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Smart Grid Power Quality Improvement Using Modified Upqc

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ABSTRACT

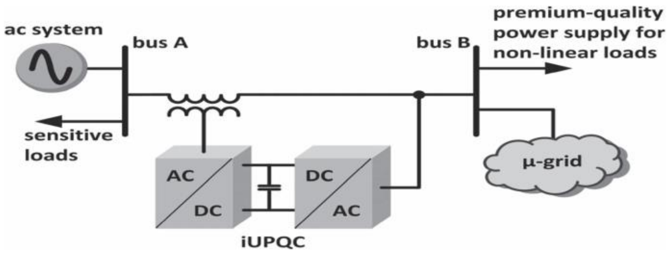
This paper presents a novel power quality enhancement approach utilizing a Modified Unified Power Quality Conditioner (UPQC) integrated with an intelligent Fuzzy Logic Controller (FLC). The proposed UPQC architecture features coordinated series and shunt converters, optimized to simultaneously mitigate various power quality issues, including voltage sags/swells, harmonics, and load unbalances. Designed for modern smart grid applications, the system enhances dynamic voltage regulation and harmonic suppression through improved converter configurations and control strategies. The FLC introduces adaptive, rule-based decision-making, enabling robust performance under varying grid conditions without reliance on precise mathematical modeling. Simulation studies in MATLAB/Simulink validate the effectiveness of the proposed method, showing significant improvements in voltage stability, total harmonic distortion (THD) reduction, and overall power quality compared to traditional PI-controlled UPQC systems. This work underscores the potential of intelligent control techniques in developing resilient and efficient smart grid infrastructures.

Keyword: Unified Power Quality Conditioner (UPQC), Modified UPQC, Fuzzy Logic Controller (FLC), Power Quality Enhancement, Voltage Sag and Swell Mitigation, Harmonic Suppression Load Un,balance Compensation

1.INTRODUCTION

The evolution of electrical power systems into smart grid architectures has introduced significant challenges in maintaining high power quality. This shift, driven by the increasing penetration of distributed generation, integration of renewable energy sources, and the widespread use of sensitive electronic equipment, necessitates advanced power quality management strategies. Power electronics-based devices—such as variable frequency drives, rectifiers, inverters, and switched-mode power supplies—are now common in modern grids. However, these non-linear loads severely degrade power quality by distorting current waveforms, generating harmonics, inducing voltage sags and swells, and contributing to load imbalance. These disturbances compromise the reliability and efficiency of energy delivery, and can even lead to malfunction or damage of sensitive equipment. Although these devices are typically designed to operate under ideal sinusoidal conditions, their actual operation introduces significant harmonic currents into the grid. This not only stresses utility infrastructure but also challenges grid stability. Moreover, in high-power applications, the energy-handling capacity of conventional power electronic converters diminishes with increasing switching frequency due to switching losses. While higher switching frequencies can improve waveform quality, they lead to greater energy losses.

In this context, the Unified Power Quality Conditioner (UPQC) emerges as a superior solution. By maintaining fundamental frequency sinusoidal references and effectively compensating for voltage and current disturbances, the UPQC offers a promising approach for improving power quality in smart grid environments, especially where high-power and non-linear loads are prevalent.



To view an example of UPQC in action, refer to Figure 1.1.

This paper presents an enhanced controller for the UPQC, which enhances its capabilities. A new feature of this improved UPQC controller that keeps all the features of previous versions is voltage law on the grid-side bus, similar to a STATCOM. Our experimental results demonstrate the new controller's well-designed nature.

2.LITERATURE SURVEY

1. Unified Power Quality Conditioner (UPQC) – Fundamentals

- **Hingorani & Gyugyi (1999)** introduced the concept of UPQC as a combination of a shunt and series active power filter to simultaneously compensate voltage and current-related power quality problems.
- **Ghosh and Ledwich (2002)** developed a detailed control strategy for UPQC using PI and hysteresis controllers. Their method proved effective for basic PQ disturbances but lacked adaptability in dynamic load conditions.

2. Power Quality Issues in Smart Grids

- **Guerrero et al. (2011)** highlighted how smart grids with high penetration of renewables suffer from harmonics, voltage unbalance, and frequency fluctuations.
- **R. Majumder (2013)** identified voltage sags and harmonic distortions as critical problems due to intermittent distributed energy resources (DERs) and bidirectional power flow.

3. UPQC in Smart Grids

- **K. Karthikeyan et al. (2016)** proposed the use of UPQC for smart grids but used traditional SRF control, which showed limitations in response time and harmonic rejection under nonlinear loads.
- **D. Mahinda Vilathgamuwa et al. (2008)** suggested a dynamic control of UPQC under distributed generation systems. It was efficient but had high implementation complexity and cost.

4. Modified or Enhanced UPQC Approaches

- **K. Sundaram and R. Kumar (2019)** introduced a Modified UPQC (M-UPQC) using neural network-based controllers, which improved transient response but required significant training time and computational resources.
- **B. Singh and V. Verma (2015)** implemented a fuzzy logic-based control algorithm for UPQC, improving adaptability to voltage and load variations.
- **M. El-Habrouk and M. Darwish (2020)** used PWM and adaptive filters in a modified UPQC for better harmonic mitigation.

5. Control Techniques for Improved UPQC

- **Sliding Mode Control (SMC)**: Robust to system parameter variations and effective for real-time PQ correction (P. Salmerón et al., 2018).
- **Artificial Intelligence (AI)-based Controllers**: Used in modern UPQC designs to adapt in real-time, especially for smart grids with variable loads (A. Jain et al., 2021).

3.UNIFIED POWER QUALITY CONDITIONER

In modern electrical power systems, ensuring high power quality has become increasingly challenging due to the proliferation of nonlinear, unbalanced, and rapidly changing loads. These loads often introduce a range of power quality issues, including voltage sags, harmonic distortion, and unbalanced current flow. Traditional compensation methods, such as passive filters and individual compensators, are often inadequate in addressing these multifaceted disturbances, especially under dynamic operating conditions. The Unified Power Quality Conditioner (UPQC) has emerged as a robust and integrated solution to tackle these challenges. As a hybrid power electronic device, the UPQC combines the functionalities of a Distribution Static Compensator (DSTATCOM) and a Dynamic Voltage Restorer (DVR), interconnected via a common DC-link. This configuration enables the UPQC to perform simultaneous control of the supply current and the load bus voltage, thereby mitigating a wide spectrum of power quality problems in both the voltage and current domains. A key advantage of the UPQC lies in its dual compensation capability—handling current-related disturbances on the source side and voltage-related issues on the load side, including severe anomalies such as voltage interruptions. This dual functionality makes it superior to conventional compensators, which typically address only a single category of disturbance. This chapter delves into the structure, objectives, operational principles, and control strategies employed in the UPQC. It also provides a comparative analysis with other power conditioning devices, such as the Unified Power Flow Controller (UPFC), emphasizing UPQC's distinctive ability to mitigate harmonic content, correct sequence imbalances, and maintain voltage regulation under highly dynamic grid conditions.

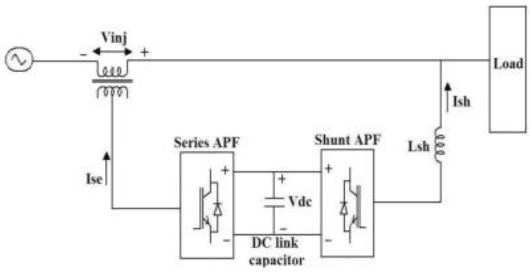


Fig. 1. Schematic block diagram of UPQC.

By integrating DSTATCOM with DVR, power quality regulation in relation to source current and load bus voltage may be accomplished more efficiently. In addition, when the DVR and STATCOM are connected on the DC side, the DC bus voltage can be controlled by the shunt-connected DSTATCOM, and the DVR can provide the necessary energy to the load even when the source voltage is temporarily interrupted. Figure shows the setup, which is called the Unified Power Quality Conditioner (UPQC).

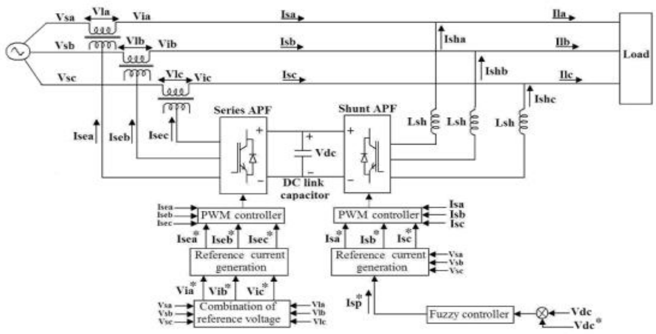


Fig 4.2: The circuit shown detailed block diagram of UPQC

Although the UPQC's control goals differ significantly from those of a UPFC, the two devices are similar in that they serve multiple purposes.

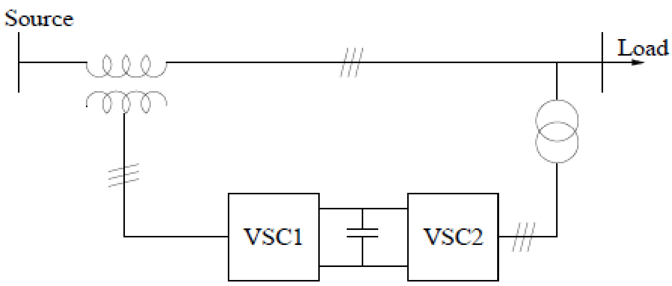


Fig 4.3: Unified power quality conditioner block diagram

Goals of Upstream Quality Control

The following control objectives are possessed by the UPQC shunt-connected converter:

One, to bring the source currents into balance by adding the negative and zero-sequence components that the load require.

2. To inject the required harmonic currents into the load current in order to minimize harmonics.

3. To guarantee the necessary reactive current is supplied at the fundamental frequency in order to control the power factor.

4. To regulate the voltage on the DC bus.

Here are the control objectives that the series-connected converter is supposed to accomplish:

First, we need to bring in negative and zero-sequence voltages to balance out the ones in the source so that the load bus voltages are balanced.

2. To inject the necessary harmonic voltages into the source voltages in order to isolate the load bus from them.

3. To regulate the load bus voltage amplitude according to the source side power factor by supplying the active and reactive components required (at fundamental frequency).

4. To control the power factor at the UPQC's source-connected input terminal. The output port, which is linked to the load, has its power factor controlled by the shunt converter.

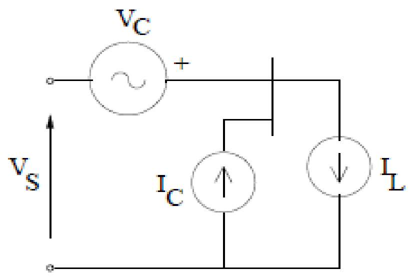
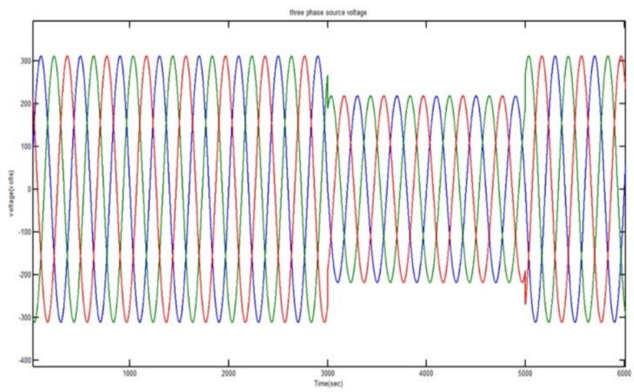


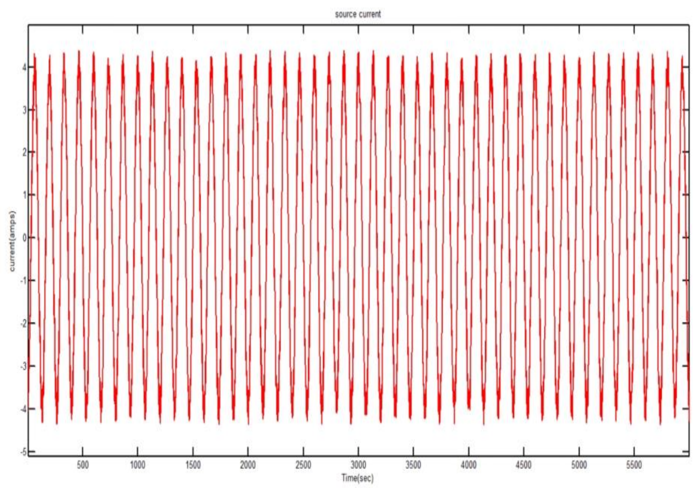
Fig 4.4 :One way to understand how a UPQC works is to loozk at the schematic of the idealized equivalent circuit

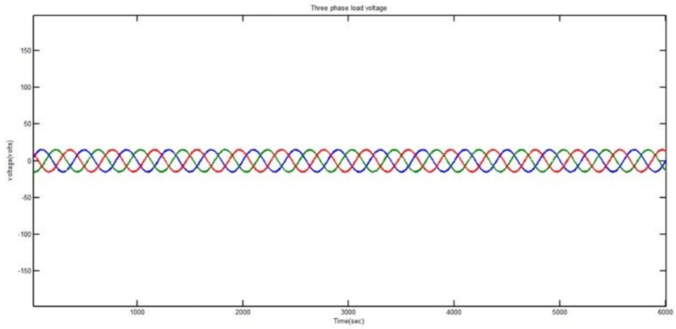
One way to understand how a UPQC works is to look at the schematic of the idealized equivalent circuit in Figure 14.16. While the shunt converter is shown as a current source \(I_C \), the series converter is shown as a voltage source \(V_C \). Be careful to note that all voltages and currents are shown as three-dimensional vectors with phase coordinates. Unlike a UPFC, a UPQC can handle harmonics, negative and zero sequence components, and currents and voltages that consist of only one component. We can express the connections between them quantitatively, ignoring converter losses.

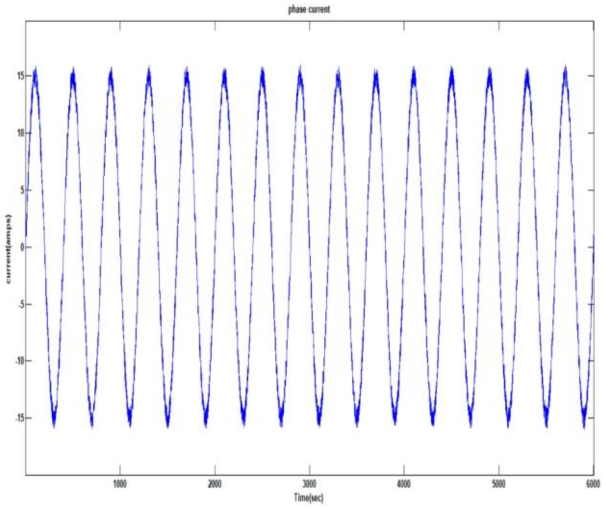
4.MATLAB/ SIMULATION RESULTS

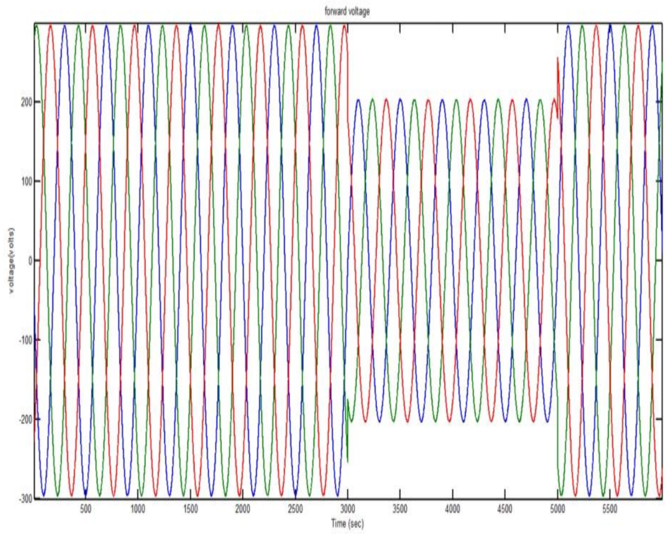
4.1 Case study of simulation waveforms for Sag:

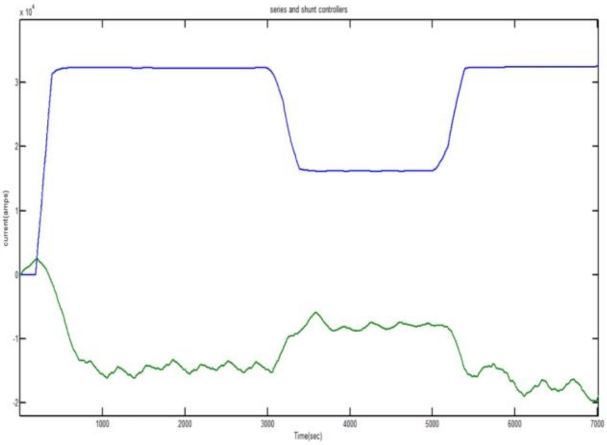




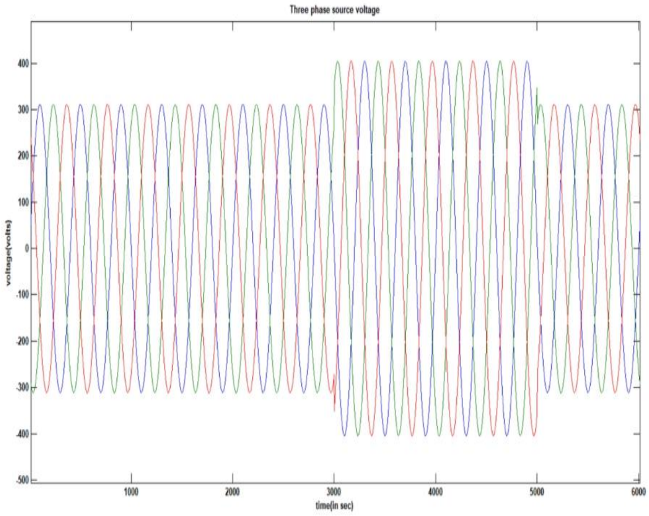

Three phase load voltage
voltage(volts)
Time(sec)

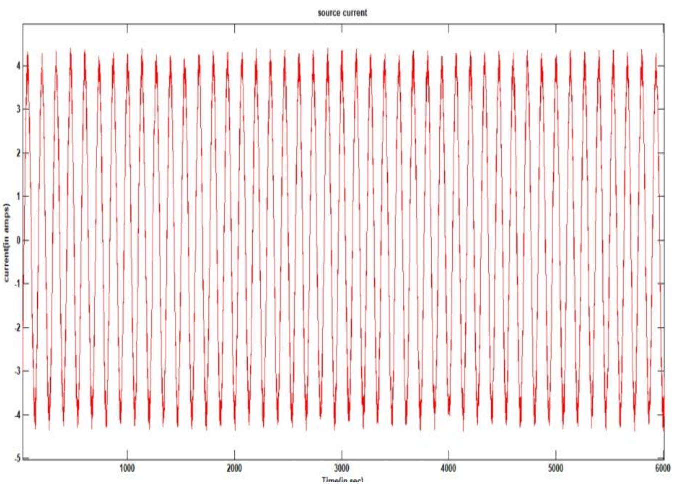

phase current
current(amps)
Time(sec)

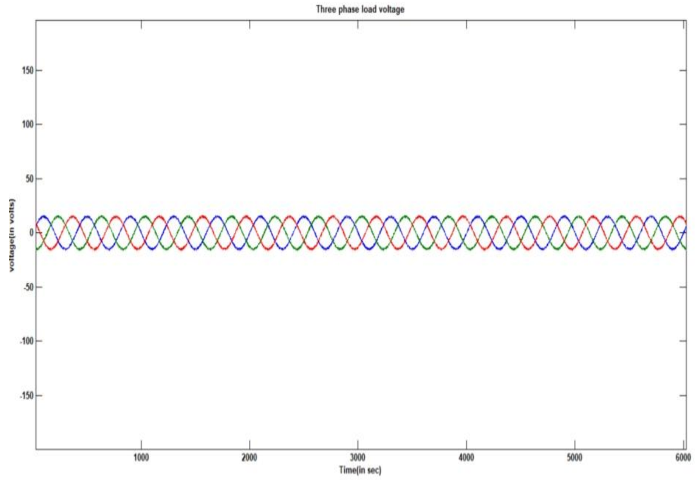

forward voltage
voltage(volts)
Time (sec)

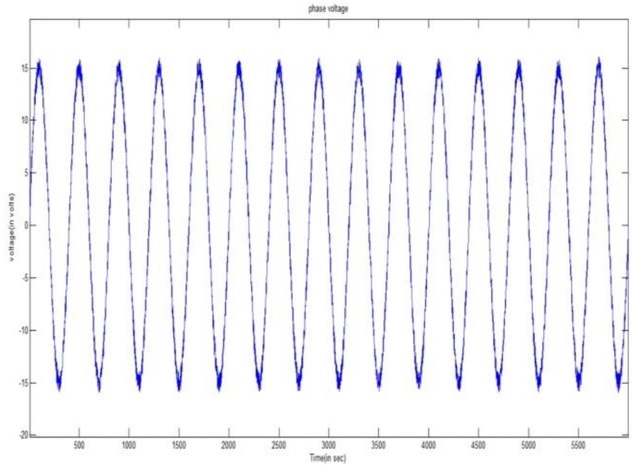


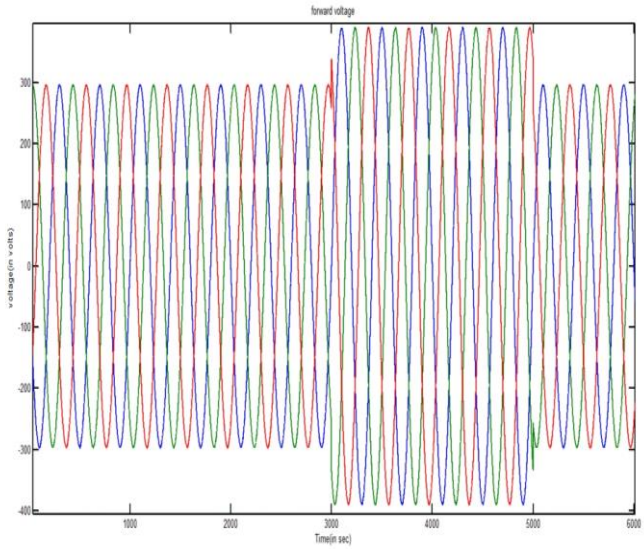
6.2 Case study of simulation waveforms for swell:






Three phase load voltage
voltage(in volts)
Time(in sec)


phase voltage
voltage(in volts)
Time(in sec)


forward voltage
voltage(in volts)
Time(in sec)

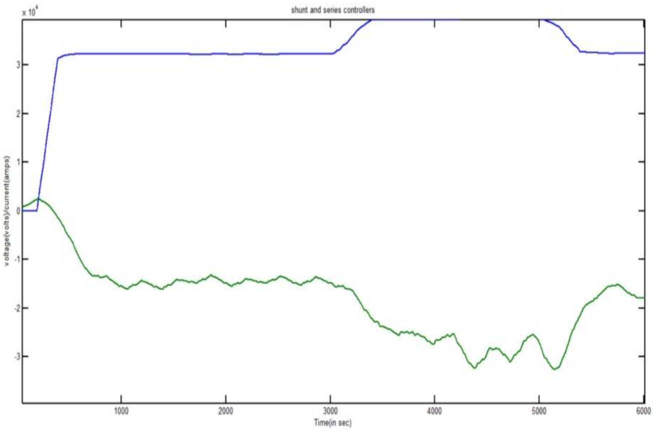


Figure: Simulation diagram of shunt and series controlled UPQC

Conclusion

This work has demonstrated the effectiveness of a Modified Unified Power Quality Conditioner (UPQC) integrated with a Fuzzy Logic Controller (FLC) for enhancing power quality in smart grid systems. The proposed configuration successfully mitigates voltage sags, swells, and harmonics while ensuring improved voltage regulation and reduced total harmonic distortion (THD). The fuzzy logic control strategy offers significant advantages over traditional linear controllers by providing adaptive, rule-based responses to dynamic and uncertain grid conditions without the need for precise system modeling.

Simulation results validate that the FLC-based modified UPQC enhances the overall power quality performance, making it a robust and intelligent solution for modern power distribution networks. This approach contributes to the development of more reliable, efficient, and stable smart grid infrastructures capable of handling increasing penetration of distributed and renewable energy sources.

Future work can explore real-time hardware implementation and the integration of advanced artificial intelligence techniques such as ANFIS or neural networks for further performance optimization.

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