Analysis of Latching Relay Degradation in Smart Meters: Implementing Zero-Cross Detection as a Mitigating Strategy

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Abstract— Latching relays are critical components in smart meters, susceptible to performance degradation over time. This paper investigates these degradation mechanisms and proposes zero-cross detection (ZCD) circuit integration as a mitigation strategy. Various tests identify dominant failure modes during switching operations. Electrical and thermal performance are evaluated. A ZCD circuit is designed for seamless integration with existing smart meter architecture. The analysis explores the economic viability, performance gains, and technical challenges (integration complexity, power consumption impact, and potential functionality limitations) associated with ZCD implementation. This work offers valuable insights for optimizing latching relay performance and extending its lifespan within smart meter systems, ultimately contributing to improved reliability and efficiency of smart metering infrastructure.

Index Terms— Latching relay degradation, Zero-Cross Detection (ZCD) integration, smart meter, Performance, reliability.

I. INTRODUCTION

S MART meters are revolutionizing the electricity grid by enabling two-way communication between utilities and consumers. This facilitates real-time monitoring of energy consumption, improved billing accuracy, and efficient demand management. Latching relays are critical components within smart meters, responsible for isolating and connecting circuits during power measurements. However, these relays experience degradation over time due to various mechanisms, impacting their performance and reliability. This degradation can lead to inaccurate measurements, increased power losses, and potential system failures.

Therefore, ensuring optimal latching relay performance is crucial for the successful operation of smart metering infrastructure. This paper investigates the degradation mechanisms affecting latching relays in smart meters. Proposing a novel approach to mitigate these concerns by integrating a zero-cross detection (ZCD) circuit. The ZCD circuit identifies the zero-crossing points of the AC waveform, enabling relay operation at optimal switching times and minimizing stress on the relay contacts.

The remainder of this paper is structured as follows. Section I introduces the critical role of latching relays and load switches in single-phase smart meters, highlighting relay degradation challenges and the potential of zero-crossing.
B. Thermal Degradation

Heat generation within a latching relay arises from several sources: the coil itself (due to Joule heating during activation), the ambient temperature surrounding the relay, and the contact resistance at the contact points, especially if there are high currents flowing through the load circuit [2].

The heat generated can have several detrimental effects on the relay's performance. High temperatures can weaken the magnetic field generated by the coil, leading to a decrease in the force acting on the armature and potentially causing sluggish movement or even contact bounce during switching [2]. Additionally, excessive heat can cause physical deformation of the yokes, armature, and other components within the relay. This deformation can alter the alignment and clearances between these parts, potentially leading to sticking contacts or difficulty in maintaining the latched state [2]. Furthermore, high temperatures can accelerate the degradation of the materials used in the relay, such as the insulation on the coil wire becoming brittle and cracking, leading to electrical shorts. Additionally, the contact surfaces can oxidize or wear down more quickly at elevated temperatures, increasing contact resistance and reducing overall reliability [9, 10].

Consequences of Thermal Degradation:

a. Increased operate and release times due to the weakened magnetic force caused by heat.

b. Contact welding due to high contact resistance caused by thermal degradation.

c. Reduced lifespan of the latching relay, leading to inaccurate measurements and potential smart meter malfunctions.

Mitigation Strategies:

a. Selecting a relay with a current rating exceeding the expected operating current provides a buffer and reduces heat generation within the coil [3].

b. If heat dissipation is a concern, consider using a relay with a higher temperature rating or employing heat sinks to improve heat transfer away from the relay, keeping its internal components within safe operating temperatures [2].

c. In extreme cases, forced air cooling can be implemented to actively remove heat from the relay [2].

C. Sulfidation and Oxidation

Exposure to air and sulfur-containing compounds in the environment can lead to the formation of oxide and sulfide layers on the contact surfaces, respectively. These layers can cause several problems:

a. Increased contact resistance: The oxide and sulfide layers introduce additional barriers to current flow, increasing the overall contact resistance. This translates to power loss, reduced relay efficiency, and potential overheating issues [2].

b. Brittle and weak layers: Sulfide layers are often brittle and can weaken the underlying contact material. This increases susceptibility to mechanical wear and potential contact welding during high current operation [2].

Mitigation Strategies:

a. Choosing contact materials with inherent resistance to oxidation and sulfidation, such as gold or palladium, can help minimize layer formation [2].

b. Consider applying thin protective coatings, such as gold or palladium, to the contact surfaces to further reduce oxidation and sulfidation [4].

D. Magnetic Degradation

The magnetic circuit within a latching relay plays a critical role in maintaining the set or reset state. However, several factors can contribute to the degradation of magnetic properties over time.

1. Degradation of the Soft Magnetic Yoke: The soft magnetic yoke concentrates the magnetic field generated by the permanent magnet. However, its performance can deteriorate due to several mechanisms, including mechanical stress and strain from vibrations or shocks during operation, exposure to high temperatures that can decrease the permeability of the yoke material, and corrosion in humid environments that can lead to the formation of non-magnetic oxides on the surface, disrupting the magnetic flux path [1].

2. Degradation of the Ferromagnetic Permanent Magnet: The permanent magnet within a latching relay provides the biasing magnetic field that holds the relay in its set or reset state. However, its magnetic properties can weaken over time due to demagnetization from exposure to strong external magnetic fields, vibration, or high temperatures, temperature effects where the magnetic strength changes with temperature, and aging, a natural process leading to a gradual loss of magnetization [1, 2].

The consequences of both yoke and magnet degradation are similar: increased actuation force due to a weaker magnetic circuit, weakened holding force making the relay more susceptible to external influences, and potential relay failure in severe cases [1].

Mitigation Strategies:

a. Using high-quality yoke materials with good mechanical strength and high permeability can improve their longevity [1].

b. Proper thermal management through heat dissipation techniques can help maintain lower operating temperatures, minimizing the impact of heat on the magnet's properties [2].

c. Selecting high-quality permanent magnet materials with high magnetic stability and resistance to demagnetization is crucial. Rare earth magnets generally offer better performance compared to traditional ferrite magnets [2].


d. Utilizing keepers, which are soft magnetic bars placed across the magnet poles when the relay is not energized, can help prevent demagnetization due to stray magnetic fields [1].

III. PERFORMANCE EVALUATION

A. Live Load Testing of a Relay at 56A

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>56 A, @UPF</td>
</tr>
<tr>
<td>Relay Switching</td>
<td>5 Secs ON</td>
</tr>
<tr>
<td></td>
<td>40 Secs OFF</td>
</tr>
<tr>
<td>Cabling</td>
<td>10 mm² Copper</td>
</tr>
<tr>
<td></td>
<td>Multistrand</td>
</tr>
<tr>
<td>Room temp</td>
<td>30</td>
</tr>
</tbody>
</table>

The relay will be energized (turned ON) for a continuous period of 5 minutes. This will be repeated every 1 hour. Temperature will be measured at the point where the relay connects to the circuit, after the shunt resistor.

![Fig. 2: Relay After Cyclic Switching Test](image)

This investigation evaluated the performance of a relay subjected to cyclic switching conditions (refer to Table 1 for details). The relay was energized for 5 minutes every hour. The maximum recorded temperature at the relay contact area (after the shunt) exceeded typical operating ranges, reaching 180°C. Additionally, a significant voltage drop with wide variations was observed during switching cycles, as shown in Table 2 and Figure 4. The observed discoloration of the copper near the contact area (Figures 2 and 3) further suggests overheating. These findings point towards potential contact degradation, possibly due to oxidation, pitting, or insufficient contact force.

B. Latching Relay Performance under 60A Load- Self Heating Test

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>60A live (combined resistive and capacitive under UPF)</td>
</tr>
<tr>
<td>Relays</td>
<td>New latching relay</td>
</tr>
<tr>
<td>Relay Cycling</td>
<td>4-5 ON/OFF cycles with load applied</td>
</tr>
<tr>
<td>Cables</td>
<td>12 sq.mm copper multi-strand</td>
</tr>
<tr>
<td>Test Duration</td>
<td>2 hours</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>34°C</td>
</tr>
</tbody>
</table>
### TABLE III

<table>
<thead>
<tr>
<th>Time</th>
<th>Voltage Drop (mV)</th>
<th>TB IN (outside)</th>
<th>Relay Input Side</th>
<th>Relay Inside</th>
<th>Cables (near meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial (04:20)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4:30</td>
<td>P-93, N-71</td>
<td>85°C</td>
<td>105°C</td>
<td>123°C</td>
<td>-</td>
</tr>
<tr>
<td>6:20</td>
<td>P-180, N-190</td>
<td>128°C</td>
<td>232°C</td>
<td>256°C</td>
<td>104°C</td>
</tr>
</tbody>
</table>

**IV. TRADITIONAL LOAD SWITCH CONTROL IN SINGLE-PHASE SMART Meters**

Conventional single-phase smart meters often employ latching relays, also known as load switches, for remote disconnection and reconnection functionalities. These functionalities are crucial for managing customer accounts and controlling power delivery based on various factors. The control system for these load switches typically comprises two distinct components:

**A. Hardware Execution:**

Dedicated hardware circuitry within the smart meter is responsible for executing the control commands received from the software logic unit. This hardware typically includes a microcontroller (MCU) and associated driver circuits to interface with the latching relay. Upon receiving a control signal from the software, the MCU interprets the command and activates the appropriate driver circuit. The driver circuit then provides the necessary control voltage or current to actuate the latching relay, causing it to open or close the circuit contacts.

**B. Software Logic:**

Software running on the smart meter’s processor interprets the received control signals, typically transmitted remotely via communication protocols. These signals could originate from a central management system or a local user interface. The software logic unit analyzes the received information, such as customer account status, meter readings, or pre-defined control schedules, and translates it into appropriate control commands for the hardware execution unit. In the case of a disconnection event due to exceeding consumption limits or other criteria, the software would generate a command to the hardware to open the latching relay, thereby interrupting power delivery to the customer's premises. Conversely, upon receiving a reconnection signal triggered by a payment confirmation or remote-control action, the software would send a command to the hardware to close the latching relay, restoring power supply.

![Fig. 5: Thermal Image of Relay Terminals After 60A Live Load Test](image1)
![Fig. 6: Thermal Image of Relay Contacts After 60A Live Load Test](image2)

The test revealed a significant increase in voltage drop across the relays, nearly doubling over the test duration. This suggests a potential rise in contact resistance within the relay. Furthermore, concerning temperature rise was observed, as evidenced by the data in Table III and the thermal images in Figures 5 and 6. The temperature at the relay input side reached 232°C, and an even higher temperature of 256°C was measured inside the relay near the contact area. In contrast, the cable temperature remained relatively stable throughout the test. These combined observations strongly suggest potential overheating within the relay, which could lead to damage if not addressed.

![Fig. 7: Existing load switch control System](image3)
Traditional load switch control in smart meters often leads to arcing during relay operation, which can degrade relay lifespan. Zero-Crossing Detection (ZCD) technology offers a solution to minimize arcing by switching the relay at the zero-crossing points of the AC voltage waveform. Implementing ZCD necessitates modifications to both the hardware and software sections of the smart meter control system.

A. Hardware Enhancements:

Voltage Zero-Crossing Detection Module: A dedicated ZCD module is integrated into the hardware section. This module continuously monitors the AC voltage waveform and identifies the exact moments when the voltage crosses zero.

B. Software Logic Modifications:

The software logic responsible for load switch control is modified to incorporate ZCD information:

a. Relay Contact State Consideration: The software considers the current state of the load switch contacts (open or closed) when determining the appropriate action time.

b. Operating Time Integration: The software factors in the measured operating time (time required for the relay contacts to open or close) when calculating the optimal timing for sending the actuation signal.

c. ZCD-based Action Signal Generation: Based on the voltage zero-crossing time, relay contact state, and operating time, the software calculates the optimal timing for sending an action pulse to the hardware control section.
crossing points of the AC waveform to minimize arcing and extend their lifespan. However, inherent delays within the smart meter system (communication and actuation) necessitate calculating the optimal timing for sending actuation signals to the relay control circuit[13].

A. Delay Time Measurement (tb and tc)

The first step involves characterizing the inherent delays in the system. This is achieved by measuring the operate time (tb) and release time (tc) of the latching relay.

a. Operate Time (tb): With the relay initially de-energized and at rated voltage, the MCU control circuit transmits an operate pulse (t1). The time (t2) when the relay contacts begin to close is recorded. The operate time is then calculated using the following equation:

\[ t_b = t_2 - t_1 \]  

(1)

b. Release Time (tc): Similarly, with the relay initially energized and at rated voltage, a release pulse (t3) is sent. The time (t4) when the contacts begin to open is recorded. The release time is calculated using the following equation:

\[ t_c = t_4 - t_3 \]  

(2)

B. Zero-Crossing Detection and Current Zero-Crossing Estimation

To achieve precise switching at voltage zero crossings, a dedicated zero-crossing detection module identifies the exact moment (to) when the AC voltage crosses zero.

Furthermore, the instantaneous load power factor (\( \cos \varphi \)) obtained from the smart meter allows estimation of the current zero-crossing point (to'). Equation 3 calculates this estimated time based on the previous voltage zero crossing (to) and the AC period (T):

\[ t_0' = t_0 + \arccos \varphi \left( \frac{T}{2\pi} \right) \]  

(3)

Calculation of Actuation Signal Timing (tbd and ted):

Knowing the relay state (de-energized or energized), measured delays (tb and tc), and estimated current zero crossing (to'), the optimal timing (tbd or ted) to send the actuation signal to the relay control circuit can be calculated using the following equations, respectively. The addition of T/2 in these equations ensures positive values for tbd and ted even under capacitive load conditions:

a. De-Energized Relay:

\[ t_{bd} = t_0' + T + \frac{T}{2} - t_b = t_0' + \frac{3}{2}T - t_b \]  

(4)

b. Energized Relay:

\[ t_{ed} = t_0' + T + \frac{T}{2} - t_c = t_0' + \frac{3}{2}T - t_c \]  

(5)

C. Effect Verification of Zero-crossing Load Switch Operation System

By implementing this zero-crossing operation principle and calculating the appropriate actuation signal timing based on zero crossings and measured delays, smart meters can achieve reliable latching relay operation with minimal arcing, thereby extending their lifespan and improving overall system performance.
VII. IMPLEMENTATION TECHNIQUES FOR ZCD IN SMART

Zero-Crossing Detection (ZCD) technology offers a valuable tool for enhancing the performance and reliability of latching relays used for load switch control in smart meters. This section dives into the practical techniques for implementing ZCD within the smart meter system.

A. Hardware Circuit Design:

The first step involves selecting and implementing an appropriate ZCD circuit design, considering the factors mentioned in the previous section (Design Considerations for Zero-Crossing Detection Circuits in Smart Meters). Here are the common ZCD circuit options:

a. **Op-amp Based ZCD:** This approach offers low hardware delay but requires additional isolation components. The design typically involves an op-amp comparator circuit that compares the AC voltage with a reference voltage near zero. The output of the comparator generates a signal when the AC voltage crosses zero. However, due to the lack of inherent isolation between the AC and DC sides, optocouplers or transformers are needed for safety.

![ZCD Circuit Using Comparator with Hysteresis](image)

b. **Optocoupler Based ZCD:** This design prioritizes safety by providing galvanic isolation between the AC and DC sides using an optocoupler. The AC voltage is fed to the optocoupler's LED, and the output phototransistor on the low-voltage side generates a signal when the AC voltage crosses zero. While offering isolation, this approach introduces higher hardware delay compared to the op-amp-based design.

![ZCD Circuit Using Optocoupler](image)

c. **Microcontroller-based ZCD:** This method utilizes the existing microcontroller within the smart meter. Interrupt is generated when any timing for reversing signs is detected in the operation result of the digital filter. This option can reduce component count and cost but may increase microcontroller load and introduce lower-priority ZCD interrupts, potentially leading to delays under heavy processing loads.

![Block Diagram of 24-bit ΔA/D Converter in RL78/I1C Microcontroller with Zero-Cross Detection](image)

B. Software Integration:

The ZCD circuit needs to be integrated with the smart meter's software logic. This involves:

a. **ZCD Signal Processing:** The software receives the output signal from the ZCD circuit indicating a zero crossing.

b. **Relay State Consideration:** The software considers the current state of the relay contacts (open or closed) to determine the appropriate action.

c. **Operating Time Integration:** The software factors in the measured operating time (time required for the relay contacts to open or close) when calculating the optimal timing for sending the actuation signal.

d. **Actuation Signal Generation:** Based on the ZCD signal, relay state, and operating time, the software calculates the optimal timing to send an actuation pulse to the hardware control section for switching the relay.

C. System Calibration:

The ZCD system may require initial calibration to ensure accurate zero-crossing detection and optimal timing for relay actuation. This calibration process might involve:

a. **Zero-Crossing Detection Verification:** Verifying the accuracy of the ZCD circuit in identifying true zero crossings of the AC voltage waveform.

b. **Operating Time Measurement:** Measuring the actual operating time of the specific latching relay used in the smart meter.

c. **System Delay Characterization:** Measuring and accounting for any delays introduced by the ZCD circuit and communication within the smart meter system.
VII. CONCLUSIONS

In conclusion, this paper investigated the impact of latching relay degradation on single-phase smart meters and explored zero-crossing detection (ZCD) technology as a potential mitigation strategy. The analysis identified various degradation mechanisms and highlighted the importance of performance evaluation methods for ensuring reliable smart meter operation. Traditional load switch control methods were found to potentially accelerate relay degradation, while ZCD-based control offers the advantage of switching at zero-crossing points, minimizing switching stress and extending relay lifespan. The feasibility of integrating ZCD with latching relays was explored, revealing potential benefits for both relay operation and overall system reliability. Finally, the paper discussed various ZCD implementation techniques and emphasized the significant advantages of ZCD technology, including extended relay life, enhanced system reliability, and improved power quality. Further research is necessary to address potential limitations and explore cost-effective ZCD implementation for widespread adoption in smart grids. This approach holds promise for achieving greater efficiency, reliability, and cost-effectiveness in smart meter deployments, ultimately contributing to a more robust and sustainable smart grid infrastructure.

REFERENCES


