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Research Article

Development of a Solenoid-Coil-Based Door Lock System for Industrial Washing Machines Using Finite Element Analysis

Kader Sever[1*], Ali Bakbak[2], Can Çivi[3]

[1]Tolkar Makine San. ve Tic. A.Ş., İzmir-TÜRKİYE
* **Corresponding Author Email:** kader.sever@tolkar.com - **ORCID:** 0009-0003-4985-7072

[2] Manisa Celal Bayar University, Faculty of Engineering and Natural Sciences, Department of Electrical and Electronics Engineering Manisa-TÜRKİYE
Email: ali.bakbak@cbu.edu.tr - **ORCID:** 0000-0002-6465-4332

[3] Manisa Celal Bayar University, Faculty of Engineering and Natural Sciences, Department of Mechaical Engineering Manisa-TÜRKİYE
Email: can.civi@cbu.edu.tr - **ORCID:** 0000-0002-5302-9072

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Abstract:

This study presents the development of a locally manufactured solenoid-coil-based door lock system for industrial washing machines, addressing the challenges associated with imported mechanisms such as high costs, frequent failures, and supply chain delays. The solenoid coil design is optimized using Finite Element Analysis (FEA) to achieve sufficient electromagnetic force while maintaining energy efficiency. The system operates at 24V DC with a nominal current of 0.65A, consuming 15W of power. Extensive testing demonstrated the system's reliability and robustness, including mechanical durability over 15,000 locking cycles, resilience under high temperature (up to 60°C) and humidity (90% RH) conditions, and resistance to forced entry. The results validate the system’s ability to meet the stringent demands of industrial environments while providing a cost-effective and reliable alternative. This development highlights the potential for scalable applications and contributes to advancing local manufacturing capabilities for industrial machinery components.

1. Introduction

The washing machine is considered an important system that has significantly changed the washing of clothes. In order to completely mechanize the physical work of washing clothes, which requires high physical effort, many inventors, starting from the 19th century, started their design journeys by looking for a way to benefit from water or steam power, and reached today's technologies with the development of electric motors, and there are thousands of patents on washing machine design [1], [2]. Today, many intensive studies are still being carried out on the relevant systems, especially on reducing energy consumption and environmental impacts [3].

Industrial laundries are establishments that process laundry in an industrial way by cleaning it with large amounts of water and different chemical cleaning products. These chemicals are used not only to increase the efficiency of the cleaning cycle, but also to reduce water and energy costs and increase the life of the machines used. The customer base is mostly professional companies, and the dirty laundry comes from a variety of sources, such as hospital linens, hotel linens, restaurant towels and tablecloths, work clothes and uniforms, shop towels and textiles from beauty salons [4]. The use of industrial laundry washing machine in the mentioned facilities demands robust and reliable components. Among these, door lock systems are critical for ensuring safety and operational efficiency. Current systems rely on imported mechanisms, which pose challenges such as supply chain delays, frequent failures, and higher costs. When looking at the evaluation and reporting of systemic faults in washing machine systems, it is seen that seals and door lock systems are among the common fault components observed [5].

Modern washing machines use a variety of sensors and actuators. Some sensors can measure parameters and output analog electrical signals.

This allows control of water level and temperature, spin speed, cycle program, load balancing, child lock systems and noise reduction systems. For example, a push-button switch is used as a "door closed" sensor, which provides a complete circuit when the closed door is pressed [6], [7]. Door lock mechanisms used for user safety, ensuring the correct operation of the device, preventing water leakage, electronic and mechanical drying and child safety are currently operated by using solenoid coils that convert electrical energy into magnetic energy [8], [9]. All these mentioned elements show that the importance of door lock mechanisms in washing machines and their correct design and reliable operation are very important.

Finite Element Analysis method is widely used in literature to make calculations to optimize the Solenoid Coil design and provide the required magnetic force. FEA is an effective method in engineering designs and many scientific studies and verification applications are carried out on the subject [10], [11]. Advanced engineering simulation software based on finite elements can now provide detailed and comprehensive analyses on solenoid coils. Magnetic forces that can be created by solenoid coils, examination of the changes in these forces with design optimizations, sample usage scenarios and especially determination of the durability, reliability and efficiency of electric lock systems in solenoid coil systems, which are discussed in this study, can be successfully carried out in the FEA method [12].

This study aims to develop a locally produced solenoid-coil-based door lock system tailored to the demands of industrial environments. By employing Finite Element Analysis (FEA), the electromagnetic coil was optimized to provide the required force while maintaining durability and efficiency. Another aim of the study is to achieve the goals of providing cost advantage, easy accessibility and high quality with a simple, new and original design.

2. Material and Methods

The developed door lock system is specifically tailored for industrial washing machines, which demand reliable and robust components due to their intensive and repetitive use in environments such as laundromats, hotels, and hospitals. The lock system is designed to address the common issues associated with imported mechanisms, including frequent failures, supply chain delays, and high costs. The system comprises three primary components: the solenoid coil, the mechanical locking mechanism, and the control unit. Figure 1 illustrates the industrial washing machine used as the test

Figure 1. *Industrial washing machine*

platform for this study. The solenoid coil is the core of the system, converting electrical energy into magnetic force to operate the lock. This force ensures that the door remains securely locked during operation and reliably unlocks when the process is complete. The mechanical locking mechanism, designed with precision, translates the magnetic force into physical motion, ensuring smooth and consistent operation over extended periods.

Figure 2. *Close-up view of the washing machine door and the solenoid-based locking mechanism*

Additionally, the control unit integrates seamlessly with the washing machine's electronics to manage the power supplied to the coil and ensure safe, efficient operation. Sensors incorporated into the system provide real-time feedback on the lock's state, enhancing safety and operational accuracy. The close-up view in Figure 2 highlights the door and locking mechanism, emphasizing the compact and efficient design of the system.

The developed door lock system consists of several critical components that work together to ensure reliable and efficient operation in industrial washing machines. Figure 3 provides an exploded view of the system, detailing each component and its role in the overall mechanism.

The primary components include:

- **Handle and Actuator (1, 2):** Facilitates the manual operation and mechanical interaction of the lock.
- **Housing and Support Plates (3, 7, 8):** Provides structural integrity and alignment for the internal components.

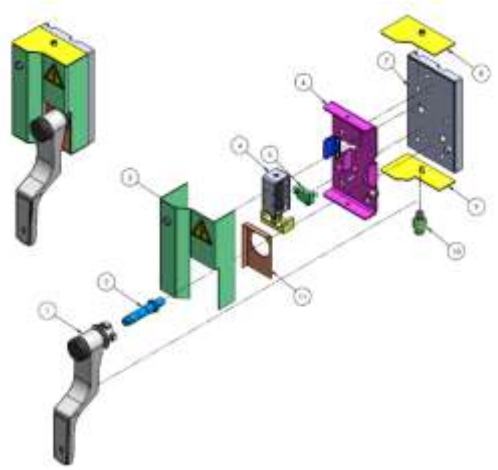

Figure 3. Exploded view of the solenoid-based door lock system

- **Solenoid Coil and Magnetic Steel Part (4, 5):** The core functional components, converting electrical energy into magnetic force to actuate the lock.
- **Control Unit and Sensors (6, 9, 10):** Ensures precise operation and feedback for safe and effective locking.

This detailed assembly is designed to meet the mechanical and operational demands of industrial environments, allowing for easy maintenance and high reliability during extended use.

2.1 Solenoid Coil Design

The solenoid coil is a critical component in the developed door lock system, responsible for generating the electromagnetic force necessary to operate the locking mechanism. To ensure optimal performance, the coil design is developed and analyzed using Finite Element Analysis. The FEA simulation enabled detailed exploration of electromagnetic properties, providing insights into the coil's behavior under operating conditions and ensuring that it could reliably generate the required magnetic force of 10 Newtons at a nominal voltage of 24V DC. The magnetic force requirement of 10 Newtons is determined based on design considerations and the operational needs of industrial washing machine door lock systems. The FEA model included the following key components: 1- Magnetic Steel Moving Part: Responsible for interacting with the generated magnetic field to perform the locking and unlocking motions. 2- Coil Housing: Provides structural support and ensures proper alignment of the magnetic flux. 3- Solenoid Coil: Converts electrical energy into magnetic force to actuate the locking mechanism. A high-quality mesh was created for the FEA model to achieve accurate

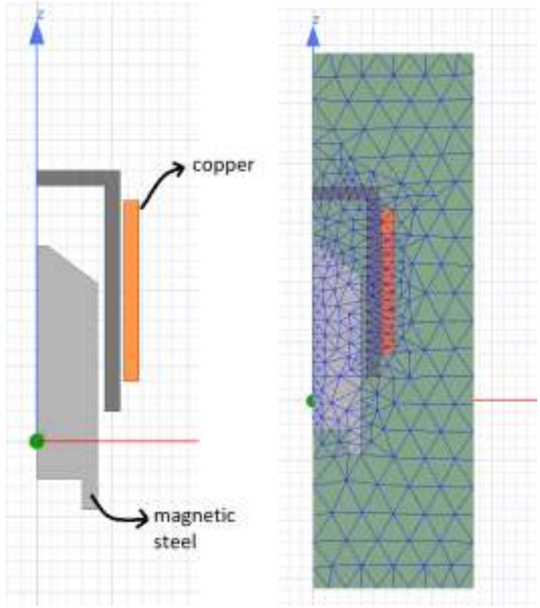

Figure 4. Finite Element Analysis model and mesh.

results, with refined elements around critical regions such as the magnetic steel part and the coil. Figure 4 depicts the FEA mesh structure, highlighting the solenoid coil, magnetic steel moving part, and housing components and the density of mesh elements.

The FEA simulation also provided detailed insights into the magnetic field behavior within the system. Figure 5 shows the magnetic flux lines, illustrating the distribution and intensity of the magnetic field generated by the solenoid coil. These flux lines ensure the efficient transfer of force to the moving magnetic steel part, enabling the locking mechanism's operation.

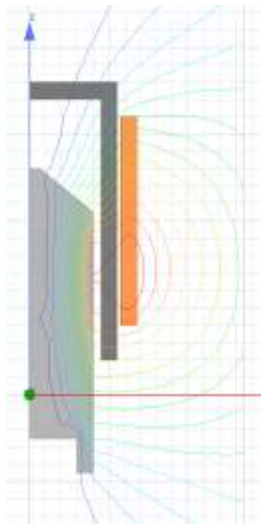

Figure 5. Magnetic flux lines generated by the solenoid coil, illustrating field distribution and its interaction with the moving magnetic steel part.

3. Results and Discussions

The system's performance was evaluated by analyzing the force generated by the solenoid coil over time at an input voltage of 24V DC. As shown in Figure 6, the force rapidly increases during the initial phase of activation, reaching a peak value of approximately 11 Newtons before stabilizing. This behavior demonstrates the coil's ability to achieve the necessary force within milliseconds, ensuring quick and reliable operation of the locking mechanism.

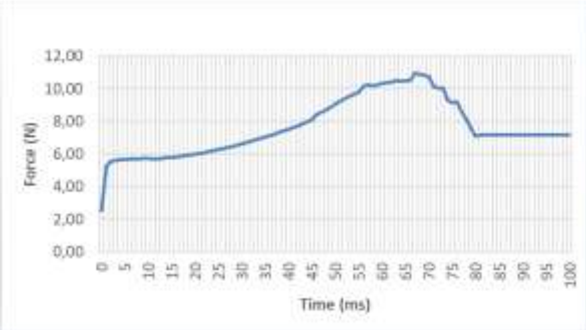

Figure 6. *Force-time graph at 24V DC*

The force-time curve indicates the system's responsiveness and efficiency. The rapid force buildup ensures the lock engages securely during operation, while the stabilization phase confirms consistent force output under steady-state conditions. The observed decline before stabilization is attributed to magnetic saturation effects, which are inherent to solenoid-based systems but have been minimized through careful design optimizations.

3.1 Testing Protocols

To ensure the reliability and effectiveness of the developed solenoid-based door lock system, a comprehensive set of tests was conducted. These tests focused on evaluating the system's electrical performance, mechanical durability, environmental resilience, and safety under real-world conditions. The following subsections provide an overview of the methodologies and results for each testing phase.

3.1.1 Electrical Performance Testing

The first phase of testing aimed to validate the electrical performance of the solenoid coil. The coil is powered with a nominal input voltage of 24V DC, and its current draw and resistance are measured to verify compliance with design specifications. The measured resistance of the coil is 32 ohms, with a tolerance of ±1%, consistent with the design requirements. During continuous operation, the power consumption is recorded as 15W, demonstrating the system's efficiency in converting electrical energy into magnetic force. This phase confirmed that the solenoid coil could operate consistently under nominal electrical conditions, providing a stable foundation for further testing.

3.1.2 Mechanical Durability Testing

The system's ability to withstand repeated use are assessed through mechanical durability testing. Over 15,000 locking and unlocking cycles are performed, simulating the real-world conditions of industrial washing machines. The tests are conducted with a 10-second interval between each cycle to mimic typical usage patterns. The results showed that the locking mechanism maintained its structural integrity and operational efficiency throughout the test, with no signs of wear or mechanical failure. The opening and closing times are measured as 400 milliseconds and 240 milliseconds, respectively, indicating the system's responsiveness and suitability for high-demand applications. Figure 7 shows the tested locking mechanism during the durability test, highlighting its compact and robust design.

Figure 7. *The tested solenoid-based door locking mechanism, showcasing its compact design and robust construction during mechanical durability testing.*

3.1.3 Environmental Resilience Testing

Given the demanding environments in which industrial washing machines operate, the lock system is subjected to environmental testing to evaluate its performance under extreme conditions. The system is exposed to a maximum temperature of 60°C and 90% relative humidity (non-condensing) for an extended period. Despite these challenging conditions, the lock mechanism continued to function reliably, demonstrating its suitability for use in humid and high-temperature industrial settings. Additionally, the system is tested under high-vibration conditions to assess the stability of its mechanical components. The results indicated that the connections and structural elements remained secure, with no loss of functionality.

3.1.4 Safety Testing

Safety is a critical consideration for any locking mechanism, particularly in industrial applications. The system is evaluated for its resistance to forced entry attempts, as well as its behavior during power failures. The mechanical structure of the lock successfully prevented unauthorized access during simulated forced entry scenarios. Furthermore, the system is designed to remain securely locked in the event of an electrical short circuit, ensuring user safety and preventing accidental openings. These safety features make the developed lock system a reliable solution for industrial washing machines, where both operational efficiency and security are paramount.

The comprehensive testing protocols validated the reliability, durability, and safety of the solenoid-based door lock system. The results indicate that the system is capable of withstanding the demands of industrial environments while maintaining consistent performance over extended periods of use.

3.2 Discussion

The developed solenoid-based door lock system successfully addresses the limitations of imported mechanisms by offering a reliable, cost-effective, and locally manufactured alternative. The comprehensive testing protocols validated its suitability for industrial washing machines, demonstrating high mechanical durability, consistent electrical performance, and resilience under challenging environmental conditions. The use of Finite Element Analysis in optimizing the solenoid coil design was particularly effective, ensuring the generation of sufficient magnetic force while maintaining energy efficiency. Moreover, the system's safety features, such as resistance to forced entry and secure locking during power failures, highlight its robust design and operational reliability. These results suggest that the developed system is not only an improved replacement for existing solutions but also a scalable option for broader industrial applications. Future studies could explore the integration of advanced sensor technologies for real-time feedback and the adaptation of the design for other heavy-duty machinery, further enhancing the system's versatility and market potential.

4. Conclusions

This study successfully developed and validated a solenoid-coil-based door lock system designed specifically for industrial washing machines. The system addresses the limitations of imported mechanisms by providing a locally manufactured, cost-effective, and reliable alternative. Through the use of FEA, the solenoid coil design is optimized to achieve sufficient electromagnetic force while maintaining energy efficiency. Comprehensive testing confirmed the system's robustness, including mechanical durability over 15,000 cycles, resilience under high temperature and humidity conditions, and safety against forced entry and electrical failures.

The results demonstrate that the developed system meets the stringent demands of industrial environments, offering a secure and efficient locking solution. Furthermore, its modular and scalable design opens the potential for application in other industrial machinery. Future work could explore the integration of advanced feedback systems, as well as adaptations for different operational requirements, to further enhance the versatility and marketability of the system. This development not only contributes to the local manufacturing industry but also paves the way for innovative solutions in electromagnetic locking mechanisms.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1] A. Sérgio et al., (2003) The design of a washing machine prototype, *Mater Des*, 24(5);331–338, doi: 10.1016/S0261-3069(03)00042-6.

[2] C. Pakula and R. Stamminger, (2010) Electricity and water consumption for laundry washing by washing machine worldwide, *Energy Effic*, 3(4);365–382, doi: 10.1007/s12053-009-9072-8.

[3] J. Kim, Y. Park, C. Yun, and C. H. Park, (2015) Comparison of environmental and economic impacts caused by the washing machine operation of various regions, *Energy Effic*, 8(5);905–918, doi: 10.1007/s12053-015-9333-7.

[4] G. Crini et al., (2024) Characterization and treatment of industrial laundry wastewaters: a review, *Springer Nature*. doi: 10.1007/s10311-024-01770-y.

[5] E. Bracquené et al., (2021) Analysis of evaluation systems for product repairability: A case study for washing machines, *J Clean Prod*, 281,doi: 10.1016/j.jclepro.2020.125122.

[6] A. Milecki and R. Regulski, (2017) Washing machine controller with a new programming method, *Acta Mechanica et Automatica*, 11(4);328–332, doi: 10.1515/ama-2017-0051.

[7] L. Bascetta, P. Rocco, A. M. Zanchettin, and G. Magnani, (2012) Velocity control of a washing machine: A mechatronic approach, *Mechatronics*, 22(6);778–787, doi: 10.1016/j.mechatronics.2012.04.005.

[8] M. Ali Koondhar, I. Ali Channa, S. ABID ALI SHAH Bukhari, and A. Hameed, (2022) Experimental based automatic control of washing machine using programmable logic Controller, *Journal of Applied and Emerging Sciences*, 12; doi: 10.36785/jaes.121533.

[9] A. Bali, R. B. E. Mohita, and S. Gupta, (2016). Study Of Various Applications Of Internet Of Things (Iot), *International Journal of Computer Engineering and Technology*, 9(2);39–50,

[10] M. J. B. Solanki, (2015) Electromagnetic Analysis of Solenoid Coil in ANSYS and IES Software : Case Study, *International Journal on Recent and Innovation Trends in Computing and Communication*, 11;6452–6455,

[11] Q. Hu, X. Wang, M. Guan, and Y. Zhou, (2020) Magneto-Mechanical Coupling Analysis of a Superconducting Solenoid Using FEM with Different Approaches, *IEEE Transactions on Applied Superconductivity*, 30(4);doi: 10.1109/TASC.2020.2969402.

[12] Ansys, “https://www.ansys.com/academic.”