

Undervoltage and Overvoltage Protection of Electrical Equipment: A Review

Dipali Kale^{1,*}, Bhushan Kadam¹, D.B. Pardeshi²

Abstract

In our modern, digitally driven world, the seamless operation of electrical equipment is paramount, spanning industries, households, and infrastructure. However, the reliability of these vital assets is inextricably linked to the quality of electrical power supplied to them. Voltage fluctuations, specifically undervoltage and overvoltage events, pose significant threats to the integrity and functionality of electrical equipment. This review paper undertakes a comprehensive exploration of undervoltage and overvoltage protection systems, shedding light on their pivotal role in mitigating power quality challenges. It delves into the multifaceted causes, classifications, and wide-reaching consequences of these voltage anomalies, addressing power quality issues from grid instabilities to load imbalances. Moreover, this paper presents a meticulously designed protection system synthesized from an extensive review of the literature. This system stands as the central guardian of the electrical network, ensuring the stability and quality of power supplied to connected equipment through vigilant monitoring and rapid corrective actions. As we navigate through this review, it becomes evident that the reliability and durability of electrical equipment are intrinsically linked to the quality of the power they receive. By addressing the multifaceted challenges presented by undervoltage and overvoltage conditions, this paper aims to make a significant contribution to the broader mission of securing the uninterrupted and secure operation of electrical equipment. It reinforces the foundations of a modern, efficient, and resilient electrical infrastructure well-equipped to face the dynamic power quality challenges of our digital age.

Keywords: Voltage protection, power quality, equipment safety, protection systems, voltage anomalies, electrical circuits, Zener diodes, circuit operation

INTRODUCTION

In the contemporary world, reliance on electrical equipment pervades every facet of life from industrial processes to household convenience. The seamless and reliable operation of these vital assets is not merely a matter of convenience but also a linchpin of modern society. However, this reliance comes with the profound responsibility of ensuring the consistent and secure functioning of electrical equipment, a responsibility intrinsically linked to the quality of the electrical power they receive [1–3].

*Author for Correspondence

Dipali Kale
E-mail: dipalikale912@gmail.com

¹Student, Department of Electrical Engineering, Sanjivani College of Engineering, Koregaon, Ahmednagar, Maharashtra, India

²Associate Professor, Department of Electrical Engineering, Sanjivani College of Engineering, Koregaon, Ahmednagar, Maharashtra, India

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Voltage fluctuations, particularly undervoltage and overvoltage events, represent substantial challenges to the integrity and performance of electrical equipment. These deviations from the nominal voltage can wreak havoc on sensitive devices, leading to reduced operational efficiency, damage, or even catastrophic failures.

This comprehensive review embarks on a meticulous exploration of undervoltage and overvoltage protection systems, unraveling their indispensable role in mitigating power quality

concerns. We delve deep into the intricate tapestry of the causes, classifications, and profound implications of these voltage anomalies. Numerous and diverse factors contribute to voltage deviations from grid instabilities to load imbalances [4].

Moreover, we presented a thoughtfully integrated proposal for a protection system meticulously designed to address these challenges. This system operates at the heart of the electrical network, serving as the guardian of the connected equipment, monitoring, and maintaining the voltage within acceptable bounds [5, 6].

As we progress through this paper, it becomes apparent that the reliability of electrical equipment is not solely dependent on their intrinsic design and functionality but is profoundly tethered to the stability and quality of the power supplied. By confronting the multifaceted issues posed by the undervoltage and overvoltage conditions, we aim to make a significant contribution to the broader mission of ensuring the continuous and secure operation of electrical equipment. This is more than a matter of convenience; it is a pillar of modern, robust, and resilient electrical infrastructure, adept at meeting the challenges of a dynamic power landscape [7].

METHODOLOGY

This review adopts a structured methodology to compile and analyze existing knowledge on undervoltage and overvoltage protection systems for electrical equipment. The methodology consists of the following steps:

- *Literature search:* A thorough and systematic search was conducted across academic databases, including IEEE Xplore, ScienceDirect, Google Scholar, and relevant industry publications. Key search terms such as “undervoltage protection,” “overvoltage protection,” and “power quality” were employed to identify pertinent sources.
- *Source selection:* The identified literature underwent rigorous selection criteria, prioritizing relevance to the topic, source credibility, publication date, and scholarly reputation. The emphasis was placed on peer-reviewed research articles, conference papers, books, and authoritative reports.
- *Data extraction:* Pertinent information, including concepts, causes, classifications, and protection methodologies, was systematically extracted from selected sources. This process involved identifying key insights to facilitate structured discussion.
- *Data synthesis:* Extracted data were synthesized to create a cohesive narrative, highlighting common themes, critical findings, and notable trends that underpin the discussions presented in this paper.
- *Proposal development:* The proposal for an integrated protection system, as presented in this paper, is derived from a comprehensive synthesis of the reviewed literature.

This methodology ensures a systematic and rigorous approach to aggregate, analyze, and synthesize a wealth of knowledge on undervoltage and overvoltage protection systems, ultimately offering readers a comprehensive understanding of the subject matter grounded in authoritative sources.

POWER QUALITY AND IT'S PROBLEM

Power quality refers to the characteristics of electrical power that enable electrical and electronic systems to function without interruption or malfunction. The key parameters of power quality include voltage stability, frequency stability, harmonics, voltage sags and swells, and transient voltage disturbances.

Causes of Power Quality Problems

- *Voltage sags and swells:* Caused by grid disturbances, faults, or load switching.
- *Harmonics:* Result from non-linear loads like variable frequency drives.
- *Voltage fluctuations:* Occur due to rapid load changes.
- *Transient voltage disturbances:* Include lightning strikes and switching transients.
- *Frequency variations:* Deviations in the system's frequency.

Effects of Power Quality Problems

- *Motors:* A voltage sag can lead to overheating and reduced efficiency. Harmonics cause additional losses.
- *Electronics and sensitive equipment:* Voltage fluctuations and harmonics can affect sensitive electronics and lead to data loss and damage.
- *Lighting systems:* Voltage fluctuations and harmonics can reduce the lifespan of a lighting system and cause flickering.
- *Productivity and downtime:* Power quality problems can result in equipment malfunctions and downtime, affecting productivity [8].
- *Energy efficiency:* Harmonics and voltage fluctuations can reduce energy efficiency.
- *Safety:* Power quality issues can lead to equipment overheating and pose safety risks.

Understanding and mitigating these power quality problems is crucial for maintaining the efficient and reliable operation of electrical systems and protecting sensitive equipment [9–13].

UNDERVOLTAGE

The waveform undervoltage protection typically represents the voltage conditions to which the protection system is designed to monitor and respond. The voltage waveform is shown in Figure 1. The waveform undervoltage protection is generally characterized by a sinusoidal voltage signal that falls below the specified voltage threshold. The following is a brief description.

- The waveform starts with a nominal sinusoidal voltage signal that represents the standard operating voltage level [14].
- When an undervoltage condition occurs, the waveform drops below this nominal voltage level, indicating a voltage drop.
- The waveform may show the duration and magnitude of the undervoltage event, which is usually defined by the settings and thresholds of the protection system.
- The waveform may also include information about the protective action taken in response to the undervoltage condition, such as opening a circuit breaker or activating a protective device.

The undervoltage protection waveform is a graphical representation of voltage conditions over time, and it is a crucial aspect of voltage protection systems, as it helps to visualize and analyze voltage anomalies, enabling appropriate responses to safeguard electrical equipment from potential damage or disruption.

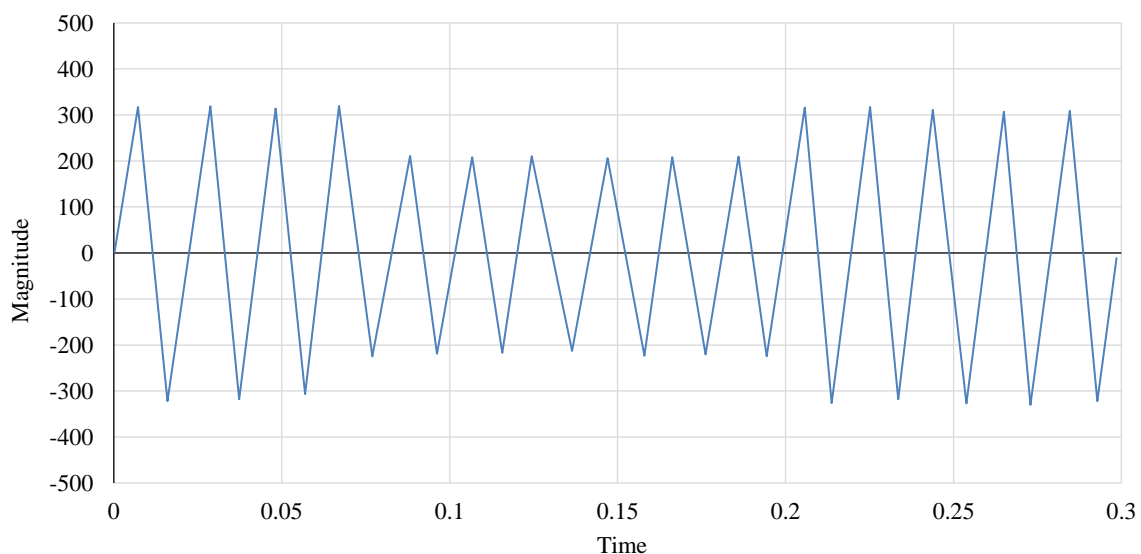


Figure 1. Undervoltage waveform.

Causes of Undervoltage Protection

Undervoltage in electrical systems can be caused by various factors, including:

- *Grid or utility voltage fluctuations:* The common cause of undervoltage is fluctuations in the voltage supplied by the utility grid. This could be due to high demand, faults in the grid, or other factors.
- *Load changes:* Sudden changes in the load connected to the electrical system can lead to undervoltage. For example, when a large motor starts up, it can cause a temporary drop in voltage.
- *Faults and short circuits:* Faults in electrical systems, such as short circuits, can cause a localized drop in voltage in the affected areas.
- *Voltage regulation issues:* Problems with voltage regulation equipment in the grid or within the electrical system can result in voltage conditions [15].
- *Lightning strikes:* Lightning strikes near power lines or substations can induce voltage sags or voltage conditions.
- *Equipment failure:* Failure of transformers, capacitors, or other voltage control equipment can lead to undervoltage.
- *Generator operation:* Undervoltage can also occur during the start-up or synchronization of generators [16].

Understanding these causes is crucial for the development of effective voltage protection systems for electrical equipment.

According to the IEEE Classification of Undervoltage, the Classification of Undervoltage is Shown in Table 1.

This classification aids in understanding the different types of undervoltage events and allows for the development of protection and mitigation strategies tailored to the specific characteristics of each type.

OVERVOLTAGE

The waveform for overvoltage protection typically represents the voltage conditions to which the protection system is designed to monitor and respond. The waveform for overvoltage protection is characterized by a sinusoidal voltage signal that exceeds the specified voltage threshold. The following is a brief description as shown in Figure 2.

- The waveform starts with a nominal sinusoidal voltage signal that represents the standard operating voltage level.
- When an overvoltage condition occurs, the waveform exhibits a spike or peak that rises above the nominal voltage level, indicating a voltage surge.
- The waveform may show the duration and magnitude of the overvoltage event, typically defined by the settings and thresholds of the protection system.
- The waveform may also include information about the protective action taken in response to the overvoltage condition, such as opening a circuit breaker or activating a surge protective device.

The overvoltage protection waveform provides a graphical representation of the voltage conditions over time, which is essential for visualizing and analyzing voltage anomalies. This visualization helps in implementing protective measures to prevent potential equipment damage or disruption owing to excessive voltage levels [17].

Table 1. Classification of undervoltage.

Type of undervoltage	Duration	Magnitude
Instantaneous	0.1–0.9 per unit	0.5–30 Cycles
Momentary	0.1–0.9 per unit	30 Cycles–3 secs
Temporary	0.1–0.9 per unit	3 secs–1 min

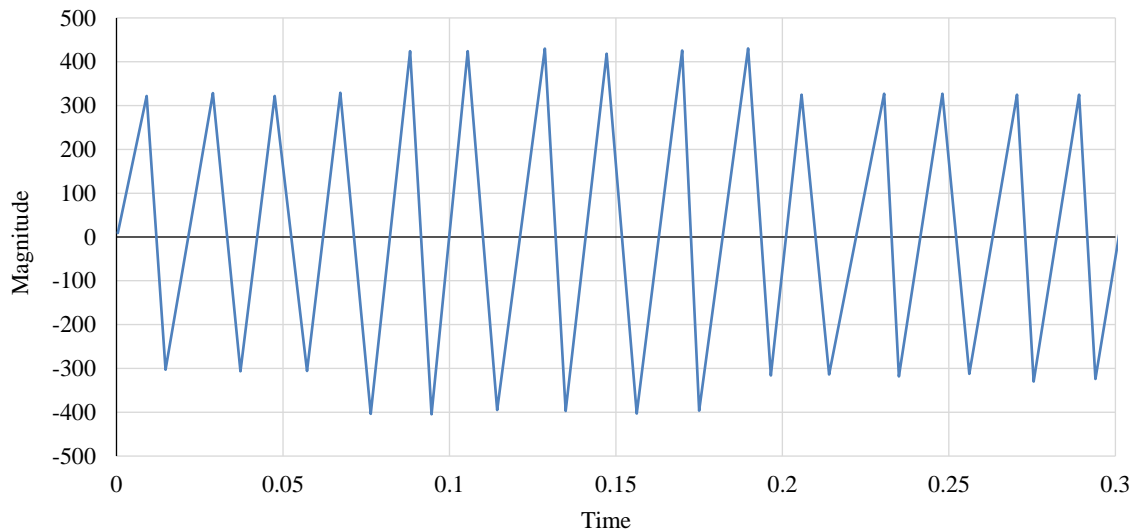


Figure 2. Overvoltage waveform.

Causes of Overvoltage Protection

Overvoltage in electrical systems can result from various factors, and they can pose a risk to electrical equipment and circuits. Some of the common causes of overvoltage include the following:

- *Lightning strikes:* Lightning strikes near power lines, substations, or other electrical infrastructures can introduce extremely high-voltage surges into the system, causing overvoltage.
- *Switching operations:* The opening or closing of circuit breakers, switches, or other electrical devices can create transient overvoltage owing to abrupt changes in the current flow.
- *Faults and short circuits:* Electrical faults or short circuits can cause overvoltage, especially if they result in the sudden disconnection of heavy load or power factor correction capacitors.
- *Generator excitation:* During synchronization or excitation of generators, there can be overvoltage conditions if the control systems are not properly managed.
- *Capacitor bank switching:* Switching in or out capacitor banks for power factor correction can introduce overvoltage if not properly coordinated [18].
- *Voltage regulator malfunctions:* Failures or malfunctions in voltage regulation equipment can lead to overvoltage conditions.
- *Grid disturbances:* Disturbances in the utility grid, such as sudden load rejection or faults, can propagate over the voltages throughout the system.
- *Harmonic distortions:* Non-linear loads, such as variable-speed drives and power electronics, can introduce harmonic distortions that may result in overvoltage.

Understanding these causes of overvoltage is crucial for implementing effective overvoltage protection and mitigation measures to safeguard electrical equipment and systems.

According to the IEEE classification of overvoltage, the classification of undervoltage is shown in Table 2.

This classification aids in understanding the different types of overvoltage events and allows for the development of protection and mitigation strategies tailored to the specific characteristics of each type.

Table 2. Classification of undervoltage.

Type of undervoltage	Duration	Magnitude
Instantaneous	1.1–1.8 per unit	0.5–30 Cycles
Momentary	1.1–0.4 per unit	30 Cycles–3 secs
Temporary	1.1–1.2 per unit	3 secs–1 min

PROPOSED PROTECTION SYSTEM

Block Diagram

Protection styles employed the primary goal of our circuit is to guard the connected cargo from the adverse goods of both undervoltage and overcurrent conditions. This protection is achieved by using an LM324 comparator to control the tripping of the relay coil. The comparator continuously compares the force voltage with a designated reference voltage and takes action by tripping the relay coil when the voltage falls below the set reference value. In addition to undervoltage protection, the relay coil is designed to respond to overcurrent conditions. This defensive medium is illustrated in the block illustration presented in Figure 3.

Methods Used for Protection

The protection system described in the block diagram you provide employs various methods and components for voltage protection. The key protection methods used in this system are as follows:

1. *Overvoltage protection*
 - i. Overvoltage protection is implemented to safeguard the equipment from excessively high-voltage levels that could damage or negatively affect the connected load equipment.
 - ii. LM324 comparators are likely to play a significant role in this system. When the voltage exceeds a predefined threshold, the comparators detect an overvoltage condition.
 - iii. The comparators then send a signal to the relays, which may disconnect power to the load equipment and protect it from high voltage.
2. *Undervoltage protection*
 - i. Undervoltage protection is designed to prevent equipment from operating at undervoltage levels that are too low, which can lead to underperformance or malfunction.
 - ii. Similar to overvoltage protection, LM324 comparators can detect voltage drops below a predefined threshold, indicating an undervoltage condition.
 - iii. The comparators signal the relays, which may disconnect the power to the load equipment to prevent it from operating in an underpowered state.
3. *Voltage regulation*
 - i. The voltage controller is responsible for maintaining a regulated output voltage. This ensured that the voltage supplied to the load equipment remained stable within a predefined range.
 - ii. This regulation helps prevent voltage fluctuations and provides a consistent power supply to the connected load.
4. *Filtering and smoothing*: The capacitors in the system filter and smooth the rectified DC voltage. They reduce voltage ripples and noise, helping maintain a steady and clean power supply to the load equipment.
5. *Automatic disconnect (relays)*
 - i. The relays are used as automatic disconnect switches in response to overvoltage or undervoltage conditions detected by the comparators.
 - ii. When an out-of-range voltage condition is detected, the relays open the circuit, disconnect power to the load equipment, and protect it from adverse voltage conditions.

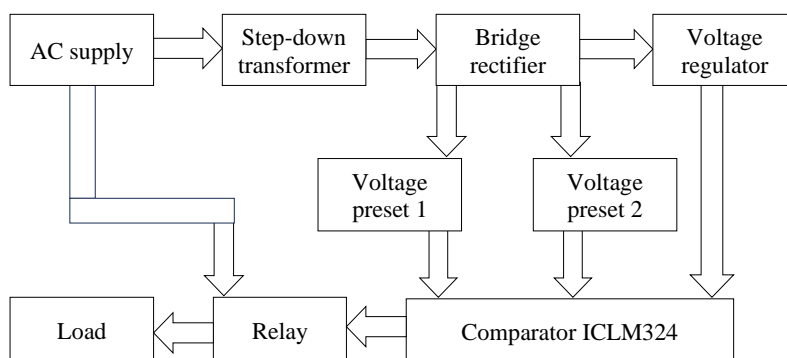


Figure 3. Block diagram of the protection system.

In summary, this protection system combines voltage monitoring, voltage regulation, and automatic disconnect methods to protect load equipment from both overvoltage and undervoltage. This ensures that the load equipment receives a stable and controlled power supply and acts swiftly to disconnect power when the voltage conditions are outside the acceptable limits, thereby preventing damage and malfunctions.

CIRCUIT DIAGRAM OF PROTECTION SYSTEM

Details description of all equipment using the circuit are as follows (Figure 4).

1. *Transformer (12 V):* The transformer steps the voltage down from the source to a lower level suitable for the circuit.
2. *Bridge wave rectifier:* The bridge rectifier converts alternating current (AC) from the transformer into direct current (DC).
3. *Zener diodes (6.8 V, 6.0 V):* Zener diodes are used as voltage references or for clamping voltage levels in the protection circuit.
4. *Resistors (10 K, 5 K, 1 K):* Resistors are used for various purposes, such as voltage division or setting bias points.
5. *ICLM324:* This can be used as an operational amplifier for signal processing in protection systems.
6. *LED:* LEDs can be used as visual indicators to determine the status of a protection system.
7. *Capacitors (480 MF, 0.1 MF):* Capacitors are used for smoothing and filtering the DC voltage.
8. *Regulator IC7812:* The voltage regulator IC7812 regulates the DC voltage to provide a stable 12V output.
9. *Potentiometer (50 K):* The potentiometer can be used to adjust the reference voltages in the protection system.
10. *Diode (IN4007):* Diodes are used for rectification or to control the flow of current in a specific direction.
11. *Relay:* Relays can be used to control the connection or disconnection of loads based on the voltage conditions.
12. *Load:* The load represents the electrical equipment that you want to protect from undervoltage and overvoltage conditions.

Circuit Diagram and Its Operations

The circuit diagram of the protection system is shown in Figure 4.

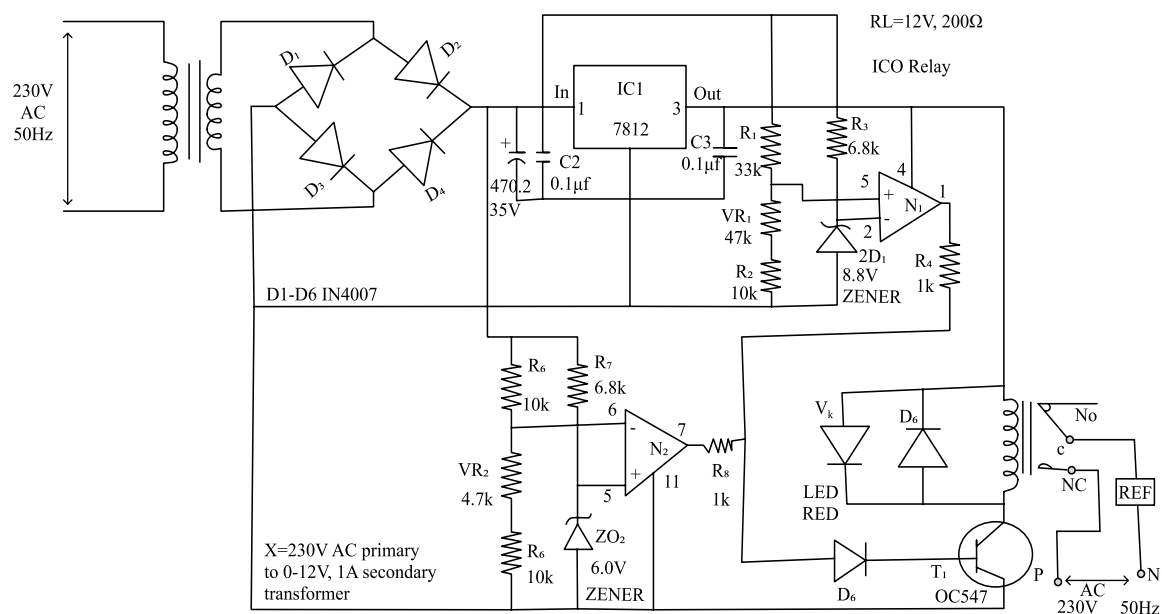


Figure 4. Circuit diagram of the protection system.

Circuit Operation

The specific circuit operation involves setting reference voltages with the potentiometer, monitoring the incoming voltage, and comparing it to these references using ICLM324 and other components. When the detected voltage falls below the undervoltage threshold or exceeds the overvoltage threshold, the circuit can control the relay to disconnect the load and prevent it from operating outside the safe voltage levels.

The circuitry for undervoltage and overvoltage protection can be more complex and may involve additional components and feedback loops to ensure accurate and reliable protection. It is essential to design and implement such a circuit carefully to effectively safeguard the electrical equipment.

CONCLUSION

In this comprehensive review, we delved into the vital domain of undervoltage and overvoltage protection systems for electrical equipment. The importance of ensuring high-power quality and safeguarding sensitive equipment from voltage variations cannot be overstated. With a detailed examination of the causes, waveforms, classifications, and impacts of undervoltage and over-addressing conditions, we have established the necessity of robust protection mechanisms. Our proposal for an integrated protection system, as outlined in this paper, is a practical approach to address these concerns. By combining various components and control elements, this system not only detects voltage anomalies but also takes timely and precise actions to safeguard connected electrical equipment. The associated circuit diagram and component descriptions provided a clear understanding of the inner workings. As we navigate an era of increasing reliance on electrical equipment, the need for effective protection systems has become paramount. The incorporation of these systems is not only a matter of convenience but also a critical step toward mitigating the economic losses and safety hazards associated with voltage disturbances. The proposed protection system, as outlined above, serves as a steppingstone in this direction. In conclusion, the research presented in this paper underscores the significance of undervoltage and overvoltage protection systems, the challenges posed by power quality issues, and the comprehensive solutions that can be implemented to ensure the uninterrupted and reliable operation of electrical equipment. We hope that this review will contribute to ongoing efforts to enhance the power quality and protect the integrity of electrical systems.

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