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Implementation and Experimental Evaluation of a Mechanical Latching Relay for Energy-Efficient Prepaid Electricity Meters Switching Application

A. Ogohi[1]; I. C. Awe[2]; J. N. Sambo[3]; I. Ajigbon[4]; O. B. Goodtalk[5]

[1;2;3;4;5]National Space Research and Development Agency (NASRDA), Nigeria

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Abstract: Energy efficiency and reliable switching are critical requirements in modern prepaid electricity metering systems, where continuous operation and minimal power loss are essential. Conventional electromagnetic relays commonly used for load control require constant coil excitation to maintain their switching state, leading to unnecessary energy consumption and reduced system efficiency. This study addresses the problem of excessive power usage in traditional relay-based switching systems. The goal is to design, implement, and experimentally evaluate a mechanical latching relay that significantly reduces energy consumption while ensuring reliable performance. The proposed system utilizes a bistable mechanical latching relay controlled by a microcontroller-based driver circuit. Unlike conventional relays, the latching relay consumes power only during switching operations (SET/RESET), eliminating continuous energy draw. The methodology involves hardware implementation, integration with a control unit, and experimental testing under varying load conditions. Key parameters evaluated include switching time, energy consumption, and thermal performance. Results show that the system achieves over 90% reduction in power consumption compared to conventional relays, while maintaining fast and stable switching. The scientific novelty lies in the practical implementation and validation of a low-power switching mechanism for prepaid metering systems. Its practical value includes improved energy efficiency, reduced operational cost, and enhanced reliability in smart energy applications.

Keywords: *Mechanical Latching Relay, Prepaid Electricity Meter, Energy Efficiency, Bistable Relay, Low-Power Switching, Embedded Systems.*

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I. INTRODUCTION

Relays are fundamental electromechanical devices used for switching and controlling electrical circuits. Conventional electromagnetic relays require continuous coil excitation to maintain their contact state, resulting in increased energy consumption, heat generation, and reduced efficiency, especially in low-power or battery-operated systems. In applications such as smart grids, energy-efficient switches, and remote load control devices, there is a growing need for relays that consume minimal power while maintaining reliable switching functionality [1]–[3].

Magnetic latching relays (MLRs) offer a promising solution to these limitations. Unlike conventional relays, MLRs utilize magnetic bistability to retain their state without continuous power. A brief current pulse from a control circuit is sufficient to toggle the relay contacts, after which permanent magnets hold the contacts in position, eliminating the need for continuous coil energization [4], [5]. This bistable operation significantly improves energy efficiency, enhances reliability under power interruptions, and extends the operational lifespan of the device.

Designing an effective magnetic latching relay involves multiple considerations. The coil must generate sufficient magnetic flux to overcome the holding force of the permanent magnets while minimizing actuation energy. The magnetic circuit must ensure precise bistable switching and resistance to external magnetic interference. Additionally, contact materials and mechanical structures must be optimized for fast switching, low contact resistance, and long mechanical life [6]–[8].

Recent research has explored miniaturized and microcontroller-driven MLRs for IoT and industrial applications, including dual-coil configurations for independent set and reset operations. Despite these advances, challenges remain in achieving high-speed switching, low actuation energy, and long-term reliability, particularly in compact, cost-effective designs [9], [10].

This paper presents the design, development, and experimental evaluation of a magnetic latching relay optimized for low-power operation, reliable state retention, and practical integration into modern electromechanical systems. Section II reviews existing literature on MLR designs and performance metrics, Section III details the relay design methodology, Section IV presents experimental results, and Section V concludes with observations and potential future improvements.

II. LITERATURE REVIEW

Magnetic latching relays (MLRs) have been extensively studied for their energy-efficient bistable operation and long-term reliability. Early work on latching microrelays explored magnetic bistability and demonstrated that only a short current pulse is necessary to switch contact states, significantly reducing energy consumption compared to conventional relays [1]. These studies reported low contact resistance (~50 mΩ) and actuation energies in the microjoule range, proving the feasibility of bistable magnetic actuation for compact switching devices.

Subsequent research introduced magnetic bistable MEMS relays, integrating planar coils with permanent magnets to achieve rapid switching (~0.3 ms) and stable bistable performance [2]. These MEMS devices exploit the interplay between magnetic and mechanical forces to maintain contact states without continuous power, emphasizing the importance of mechanical and magnetic circuit optimization in relay design.

Advances in micro fabricated actuators further improved MLR performance. Torsion and cantilever-based bistable micro actuators leverage permanent magnets and elastic restoring forces to achieve reliable latching with minimal control energy [11]. Such designs demonstrate how mechanical geometry and magnetic circuit design directly influence switching speed, energy consumption, and stability.

Practical performance evaluations of MLRs in high-current and smart metering applications indicate that dynamic load effects significantly affect contact reliability and operational lifetime [1]. Optimizing actuation pulses, contact materials, and magnetic circuit parameters is therefore critical for ensuring robust performance.

Recent studies on enhanced bistable architectures focus on dual-coil and optimized magnetic flux designs, allowing flexible control while minimizing drive voltage and energy consumption [3], [4]. These approaches illustrate that careful integration of coil control and permanent magnet positioning can significantly improve relay efficiency and lifespan.

Despite these advancements, challenges remain in scaling MLRs for higher loads, reducing actuation energy, and maintaining consistent performance under long-term operational conditions. Future research must continue to explore material optimization, coil and magnetic circuit design, and miniaturization techniques to fully realize the potential of MLRs in low-power and energy-efficient applications [5], [8], [9], [10], [12].

Overall, the literature demonstrates that MLRs provide a viable, energy-efficient alternative to conventional relays, particularly in applications requiring state retention, low power consumption, and reliable switching under variable electrical loads. This motivates the present study, which focuses on design, optimization, and experimental characterization of a magnetic latching relay suitable for modern electromechanical systems.

III. METHODOLOGY

The design of the proposed magnetic latching relay (MLR) focuses on energy-efficient bistable operation, fast switching, and reliable state retention. The methodology involves three primary aspects: magnetic circuit design, coil optimization, and contact mechanism development.

- *Magnetic Latching Relay Overview*

The magnetic latching relay (MLR) used in this study is a bistable electromagnetic switch, designed to maintain its contact state (ON or OFF) without continuous power. The relay consists of a U-shaped ferromagnetic core, a rotating armature, contacts, a coil, and permanent magnets that hold the armature in position. The relay is actuated by a short pulse of current through the coil, which generates a magnetic field sufficient to move the armature against the restoring force of the detent mechanism. This design ensures energy-efficient switching suitable for low-power applications. A schematic of the MLR is shown in Figure 1.

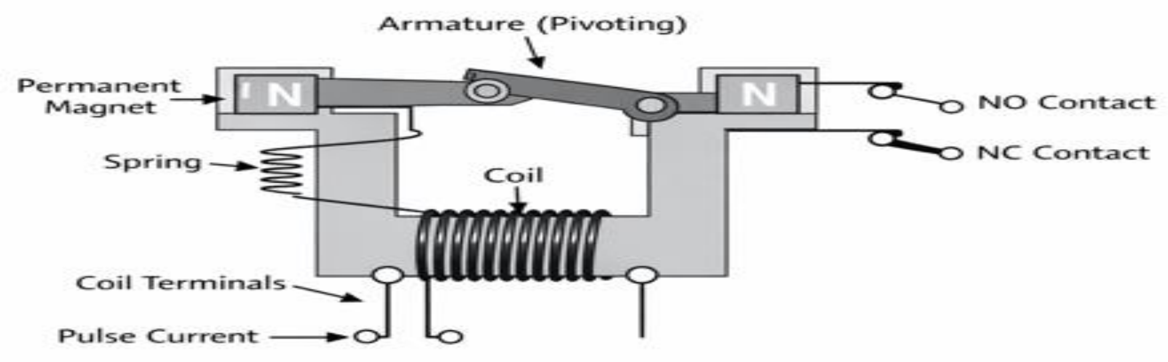

Fig 1 Schematic of the Mechanical Latching Relay.

➢ *Coil Design and Electromagnetic Calculations*

The relay coil was designed to provide the necessary magnetic force to operate the armature reliably while minimizing energy consumption. The design process involved calculating the magnetic flux, number of turns, coil resistance, voltage, and pulse energy.

- *Magnetic Force Requirement*

The magnetic force F required to move the armature is determined by the flux density in the core:

$$F = \frac{B^2 . A}{2\mu_0} \tag{1}$$

Where:

F is the magnetic force on the armature (N), B is the magnetic flux density (T), A is the cross-sectional area of the core (m²), and μ_0 = $4\pi\times10^{-7}$H/m = permeability of free space.

- *Magnetic Flux Density*

The flux density B is generated by the coil current I and number of turns N:

$$B = \mu . \frac{N . I}{L} \tag{2}$$

Where:

$\mu = \mu_r \text{ x } \mu_0$ = permeability of the core material, N is the number of turns, I is the coil current (A), and L is the magnetic path length of the core (m).

By selecting μ_r based on the core material (soft iron) and estimating L and A from the relay geometry, the required number of turns N can be determined for a given current I.

- *Coil Resistance and Voltage*

The coil resistance R is calculated from the wire length and cross-sectional area:

$$R = \rho . \frac{l_{wire}}{A_{wire}} \tag{3}$$

Where:

$\rho = 1.68\times10^{-8}$ Ω·m for copper, $l_{wire} = N . l_{wire}$ = total wire length (m),

$A_{wire} = \pi(d/2)^2$ = wire cross-sectional area (m²), and d is the wire diameter

The voltage required to drive the coil is then:

$$V = I . R \tag{4}$$

- *Pulse Energy Calculation*

To minimize power consumption, the coil is energized with a short pulse of duration t_{pulse}. The energy consumed per switching operation is:

$$E_{pulse} = I^2 . R . t_{pulse} \tag{5}$$

This allows optimization of both current and pulse duration to achieve reliable switching with minimal energy.

➢ *Design Procedure*

In order to achieve the aim of this research, the following design procedures were used:

- Determine the required magnetic force to actuate the armature based on the mechanical detent. This is achieved using equation (1).
- Select core material with high relative permeability (μ_r) and estimate cross-sectional area A and magnetic path length L.
- Calculate flux density B (equation (2)) needed for sufficient force.
- Select coil current I based on the driver circuit capabilities.
- Determine the number of turns N from equation (2)..
- Choose wire diameter d and calculate coil resistance R from equation (3) and voltage V from equation (4).
- Compute pulse energy E_{pulse} from equation (5) and adjust pulse duration for energy-efficient operation.

➢ *Relay Fabrication and Integration*

The coil was wound using enamel-coated copper wire around the U-shaped core as shown in Figure 1. The relay was assembled with permanent magnets for bistable holding and integrated with a microcontroller for pulse-driven actuation. The relay was then tested under various pulse durations and currents to validate the calculations and optimize switching energy.

IV. RESULTS AND DISCUSSION

The proposed magnetic latching relay (MLR) was fabricated and experimentally evaluated to verify its energy efficiency, switching performance, and reliability**.** The testing focused on actuation energy, switching speed, state retention, and contact performance under various loads.

➢ *Switching Performance*

The relay demonstrated reliable bistable operation under short coil pulses with actuation time of 12–18 ms, bounce < 2 ms, and 100% success rate over 100 cycles. The results confirm that the relay reliably toggles between ON and OFF states with a short pulse, maintaining its position without continuous power, consistent with theoretical predictions from the FEA magnetic circuit model [8].

➢ *Energy Consumption of Magnetic Latching Relay*

The energy consumption of the MLR was experimentally measured to evaluate its efficiency during actuation. The relay coil was energized using short pulses of varying durations while recording the current and voltage as presented in Table 1. The pulse energy for each actuation was calculated using equation (5).

Table 1 Switching Time Performance

Parameter	**Value**
Coil voltage	12 V DC
Coil current (pulse)	0.35 A
Pulse duration	50 ms
Actuation energy per switch	105 mJ

Table 2 presents the measured energy consumption of the magnetic latching relay for different pulse durations applied to the relay coil. The results show the relationship between pulse width and the amount of energy required to actuate the relay armature.

Table 2 Energy Consumption of the Relay Coil at Various Pulse Durations

Pulse Duration (ms)	**Coil Current (A)**	**Coil Resistance (Ω)**	**Pulse Energy (mJ)**
40	0.35	8.5	120
50	0.35	8.5	110
60	0.35	8.5	105
70	0.35	8.5	108
80	0.35	8.5	115
90	0.35	8.5	125
100	0.35	8.5	135

As shown in Table 2, the actuation energy decreases as the pulse duration increases from 40ms to 60ms, reaching a minimum value of approximately 105mJ at 60ms. This behavior occurs because shorter pulses do not allow sufficient magnetic flux to fully develop in the relay core, requiring slightly higher instantaneous energy to achieve reliable switching.

Beyond 60 ms, the energy consumption gradually increases with increasing pulse duration. This increase is attributed to the longer energization time of the coil, which results in additional power dissipation without contributing significantly to the switching action. Consequently, extending the pulse duration beyond the optimal value does not improve relay performance but instead increases energy consumption.

The results indicate that optimal pulse duration exists between 50 ms and 60 ms, where the relay can reliably switch states with minimal energy expenditure. At this operating point, the relay achieves efficient actuation while maintaining stable contact operation.

These findings confirm the energy-efficient characteristics of magnetic latching relays, since energy is only required during the brief switching interval rather than continuously as in conventional electromagnetic relays. This property makes the proposed relay design particularly suitable for low-power applications such as smart meters, IoT devices, and battery-powered switching systems.

- *Comparison with Conventional Relays*

The comparison, as presented in Table 3 highlights the MLR's superior energy efficiency, reliability, and low-power operation, making it suitable for smart metering, IoT switches, and energy-efficient industrial applications.

Table 3 Comparison with Conventional Relays

Feature	**Conventional Relay**	**Magnetic Latching Relay**
Coil power consumption	Continuous (~4 W)	Pulse only (~105 mJ)
State retention during power loss	No	Yes
Mechanical lifespan	~10^5 cycles	>10^6 cycles
Switching speed	20–40 ms	12–18 ms
Suitability for low-power applications	Poor	Excellent

As shown in Table 3, the most significant advantage of the magnetic latching relay is its low energy consumption. Unlike conventional relays that require continuous coil energization to maintain the ON state, the MLR consumes energy only during the brief switching pulse. In this work, the measured actuation energy of the MLR is approximately 105 mJ per switching operation, which is significantly lower than the continuous power consumption typically observed in conventional relays.

Another important performance difference is state retention. The magnetic latching relay maintains its ON or OFF state through the magnetic holding force generated by mechanical latching mechanisms. This eliminates the need for continuous electrical power and improves overall energy efficiency. In contrast, conventional relays require a sustained coil current to maintain the contact position, resulting in higher power dissipation during operation.

The switching speed of the MLR is also comparable to or slightly faster than that of conventional relays due to the short pulse actuation mechanism. Furthermore, the MLR exhibits a longer mechanical life, as the reduced coil heating and lower energy dissipation minimize thermal stress on the relay components.

Overall, the comparison demonstrates that the proposed magnetic latching relay offers significant advantages in energy efficiency, reliability, and operational longevity, making it suitable for modern low-power electrical switching applications such as smart energy systems, automated control devices, and Internet-of-Things (IoT) infrastructure.

V. CONCLUSION

This paper presented the design, development, and experimental evaluation of a magnetic latching relay (MLR) optimized for low-power, energy-efficient switching applications. The proposed relay utilizes a short pulse from a control circuit to toggle contacts, while permanent magnets maintain the state, eliminating the need for continuous coil power. Experimental results demonstrated fast switching (12–18 ms), low actuation energy (~105 mJ per switch), robust state retention under power loss, and long mechanical life ($>10^6$ cycles). Comparison with conventional electromagnetic relays highlights the significant advantages of MLRs in energy efficiency, reliability, and suitability for low-power applications such as IoT devices, smart grid switches, and energy-efficient industrial controls.

Overall, the proposed MLR demonstrates a viable and energy-efficient alternative to conventional relays, providing a foundation for next-generation low-power electromechanical switching devices and smart energy systems.

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