motion and send them to the controller.

The feedback signals form a closed-loop control system. The controller compares actual movement with programmed values and corrects any deviation, ensuring high precision.

TYPES OF CNC MACHINES OBSERVED AT BDL

Three-Axis CNC Machine

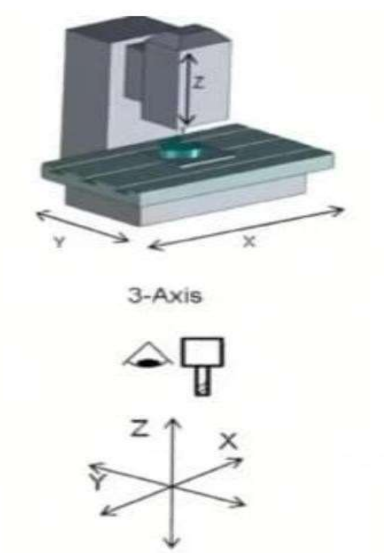

Fig 4 -Axis Machine

A three-axis CNC machine is a computer-controlled machine tool in which the cutting tool moves along three mutually perpendicular linear axes: X, Y, and Z. This configuration represents the most widely used CNC system in manufacturing industries. The X-axis provides lateral motion, the Y-axis enables longitudinal movement, and the Z-axis controls vertical displacement of the spindle or tool.During machining, coordinated motion along these three axes allows material removal according to programmed instructions. The movements are governed by a CNC controller that interprets G-code and M-code commands. Servo motors drive each axis, while feedback devices such as encoders ensure accurate positioning through closed-loop control. Three-axis machines are commonly used for milling, drilling, slotting, contouring, and surface machining operations. They are particularly suitable for components having prismatic shapes and moderate geometric complexity.

Construction
The construction of a three-axis CNC machine consists of a rigid mechanical structure integrated with precision motion and control components. The base and frame form the foundation of the machine and are typically manufactured from cast iron or welded steel to provide rigidity and vibration damping. This structure supports all major assemblies and maintains alignment during machining.

The machine bed is mounted on the base and carries the guideways and worktable. A vertical column is fixed to the bed and supports the spindle head assembly. The worktable is designed to hold the workpiece securely using fixtures and T-slots. Linear motion along the X-axis is generally provided by the table, while the saddle beneath it enables movement along the Y-axis.

The spindle head assembly is mounted on the column and houses the spindle motor and tool-holding mechanism. It moves vertically along the Z-axis to control the depth of cut. Axis movement is achieved using servo motors coupled with ball screw mechanisms and precision linear guideways. These components convert rotational motion into accurate linear displacement.

Additional systems include the spindle drive, CNC controller enclosure, feedback devices such as encoders, coolant system, lubrication unit, chip removal mechanism, and safety enclosures. These elements collectively ensure reliable and precise machining performance.

Five-Axis CNC Machine
A five-axis CNC machine is an advanced machining system capable of simultaneous motion along five different axes. In addition to the three linear axes (X, Y, and Z), the machine includes two rotational axes that allow the tool or workpiece to tilt and rotate. This capability enables machining of complex geometries in a single setup.

The three linear axes provide translational motion, while the rotational axes offer angular positioning. Typically, the A-axis represents rotation about the X-axis, the B-axis corresponds to rotation about the Y-axis, and in some configurations the C-axis provides rotation about the Z-axis. By combining linear and rotary movements, five-axis machines can access multiple surfaces of a component without repositioning.

These machines use advanced CNC controllers, servo drives, and high-precision feedback systems to coordinate simultaneous multi-axis motion. This results in improved machining accuracy, reduced setup time, and superior surface finish.

Multi-Axis Motion Control

Multi-axis motion control refers to the coordinated movement of all five axes during machining. The CNC controller reads the part program and calculates the tool path using interpolation techniques. It generates synchronized command signals for each axis to ensure smooth and accurate motion.

Servo drives regulate power supplied to motors, allowing precise control of position, speed, and torque. High-response motors provide smooth acceleration and deceleration. Advanced interpolation methods such as linear, circular, and spline interpolation allow machining of complex curved surfaces with high precision.

ELECTRICAL AND CONTROL SYSTEMS IN CNC MACHINES

CNC Control Unit

Fig 5 CNC Control Unit

The CNC control unit is the central processing element of a CNC machine responsible for coordinating all machining operations. It functions as the core decision-making component by interpreting programmed instructions and converting them into precise electrical signals for axis movement and auxiliary functions.

The control unit receives the part program consisting of G-code and M-code commands. These instructions define tool paths, feed rates, spindle speeds, and operation sequences. After decoding the program, the controller generates motion commands for the machine axes and spindle drive system.A major function of the CNC control unit is interpolation, where intermediate points are calculated between programmed coordinates. This allows smooth and accurate movement of the cutting tool while machining straight lines, arcs, and complex contours. The generated motion commands are transmitted to servo drives, which control the motors responsible for axis positioning.The CNC controller also supervises spindle rotation, coolant operation, automatic tool changing, and other auxiliary machine functions. It operates in conjunction with a closed-loop feedback system that receives real-time data from encoders and sensors. The controller continuously compares the actual position with the programmed values and performs automatic correction to maintain accuracy and repeatability.

Programmable Logic Controller (PLC)

Fig 6 PLC Controller

A Programmable Logic Controller (PLC) is an industrial digital control device used to automate machinery and manufacturing processes. It is designed for reliable operation in harsh industrial environments and performs real-time control functions.A PLC operates by continuously monitoring input signals from sensors and switches, processing these inputs using a stored control program, and generating output signals to actuators such as motors, relays, and valves. The control program is typically written using ladder logic or other industrial programming languages.The main components of a PLC include the CPU, input modules, output modules, and power supply. The CPU executes the control program, input modules receive signals from field devices, and output modules control actuators.In CNC machines, PLCs are primarily used for auxiliary control rather than direct motion control. They handle functions such as tool changing, coolant system control, lubrication, door interlocks, safety operations, and machine start/stop sequences. The PLC operates through a

scan cycle that includes reading inputs, executing logic, and updating outputs. This cyclic operation ensures continuous monitoring and control.
PLCs provide flexibility, reliability, and easy modification of control logic, making them essential components in CNC automation systems.

Role of PLC in Industrial Automation

PLCs play a vital role in industrial automation by controlling and coordinating different processes. They replace traditional relay-based circuits with programmable logic, allowing flexible control of machines and production systems.The PLC receives signals from sensors, switches, and limit devices, processes them, and controls actuators such as motors and valves. This enables automated operation without manual intervention. PLCs are widely used for process sequencing, machine synchronization, and production line coordination.They also perform safety functions by monitoring critical parameters and implementing emergency shutdowns, interlocks, and fault detection. Modern PLCs support integration with supervisory systems such as HMI and SCADA, enabling centralized monitoring and diagnostics. Their flexibility allows easy modification of control programs to meet changing production requirements.

Servo Motor System

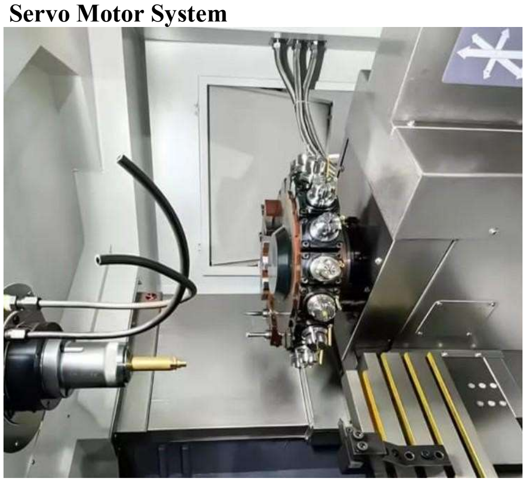

Fig 7 Servo Motor in CNC Machine

A servo motor system is a closed-loop motion control system used in CNC machines for precise control of position, speed, and torque. It is essential for achieving accurate axis movement during machining operations.
The servo system consists of a servo motor, servo drive, and feedback device such as an encoder or resolver. The servo motor converts electrical energy into mechanical motion, while the servo drive regulates voltage and current supplied to the motor. The feedback device continuously measures position and speed.
The system operates using a closed-loop principle. The CNC controller sends a command signal to the servo drive, which drives the motor. The feedback device measures actual motion and sends data back to the controller. If any deviation occurs, corrective action is taken immediately. This continuous feedback ensures high precision and stability.

Working Principle of Servo Motor

Servo motors operate based on feedback control. A command signal specifying desired position or speed is sent from the controller to the servo drive. The drive amplifies the signal and powers the motor. As the motor rotates, a feedback device measures its actual motion and sends this information to the controller. The controller compares actual output with the desired value. If an error exists, correction signals are generated to adjust motor performance. This continuous process ensures accurate positioning and smooth operation.

Closed-Loop Control Mechanism

Closed-loop control is a system in which output is continuously monitored and compared with a reference input. Any difference between desired and actual output is corrected automatically through feedback.
The process involves reference input, controller action, actuator output, feedback measurement, and correction. This loop operates continuously, providing high accuracy, stability, and automatic error correction. In CNC machines, closed-loop control ensures precise axis positioning and consistent machining quality.

Encoders

Encoders are feedback devices used to measure position, speed, and direction of motion in CNC machines. They convert mechanical movement into electrical signals that are interpreted by the CNC controller. Encoders are mounted on servo motors or machine axes and provide real-time feedback for closed-loop control.

Incremental Encoders

Incremental encoders generate electrical pulses corresponding to rotational movement. Each pulse represents a small displacement. By counting pulses, the controller determines position and speed.
These encoders typically provide two phase-shifted signals that help determine direction of rotation. Some models include a reference pulse for establishing a fixed position. Incremental encoders are widely used due to their simplicity and cost-effectiveness.

Absolute Encoders

Absolute encoders provide a unique digital value for each shaft position. They use coded tracks on a rotating disk, which are read by sensors to determine exact position.
Absolute encoders retain position information even after power loss, eliminating the need for homing. They are available as single-turn and multi-turn types. Although more expensive, they offer higher reliability and accuracy for critical applications.

CNC MACHINE OPERATION PROCESS

Operational Flow of CNC Machine

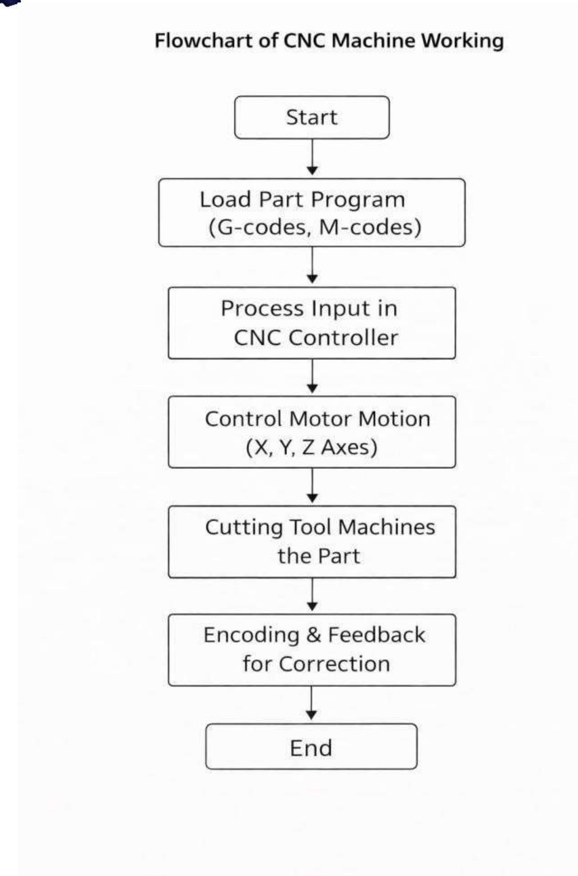

Fig 8 Flow chart of CNC Machine Operation

The operation of a Computer Numerical Control (CNC) machine follows a systematic sequence beginning with program loading and ending with feedback-based correction. Each stage contributes to precision machining, automation, and repeatability. The operational workflow includes program loading, instruction processing, motor control, machining, and feedback correction.

Loading of Part Program (G-Code and M-Code)

The initial stage of CNC machine operation involves loading the machining instructions into the controller. These instructions are written in G-codes and M-codes, which define the movement and operational functions of the machine.

G-codes primarily control geometric movements such as linear interpolation, circular interpolation, feed rate, and tool positioning. These codes determine the tool path and machining strategy required to manufacture the component. M-codes, on the other hand, control auxiliary machine functions including spindle start/stop, coolant operation, tool changes, and program termination.

The part program can be loaded into the CNC controller using various methods such as manual input through the control panel, USB storage devices, or direct transfer from CAD/CAM systems. After loading, the controller checks the program for syntax errors, verifies tool offsets, and confirms machine readiness. Once validated, the program is stored in memory and prepared for execution.

Processing Input in CNC Controller

After program loading, the CNC controller interprets and processes the instructions. The controller decodes each block of the program and identifies the required machining operations, axis movements, coordinates, spindle speed, and feed rate.

Interpolation is then performed to calculate intermediate points between programmed coordinates. This ensures smooth and accurate tool movement along straight lines, curves, and complex contours. The controller also performs coordinate transformation by applying tool offsets and workpiece reference points to convert programmed values into machine coordinates.

Following processing, the controller generates control signals for servo drives and spindle motors. Simultaneously, it integrates feedback from encoders and sensors to compare commanded and actual positions. Auxiliary operations such as coolant control, tool change, and safety interlocks are managed through PLC integration.

Control of Motor Motion

Motor motion control is essential for precise positioning of CNC machine axes. Based on the part program, the controller sends command signals to servo drives specifying required position, velocity, and direction.Servo drives amplify the low-power control signals and convert them into regulated electrical power suitable for driving servo motors. These motors move the machine axes (X, Y, Z) and spindle, enabling accurate machining operations.Encoders continuously monitor motor position and speed, sending feedback signals to the controller. The controller compares actual and desired values and generates correction signals when deviations occur. This closed-loop control system ensures precise motion, smooth acceleration and deceleration, and consistent speed under varying load conditions.

Precision Component Manufacturing

At Bharat Dynamics Limited (BDL), CNC machines are widely used for manufacturing high-precision components required for defence systems. Multi-axis CNC machines produce structural parts, housings, brackets, and missile sub-assemblies with micron-level accuracy.

The manufacturing process involves design specification, CNC programming, machining, and quality inspection. Advanced servo systems and closed-loop feedback ensure accurate positioning and repeatability. Strict quality control procedures and precision measuring instruments verify dimensional accuracy and surface finish. Controlled machining environments further improve reliability and efficiency.

Aerospace and Defence Parts Production

CNC machines are essential for producing aerospace and defence components that require extremely high precision and reliability. Materials such as titanium alloys, aluminum, and high-strength composites are machined using advanced CNC systems.Typical components include structural frames, engine parts, missile components, precision housings, and control system elements. The production process involves programming, machining, finishing, and inspection stages. Feedback systems and servo controls ensure accuracy, while coordinate measuring machines are used for quality verification. Strict adherence to defence manufacturing standards ensures operational safety and reliability.

High-Tolerance Machining

High-tolerance machining refers to manufacturing components within very tight dimensional limits. CNC machines achieve these tolerances through precise programming, rigid machine structures, and advanced feedback systems.Maintaining high tolerance requires precision tooling, stable environmental conditions, and proper machine calibration. Closed-loop control systems continuously monitor and correct deviations to maintain dimensional accuracy. Such machining is critical for components where even minor dimensional errors may lead to functional failure.

Conclusion

The present study examined the electrical systems employed in CNC machines and their contribution to precision manufacturing, automation, and operational reliability. The analysis confirms that electrical components such as CNC controllers, servo drive systems, PLCs, encoders, and feedback devices collectively enable accurate motion control and stable machining performance. These integrated subsystems form the foundation for achieving consistent dimensional accuracy and high productivity in modern manufacturing environments.The investigation further highlights the importance of closed-loop control architecture, where continuous feedback from sensors and encoders allows real-time error detection and correction. This capability significantly improves positioning accuracy, repeatability, and surface finish. In addition, the use of programmable logic controllers enhances automation by coordinating auxiliary operations, safety mechanisms, and machine sequencing. Power electronic drives and motor control systems contribute to efficient energy utilization and smooth machine operation.

At Bharat Dynamics Limited (BDL), CNC machines equipped with advanced electrical control systems are effectively utilized for the production of precision components required in defence applications. These systems support high-quality manufacturing, reduce manual intervention, and improve operational efficiency. The study concludes that well-designed electrical infrastructure in CNC machines plays a crucial role in ensuring reliability, productivity, and adherence to strict defence manufacturing standards.

Future Scope

Future developments in CNC electrical systems are expected to emphasize intelligent automation, enhanced connectivity, and improved energy efficiency. Integration with Industry 4.0 technologies, including IoT-based monitoring, artificial intelligence, and cloud-based data analytics, will enable smart manufacturing environments with real-time performance tracking. These advancements will allow predictive maintenance, reducing unexpected machine failures and minimizing downtime.

The implementation of condition-monitoring sensors combined with data-driven diagnostics can further enhance system reliability. Advanced predictive maintenance strategies will help identify electrical faults, motor degradation, and drive abnormalities before they impact production.Adoption of high-efficiency servo drives and modern power electronics will improve energy management and support sustainable manufacturing practices. Additionally, further advancements in multi-axis CNC machines, including five-axis and hybrid machining systems, will enable production of complex geometries with improved accuracy and reduced setup time.

Improved human-machine interfaces and remote monitoring capabilities will enhance usability and allow operators to supervise machines from centralized control stations. These developments will contribute to safer operation, better diagnostics, and optimized production planning.Overall, future CNC electrical systems will evolve toward intelligent, energy-efficient, and highly connected manufacturing solutions capable of meeting the increasing demands of precision industries.

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