Adaptive Reactive Power Management with Thyristor-Controlled Transformer and Fixed Capacitor

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Abstract:- The objective of this article is to develop and analyse a thyristor-controlled transformer with a fixed capacitor for reactive power compensation in power systems. Reactive power compensation is crucial for enhancing the efficiency and stability of power systems by reducing power losses, improving voltage profiles, and minimizing equipment stress. Traditional compensation methods often rely on fixed capacitors, reactors, or static VAR compensators, but these systems lack the flexibility required for dynamic control of reactive power under varying load conditions. The proposed approach integrates a thyristor-controlled transformer with fixed capacitors, allowing for precise, real-time adjustment of reactive power flow. The novelty of this article lies in the hybrid configuration of the thyristor-controlled transformer and fixed capacitor, which provides a cost-effective and robust solution compared to conventional systems. Unlike traditional methods that depend solely on switching capacitors or reactors, the use of thyristors allows for fine-tuning of reactive power, offering improved performance under variable loading conditions without the need for complex control algorithms. This setup enhances the adaptability of reactive power management, thus maintaining optimal power factor and voltage regulation. The findings from the simulation and experimental results demonstrate significant improvements in power factor correction, voltage stabilization, and reduction in harmonic distortion. The proposed system exhibits a faster response time and greater control accuracy compared to existing compensation techniques. These advantages make the thyristor-controlled transformer with a fixed capacitor a promising alternative for power utilities seeking to enhance the operational efficiency and reliability of their networks. This article contributes to the advancement of reactive power compensation technologies, providing a scalable solution suitable for modern power system.

Keywords:- *Flexible AC Transmission System Devices, Power Systems, Power Electronics, Reactive Power, Voltage Stability.*

I. INTRODUCTION

Reactive power plays a critical role in the operation of electrical power systems, even though it does not directly contribute to the work output, like driving motors or lighting lamps. It is essential for maintaining the voltage levels necessary for active power (the real power that performs useful work) to flow through the grid. Understanding reactive power is crucial for ensuring the stability, efficiency, and reliability of power systems[1].

Reactive power is the component of alternating current (AC) power that oscillates between the source and load, rather than being consumed. It is measured in volt-amperes reactive (VAR). Unlike active power, which is measured in watts and does useful work, reactive power does not perform any real work but is essential for maintaining the voltage necessary for power transmission. It is associated with the energy stored and released by inductive (e.g., motors, transformers) and capacitive (e.g., capacitors, cables) components of the system[2].

One of the primary functions of reactive power is voltage regulation. In an electrical system, voltage levels must be maintained within specific limits to ensure the proper functioning of electrical equipment. Reactive power is key to achieving this balance. For instance, when reactive power is insufficient, voltage levels drop, potentially leading to undervoltage conditions that can harm sensitive equipment. Conversely, excess reactive power can cause overvoltage, which can also damage the system. Reactive power supports voltage at various points in the power system, enabling the effective transfer of active power from generators to consumers. Without adequate reactive power, voltage levels could fluctuate excessively, leading to system instability or even outages. Reactive power supports voltage at various points in the power system, enabling the effective transfer of active power from generators to consumers. Without adequate reactive power, voltage levels could fluctuate excessively, leading to system instability or even outages[3].

Reactive power is vital for system stability, especially during disturbances such as faults, sudden load changes, or the loss of a generation unit. During such events, the ability to quickly supply or absorb reactive power helps maintain system stability and prevents cascading failures that could lead to widespread blackouts. Reactive power support is especially crucial during transient conditions, where voltage levels can quickly deviate from their set points. The proper management of reactive power helps ensure that generators, transmission lines, and other components operate within safe voltage limits. This minimizes the risk of equipment damage and enhances the overall security of the power system[4].

Reactive power also affects the efficiency of power transmission. Transmission lines, transformers, and other system components experience losses when transferring power, which can be exacerbated by poor reactive power management. Excess reactive power causes additional current to flow through the system, increasing losses due to resistance in conductors. By optimizing the reactive power flow, these losses can be minimized, thereby improving the overall efficiency of power delivery. Utilities often deploy reactive power compensation devices, such as capacitors and reactors, to manage the flow of reactive power. These devices help balance the reactive power in the system, reducing losses and improving voltage profiles, which ultimately enhances the efficiency of power delivery to end users[5].

The growing integration of renewable energy sources, such as wind and solar, has increased the importance of reactive power management. Unlike conventional generators, which provide both active and reactive power, renewable sources often lack inherent reactive power capabilities. For example, solar inverters and wind turbines primarily supply active power, and additional equipment is needed to manage reactive power. Proper reactive power management helps integrate these variable renewable energy sources into the grid without compromising system stability and performance[6].

A. Power Electronics Technology and Its Role in Enhancing Power Quality in Power Systems

Power electronics technology plays a crucial role in modern power systems by improving power quality, enhancing system stability, and enabling the integration of renewable energy sources. Power quality refers to the stability and reliability of the voltage, current, and frequency in the electrical system, which is vital for the efficient operation of electrical equipment and industrial processes. Power electronics devices, such as inverters, converters, and solid-state controllers, are integral in managing and conditioning power to meet stringent quality standards[7].

Power electronics technology significantly enhances power quality by mitigating common power issues such as voltage sags, swells, harmonics, flicker, and unbalanced loads. These disturbances can lead to inefficiencies, equipment malfunction, or even damage. Power electronics devices help maintain voltage stability, reduce harmonic distortion, and ensure the reliability of power delivered to consumers[8].

Power electronics devices like static synchronous compensators (STATCOMs) and dynamic voltage restorers (DVRs) are employed in power systems to regulate and stabilize voltage levels. STATCOMs, for instance, provide fast and dynamic reactive power compensation, which helps maintain steady voltage levels even during sudden load changes or faults. DVRs can inject or absorb voltage to counteract sags and swells, ensuring that sensitive loads receive consistent power[9].

Harmonics are unwanted frequency components in the power system that can distort waveforms and cause equipment overheating, increased losses, and electromagnetic interference. Power electronics devices, such as active power filters (APFs), are designed to detect and compensate for harmonic distortions by injecting compensating currents, thus maintaining a clean and stable power waveform[10].

Poor power factor, often caused by inductive loads, results in inefficient power usage and increased losses. Power electronics technologies like synchronous condensers and static VAR compensators (SVCs) improve power factor by dynamically adjusting reactive power flow, leading to more efficient energy consumption and reduced transmission losses[11].

Power electronics technology is pivotal in enhancing power quality within modern power systems. By providing advanced control over voltage, current, and frequency, power electronics devices help mitigate common power quality issues, support the integration of renewable energy, and improve the efficiency and stability of the electrical grid. As power systems continue to evolve, the role of power electronics will only grow, driving the transition towards more reliable, efficient, and sustainable power delivery[12].

B. The Role of Flexible AC Transmission System (FACTS) Devices in Enhancing Power Quality in Power Systems

Flexible AC Transmission System (FACTS) devices are a family of power electronics-based systems designed to enhance the reliability, stability, and efficiency of power systems. FACTS devices improve power quality by dynamically controlling various electrical parameters, such as voltage, impedance, and phase angle, which are crucial for maintaining optimal power flow and ensuring a stable and high-quality power supply. Their ability to provide real-time reactive power compensation, voltage regulation, and

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power flow control makes them vital components in modern power systems[13].

FACTS devices contribute to overall system stability by quickly responding to disturbances and adjusting power flows to prevent cascading failures. Their ability to reduce power losses by optimizing reactive power flow and balancing loads improves the overall efficiency of power transmission. This not only enhances power quality but also reduces operational costs for utilities[14].

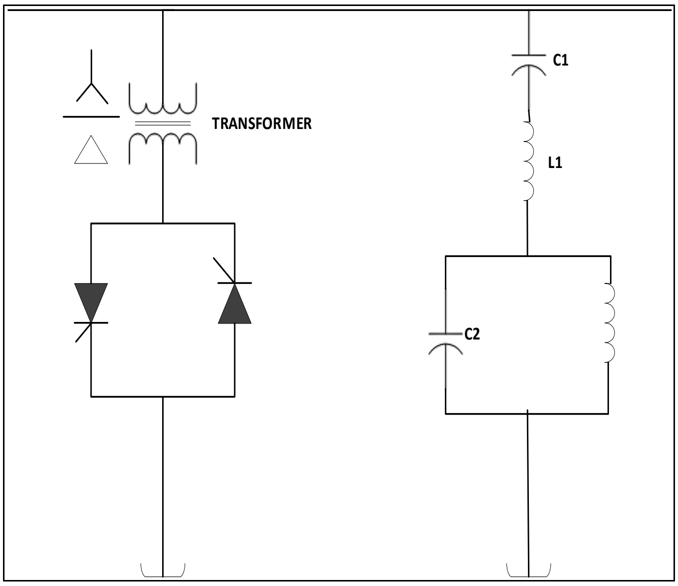

Fig 1 Schematic Diagram of FACTS Device

The increasing penetration of renewable energy sources, such as wind and solar, presents challenges related to power quality due to their intermittent nature. FACTS devices help mitigate these issues by providing grid support services, such as voltage regulation, reactive power compensation, and harmonics filtering[15].

Voltage flicker, caused by rapid changes in load, can lead to noticeable fluctuations in lighting and other sensitive equipment. FACTS devices such as SVCs can respond rapidly to these variations, compensating for the reactive power swings that cause flicker. This makes them highly effective in industrial environments where large, rapidly changing loads are common[16].

FACTS devices are indispensable tools for enhancing power quality in modern power systems. By providing dynamic control over voltage, reactive power, and power flow, these devices help maintain stable and reliable electricity supply, mitigate harmonic distortions, and support the integration of renewable energy sources. As power grids become more complex and the demand for high-quality power increases, the role of FACTS devices will continue to expand, driving improvements in power system performance and resilience[17].

II. PROPOSED FACTS DEVICE

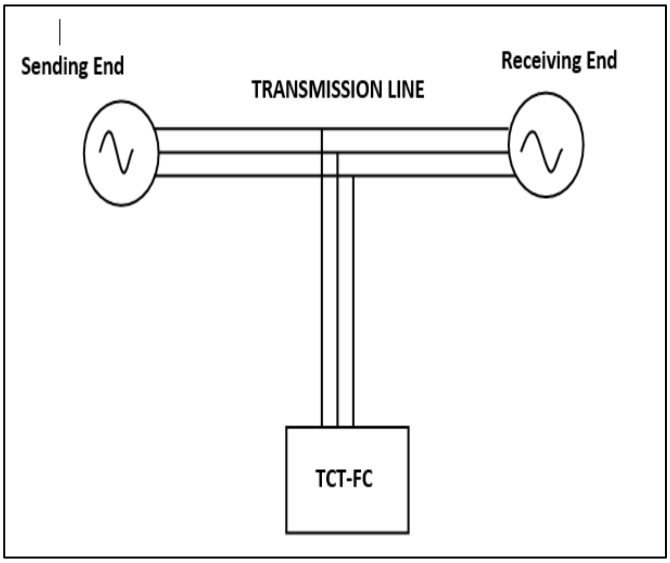

Fig 2. Block Diagram of TCT-FC

Proposed FACTS Device is one of the classifications of Static Var Compensator. Which is sunt active device. Adaptive Reactive Power Management with Thyristor-Controlled Transformer (TCT) and Fixed Capacitor (FC) is a specific configuration of a Static VAR Compensator (SVC), which is widely used for dynamic voltage regulation and reactive power compensation in power systems. This configuration combines the controllability of thyristor-controlled transformers with the steady reactive power supply from fixed capacitors, allowing precise and adaptive management of reactive power to maintain voltage stability and improve power quality.

A. Construction

The Thyristor-Controlled Transformer (TCT) and Fixed Capacitor (FC) system is a type of SVC device that provides both continuous and stepwise control of reactive power in the electrical grid. The system comprises:

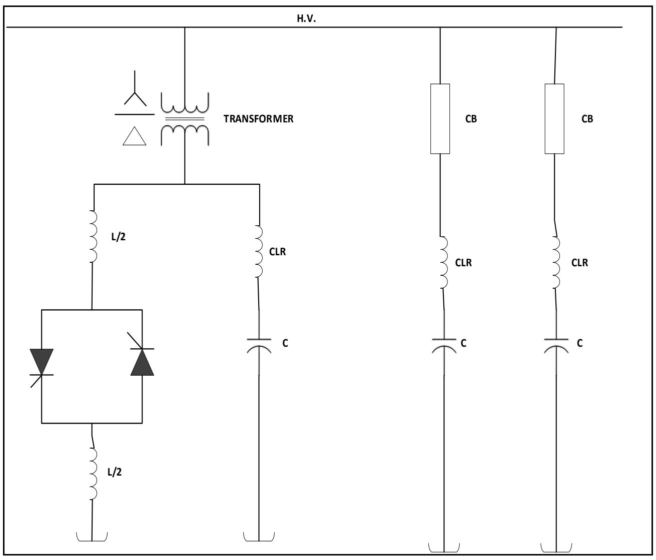

Fig 3 Schematic Diagram of TCT-FC

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- *Fixed Capacitor (FC)*

Provides a constant source of capacitive reactive power. Fixed capacitors are usually sized based on the steady-state reactive power requirements of the system.

- *Thyristor-Controlled Transformer (TCT)*

A transformer whose output is controlled using thyristors to adjust the level of reactive power compensation dynamically. The TCT can either absorb or inject reactive power, depending on the grid's needs.

B. Working Principle

The working principle of Adaptive Reactive Power Management with TCT and FC involves controlling the reactive power output dynamically through the thyristor-controlled transformer while leveraging the fixed reactive power supplied by the capacitor. Here is a detailed step-by-step explanation of how this system operates:

- *Fixed Capacitor Operation:*

The Fixed Capacitor provides a baseline level of capacitive reactive power to the power system. It is typically connected to the power line in parallel and supplies reactive power continuously, regardless of the varying conditions in the grid. This constant supply helps maintain voltage levels during normal operation and provides a stable reference for reactive power compensation.

- *Thyristor-Controlled Transformer (TCT) Operation:*

The TCT uses thyristors to adjust the transformer’s operation dynamically. Thyristors are semiconductor devices that can rapidly switch on and off, allowing for precise control over the transformer's output.

The thyristors are connected to the transformer windings and are triggered based on the system’s reactive power requirements. When the system requires additional reactive power, the thyristors adjust the transformer tap settings, altering the reactive power flow.

The TCT can absorb reactive power when there is excess capacitive reactive power in the grid or inject reactive power when additional support is needed, such as during voltage sags or heavy load conditions.

The control system continuously monitors the grid’s voltage and reactive power conditions using sensors and adaptive control algorithms. These algorithms assess the reactive power demand in real-time and determine the appropriate response from the TCT and FC combination. When the grid voltage drops or there is a reactive power deficit, the thyristors in the TCT adjust to increase the reactive power injection, supporting the grid voltage. Conversely, when there is an excess of reactive power or voltage swell, the TCT absorbs reactive power to stabilize the voltage. This adaptive response ensures that the reactive power compensation is precisely matched to the grid’s needs, enhancing voltage stability and power quality.

One of the additional benefits of using a TCT with FC is the potential for harmonic filtering. The thyristor switching action can generate harmonics, which are typically managed using passive filters integrated into the system. This helps maintain a clean power waveform, reducing the impact of harmonics on the overall power quality.

The rapid response of the thyristor-controlled transformer allows the system to react almost instantaneously to changes in grid conditions, providing a dynamic and flexible approach to reactive power management. The system’s adaptive nature ensures that it can handle varying load conditions, system faults, and fluctuations in renewable energy generation, making it highly suitable for modern power grids with variable demand.

C. Applications and Benefits

- *Voltage Stabilization*

By providing fast and adaptive reactive power compensation, the system maintains voltage levels within acceptable limits, preventing undervoltage and overvoltage conditions that can affect sensitive equipment.

- *Enhanced Power Quality*

The combination of TCT and FC helps reduce voltage flicker, harmonic distortion, and other power quality issues, ensuring a stable and reliable power supply.

- *Improved Grid Efficiency*

Efficient management of reactive power reduces transmission losses and enhances the overall efficiency of power delivery, especially in heavily loaded or weak grid sections.

- *Renewable Energy Integration*

The system supports the integration of renewable energy sources by compensating for their intermittent reactive power requirements, thus maintaining grid stability.

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III. RESULTS

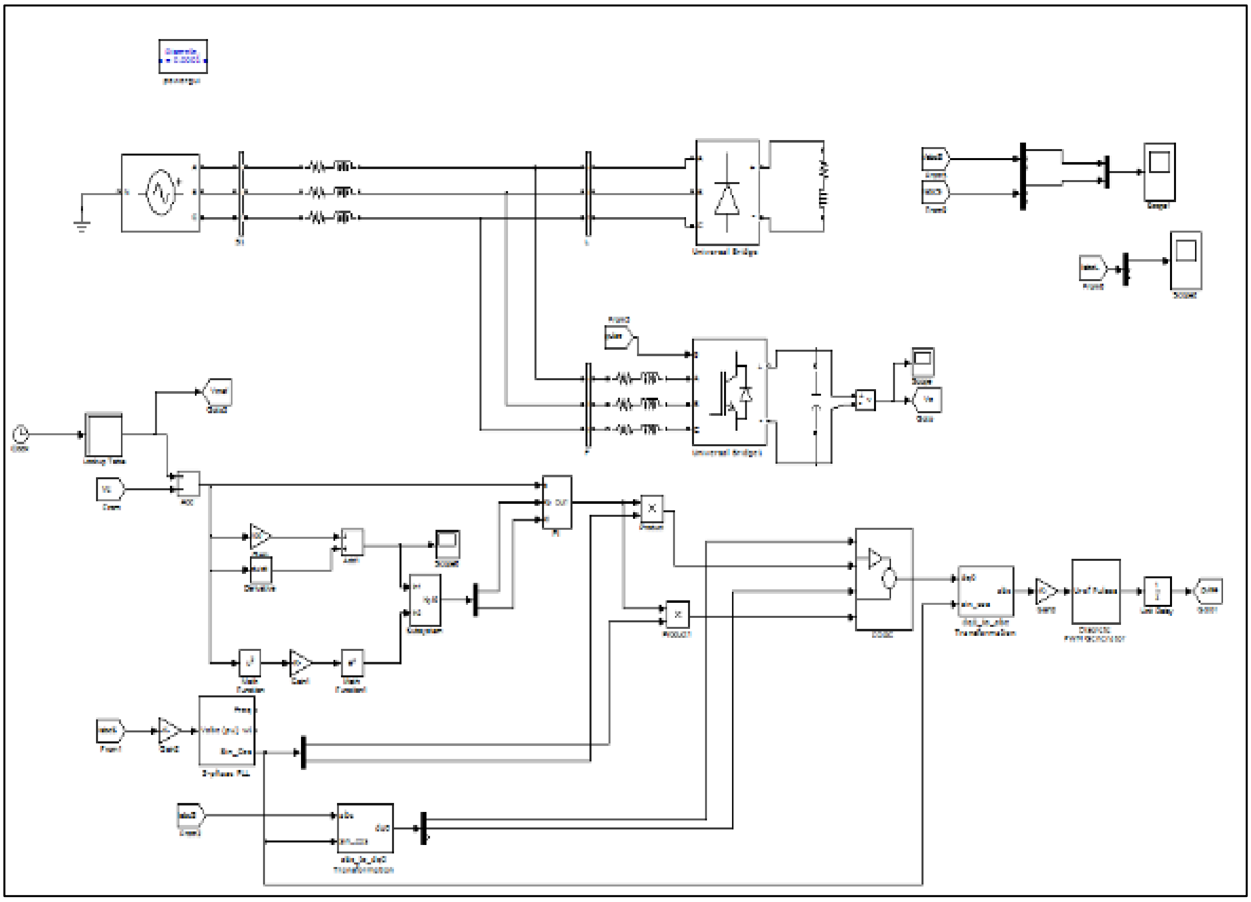
Fig 4. Simulation Diagram of Proposed Topology

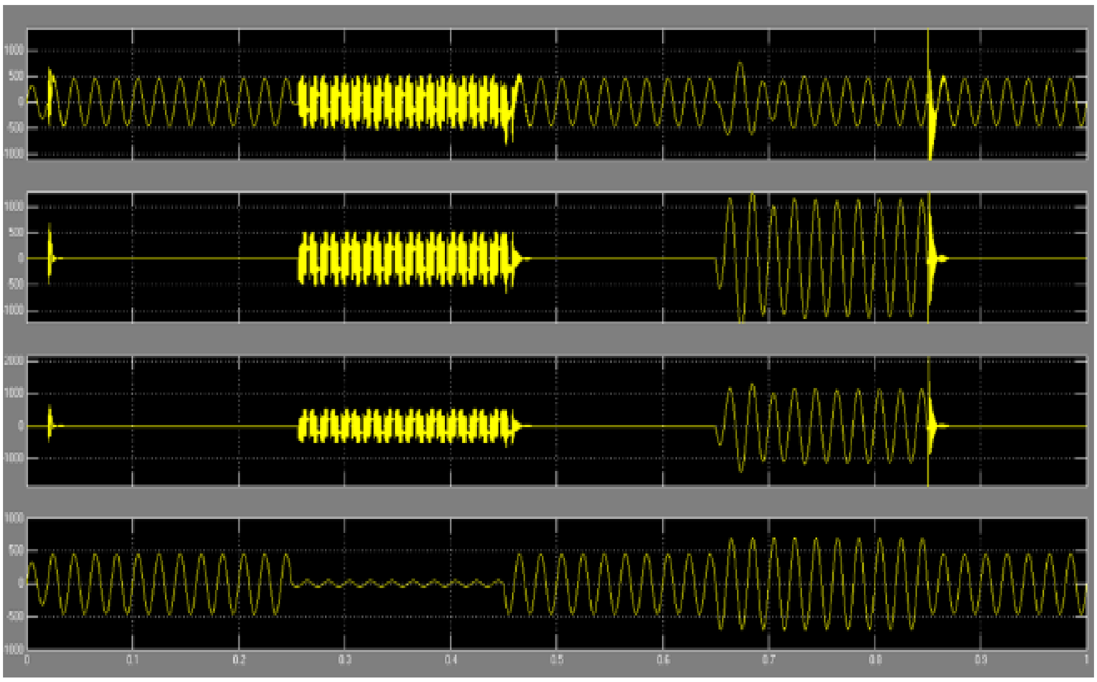
Fig 5. Simulation Results

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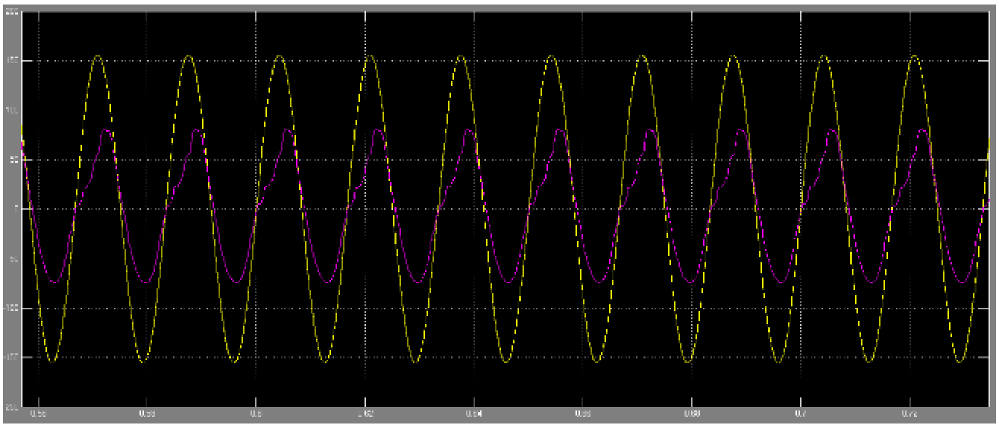

Fig 6. Simulation Results

IV. CONCLUSION

Adaptive Reactive Power Management with Thyristor-Controlled Transformer and Fixed Capacitor provides a robust solution for dynamic voltage control and reactive power compensation. By combining the continuous reactive power supply from fixed capacitors with the dynamic controllability of thyristor-controlled transformers, this SVC classification device enhances the power quality and stability of modern power systems. Its ability to adaptively manage reactive power makes it an invaluable tool in maintaining reliable and efficient grid operation, especially in environments with rapidly changing power demands and high penetration of renewable energy sources.

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