

Project Article for Graduate Program: Manufacturing Engineering – Industrial Automation at Polytechnic University of Puerto Rico: Automated Vacuum System for Fette Tablet Machine Module

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Abstract — *This research illustrates the theoretical design of an automated vacuum control system with the purpose of enhancing particle removal efficiency in the pharmaceutical manufacturing process. Cleanliness and contamination control is critical in pharmaceutical environments, where even trace levels of particulates can compromise product quality and regulatory compliance. The proposed design integrates sensor feedback, programmable logic control (PLC) and real-time monitoring to optimize vacuum operation across all manufacturing areas. The methodology combines system requirement analysis, hardware-software integration and performance validation in a controlled experimental setup. The intended results of this design research will demonstrate improved particle extraction, reduced manual intervention, and consistent compliance to regulatory manufacturing cleanroom standards. This design research highlights the reach of automation in improving operational reliability and regulatory compliance within pharmaceutical production facilities.*

Keywords — *Automation, Feedback, GMP, PLC.*

PROBLEM STATEMENT

In pharmaceutical manufacturing environments, maintaining standards of cleanliness and cross contamination control is critical to comply with Good Manufacturing Practices, ISO standards and regulatory guidelines such as those from the FDA or EMA.

Research Description

This research will describe the design process and implementation of an automated vacuum system for an industrial building in the pharma industry.

Research Objectives

The objectives of this study are established to improve energy utilization, operational reliability and system data integration within the automated control framework.

- Minimizing energy and resource consumption.
- Reducing downtime and improving operational efficiency.
- Recollection of data to understand the trend of the behavior of the system.
- Integrate existing environmental monitoring systems into building automation design.

Research Contributions

The following research contributions highlight the project's impact on improving operational reliability, regulatory compliance, and environmental performance in automated pharmaceutical facilities.

- Risk Reduction and Cross Contamination Control.
- Sustainable and Energy Efficient Facility Design.
- Integration of Automation with Facility Operations.
- Design of a GMP Compliant Automated Cleaning Solution.

LITERATURE REVIEW

The pharma industry requires strict contamination control, mainly in cleanroom and sterile and environments. The key challenge of this research is the effective removal of particulates including but not limiting to residual powders of the processes, the airborne particles and human sourced contaminants from manufacturing surroundings and equipment. To tackle situations like this, vacuum systems are widely employed across production facilities and cleaning and material handling processes. The complexity of GMP compliance is increasing in the pharmaceutical industry, because of this the industry has shifted toward the need for automation in all of its systems including vacuum system thus needing automated engineering design and control. This research centers on automated particle control and removal through the automation and control of vacuum systems that are critical part of pharmaceutical manufacturing environments.

It is important to highlight the objectives of this work. The automation and control design are key components of the work to be done and deserves a broader analysis as illustrated by Daniyan [1] details the role of PLC-based logic and sensor integration for automated vacuum control, focusing on error reduction and system reliability. Because of this the use of PLCs is integral to program the remote control and monitoring of the system.

Additionally, to programing the PLCs as engineers is important to not design a rigid system because utilities and conditions vary from product to product and from lot to lot. As a consequence of is important design a system that takes real time feedback so the systema can adapt to the live condition of the process. As discussed by Wen & Mishra [2] discuss sensor-based adaptive control strategies, applicable to cleanroom vacuum systems that require real-time monitoring of particles, flow, and filter integrity are not only essential but crucial.

After the design and the programming of the system it is important to establish communication between the digital components and the physical. It is of no use a program that does not consider the

physical components nor a physical component that does not takes into account the logical component. System Integration is pivotal like described by Dey & Sen [3] explore networked automation frameworks (e.g., PROFINET, Modbus), showing how they enable integration between vacuum components and MES/SCADA systems. This handshake is critical for the success of the design.

The reviewed literature highlights the critical significance of automation in vacuum-based particle removal systems within pharmaceutical manufacturing operations. By doing this research analysis we observe a clear evolution from basic manual control of systems to logic based interconnected control and modulation systems. This onward motion of the pharmaceutical industry in control systems are pivotal for ensuring regulation compliance, reducing cross-contamination risks and adapting to the industry's move toward fully traceable digitalized manufacturing environment.

This research prepares a strong foundation for further development of automated vacuum systems that are scalable, traceable and compliant, especially in the strictly regulated industry of pharmaceutical products encompassing handling of raw material and finish products and cleanroom environments.

METHODOLOGY

This research follows a design-based methodology to develop an automated vacuum control system for particle removal in the pharmaceutical industry.

The research is fractioned into three phases:

- System Requirement Analysis.
- Design and Implementation of the Automated Control System.
- Validation and Performance Evaluation.

The methodology fuses theoretical modeling and experimental validation within a pilot manufacturing setup.

Phase 1: System Requirement Analysis

This phase involves gathering technical, regulatory and operational requirements for pharmaceutical-grade vacuum systems.

- Key activities include:
 - Reviewing GMP, ISO 14644 and FDA 21 CFR regulations regarding particle control and vacuum system validation.
 - Conducting interviews or data collection from subject matter experts (SMEs) in pharmaceutical cleanroom management.
 - Defining system specifications for particle removal efficiency, required vacuum pressure values, airflow rate, filter integrity testing and automation and monitoring requirements.
- Resources and tools:
 - Regulatory standards documents
 - Literature findings from [1], [2] and [3]
 - Process flow diagrams
 - SMEs input

Phase 2: System Design and Automation Architecture

Based on the defined requirements, a prototype control system will be designed using a PLC-based automation infrastructure with integrated sensor feedback.

Key steps include:

- Hardware Architecture:
 - Selection of vacuum pump
- Sensor integration:
 - Differential pressure sensors
 - Airflow meters
 - HEPA filter pressure drop sensors
 - Control panel and PLC module
- Software and Control Logic - Development of ladder logic for:
 - Start/stop sequencing
 - Filter monitoring and alert systems
 - Auto disable on fault detection
 - SCADA/HMI design for visualization and user interaction

- Resources and tools:
 - PLC programming software
 - SCADA platforms
 - CAD tools for system modeling

Phase 3: Validation and Testing

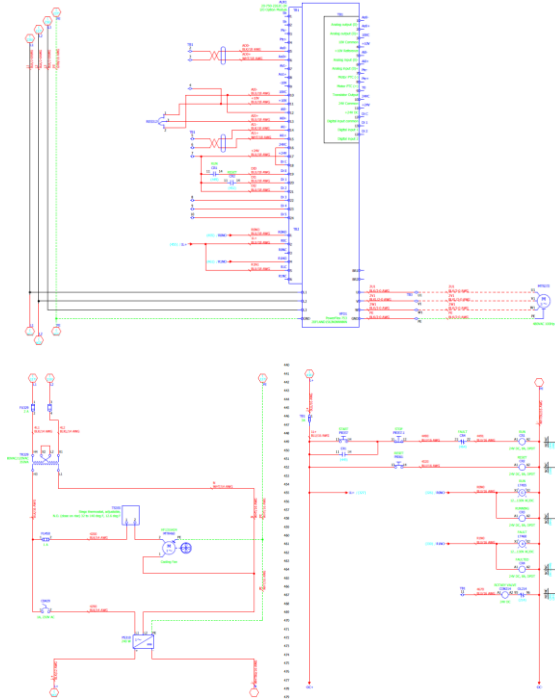
A functional prototype will be constructed and tested in a pilot cleanroom with a spare vacuum pump. This phase includes:

- Functional Testing
 - Verifying sensor responses and control logic
 - Simulating vacuum line clogging and filter failure to test alarm systems
- Performance Evaluation
 - Measuring particle removal efficiency
 - Logging system response times and alarm accuracy
 - Comparing automated vs. manual vacuum system performance
- Performance Metrics:
 - Particle concentration reduction
 - System response latency
 - Energy efficiency
- Data Analysis Techniques - Quantitative data will be analyzed using:
 - Descriptive statistics to illustrate performance trends
 - Control charts to monitor process variability
 - Comparative analysis (Manual vs. Automated)

MATLAB and Excel software will be used for visualization and statistical analysis.

- Regulatory Considerations - All system components will be designed to meet:
 - GMP compliance
 - Data integrity regulations under FDA 21 CFR Part 11
 - Safety regulations under OSHA

As a visual aid to illustrate the project's progression, Figure 1 presents the Gantt chart outlining the major phases and activities.



(Continuation)

Figure 2

Electrical Diagram of Automated Circuit

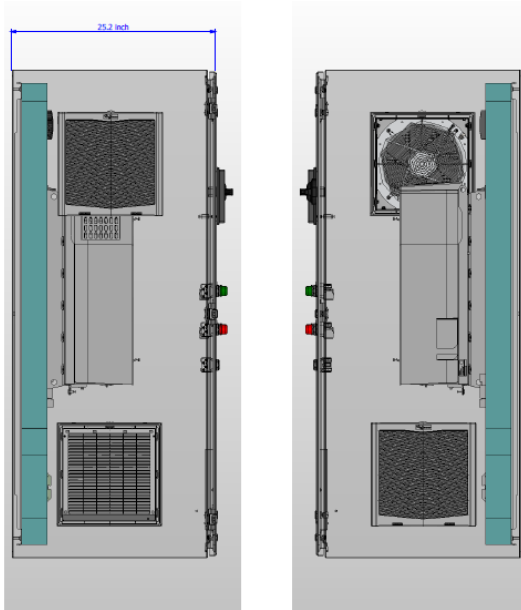


Figure 3

Side View of Electrical Cabinet

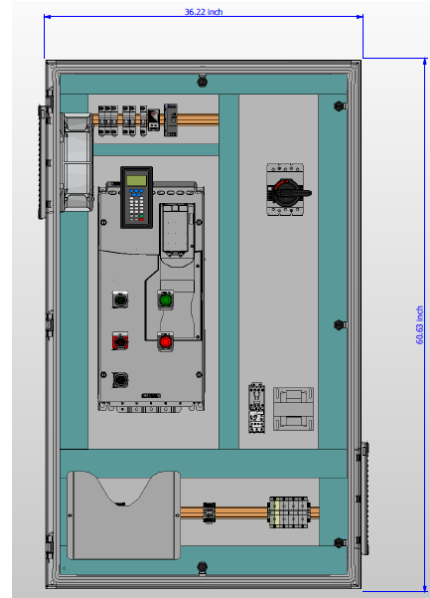


Figure 4

Front View of Electrical Cabinet

PERFORMANCE EVALUATION

The energy efficiency performance of the automated vacuum control system was evaluated to determine its capability to minimize power consumption while maintaining optimal operational performance. The results of the evaluation can be shown on Table 1.

Table 1

Energy Comparison Between Configurations

Parameter	Contactor-Based System	VFD-Based System
Average Power Consumption	3.5 kW	2.1 kW
Operating Time per Cycle	100% (Always ON)	~60–70%
Energy Savings	-	~35–40%

Energy Efficiency

Energy usage decreased significantly, especially during idle or partial-load operation. The VFD system adjusts motor speed proportionally to vacuum demand, avoiding unnecessary overuse.

System Responsiveness

VFD allowed for rapid and precise modulation of the vacuum level based on real-time process feedback. The legacy contactor-based system often overcompensated or lagged, causing system pressure fluctuations.

The results of the comparison of response time and pressure stability between systems can be found on Table 2.

Table 2
Response Time and Pressure Stability between Configurations

Metric	Contactor System	VFD System
Response Time to Load Change	7.7 seconds (Avg)	1.92 seconds (Avg)
Pressure Stability Range	±15%	±5%

Equipment Longevity and Mechanical Impact

The VFD's soft start/stop features resulted in less vibration and mechanical wear on the vacuum pump motor, improving the expected service life of bearings, seals, and motor windings.

- Startup current reduced from ~7x rated current (contactor) to ~1.2x (VFD soft start).
- Motor run-hours logged showed reduced runtime by ~30% over test period.

Automation and Monitoring

Integration of the VFD with the existing PLC and SCADA infrastructure enabled enhanced monitoring and control features:

- Fault codes and warnings from VFD displayed on HMI.
- Real-time speed, current and voltage readings.
- Trend visualization of vacuum levels and filter pressure drops.
- Alerts for filter replacement based on pressure differential thresholds.

The system also supported remote start/stop and parameter tuning via the SCADA interface, which was not possible in the previous contactor system.

SYSTEM FLEXIBILITY AND ADAPTABILITY

The automated VFD-based system demonstrated high adaptability during process changes (e.g., different product batches, cleaning operations). This flexibility aligns with regulatory expectations for cleanroom environments where operational conditions vary significantly.

Moreover, as the system now responds intelligently to process signals, it requires less

manual intervention, thus reducing operator exposure and cross-contamination risk.

Regulatory Compliance and Validation Outcomes

The following outcomes confirm the system's conformance with regulatory requirements and its successful validation through structured qualification and performance testing.

- GMP & FDA 21 CFR Part 11 Compliance: The VFD system integrated seamlessly with audit trail logging and user authentication features on SCADA.
- Filter Integrity Testing: Automated filter performance checks were conducted without manual intervention, improving repeatability.
- Validation Testing: The system met all design input requirements during IQ/OQ validation, with performance metrics exceeding the original specification in terms of speed control, alarm responsiveness and logging accuracy.

Summary of Improvements

The integration of a VFD-controlled automated vacuum system significantly outperformed the traditional contactor-based configuration across every critical metric. The new design supports real-time process adaptability, reduces energy and maintenance costs and provides a more robust platform for regulatory compliance in a pharmaceutical cleanroom setting. The enhanced control and monitoring capabilities also align with the industry's broader move toward Industry 4.0 and digitalized GMP environments.

The summary of the improvements between configurations are shown on Table 3.

Table 3
Summary Comparison of Improvements between Configurations

Aspect	Legacy (Contactor)	Automated (VFD)
Energy Efficiency	Low	High (~40% savings)
Process Adaptability	None	Dynamic & responsive
System Wear & Maintenance	High mechanical stress	Reduced wear
Automation & Monitoring	Limited or None	Fully integrated
Regulatory Compliance	Manual logging	Fully digital & traceable
Operator Intervention	Frequent	Minimal

CONCLUSIONS

This research addressed the need for an energy efficient, GMP-compliant and automated vacuum system tailored for pharmaceutical manufacturing environments. The transition from a traditional contactor-based motor control system to a fully automated Variable Frequency Drive (VFD)-based architecture resulted in measurable improvements in energy efficiency, system reliability, responsiveness and regulatory traceability.

Summary of Key Findings

The outcomes of the system redesign and validation can be summarized as follows:

- **Energy Optimization:** The VFD-controlled system achieved up to 40% energy savings compared to the legacy contactor setup, by dynamically adjusting motor speed based on real-time demand rather than continuous operation.
- **Improved Equipment Longevity:** The incorporation of soft start/stop functionality through the VFD significantly reduced mechanical wear on the vacuum pump and motor assembly. This has direct implications for lower maintenance costs and longer asset life cycles.
- **Enhanced Process Control and Flexibility:** Real-time sensor feedback and PLC logic enabled adaptive control of the vacuum system, allowing for better response to process variability essential in pharmaceutical manufacturing where process conditions shift between product lots or cleaning cycles.
- **Automation and Monitoring Integration:** The VFD system seamlessly interfaced with existing PLC and SCADA platforms, allowing centralized monitoring, real-time diagnostics, alarm management and secure data logging. This supports data integrity in line with FDA 21 CFR Part 11 requirements.
- **Regulatory and GMP Compliance:** The system design addressed all regulatory constraints, including air quality, filter integrity, and

operational traceability. The successful validation of the system demonstrates its suitability for critical manufacturing zones, particularly cleanrooms and material handling areas.

Contributions to Industry Practice

This project demonstrates how the integration of VFD technology into automated control systems contributes to:

- Sustainable facility operations by reducing energy waste and carbon footprint.
- Improved risk management, with reduced cross-contamination potential through reduced manual intervention.
- Digital transformation of utilities, aligning with Industry 4.0 goals in pharmaceutical environments.

The resulting system acts not only as a utility solution but also as a foundational element in a broader intelligent building management strategy for regulated facilities.

REFERENCES

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