



Modified Phase-Locked Loop for Enhanced Synchronization in Single-Phase Grid-Connected PV Systems

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ABSTRACT

Effective synchronization between grid-connected photovoltaic (PV) inverters and the utility grid is paramount for seamless energy injection, grid stability, and compliance with international standards. While conventional Phase-Locked Loops (PLLs) are fundamental for this purpose, they often struggle under non-ideal grid conditions such as voltage sags, harmonic distortion, and frequency deviations. This paper presents a comprehensive review of Modified PLL (MPLL) algorithms developed to address these limitations, proposing a novel taxonomy for their classification based on algorithm type, enhancement methodology, grid conditions addressed, and validation scope. Furthermore, the paper details the implementation of a specific MPLL algorithm that integrates adaptive filtering and fuzzy logic control to enhance synchronization performance under adverse grid conditions. Simulation results demonstrate the proposed MPLL's superior accuracy and response time during a 20% voltage sag, achieving a phase error within $\pm 1^\circ$ and a settling time of 80 ms, outperforming conventional PLLs. The paper also critically examines existing research gaps and challenges in MPLL development, including robustness against multiple concurrent disturbances, real-time implementation feasibility, scalability to weak grids and evolving standards, and limitations in validation methodologies. Finally, it outlines promising future directions leveraging artificial intelligence, the Internet of Things, and hybrid control techniques to pave the way for more intelligent and resilient synchronization solutions that support the reliable integration of PV systems into future smart grids.

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INTRODUCTION

The increasing adoption of sustainable energy sources has made grid-connected photovoltaic (PV) systems crucial, especially in single-phase residential settings [1]. For seamless energy injection, grid stability, and adherence to standards like IEEE 1547 and IEC 61727, effective synchronization between the PV inverter and the grid is paramount [2-3]. The Phase-Locked Loop (PLL) serves as a fundamental component in this process, accurately tracking the grid's phase and frequency to align the inverter's output. However, conventional PLLs often falter

under weak grid conditions, such as significant voltage sags (e.g., up to 50% reduction), high harmonic distortion (exceeding 5% THD), and frequency fluctuations, potentially leading to synchronization errors or even inverter disconnection [4].

To address these limitations, Modified PLLs (MPLLs) have emerged, employing advanced techniques like adaptive filtering, fuzzy logic, Kalman filtering, and hybrid structures [3]. This paper reviews various MPLL algorithms tailored for single-phase PV systems, proposes a novel taxonomy for their classification to facilitate

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comparison and understanding, and implements a specific MPLL design optimized for robustness and real-time performance under challenging grid conditions. Furthermore, we identify existing research gaps and suggest future directions that leverage machine learning and IoT to further enhance synchronization in increasingly dynamic grid environments.

LITERATURE REVIEW AND TAXONOMY

The development of PLL algorithms for single-phase grid-connected PV systems has evolved significantly. This section categorizes existing research based on algorithm type, enhancement methodology, grid conditions, and validation scope.

The Evolving Landscape of PLLs in Grid-Connected PV Systems

The integration of renewable energy sources (RESs), particularly single-phase grid-connected PV systems in residential applications, has placed stringent demands on the synchronization algorithms employed [5-6]. Effective and robust synchronization is paramount for seamless power injection, maintaining grid stability, and adhering to evolving grid codes such as IEEE 1547 and IEC 61727 [7].

Early implementations of PLL, while fundamental, often exhibit limitations when subjected to the non-ideal conditions prevalent in modern power grids. These conditions, including

harmonic distortion, voltage sags and swells, and frequency variations, necessitate the development of more sophisticated synchronization techniques [8]. The increasing penetration of distributed generation further exacerbates these challenges, requiring PLLs to be highly adaptable and resilient. This section aims to categorize and analyse the diverse range of Modified PLL (MPLL) algorithms developed to address these limitations through a comprehensive taxonomy.

Proposed Taxonomy for Single-Phase MPLL Algorithms

To provide a structured understanding of the advancements in PLL technology for single-phase grid-connected PV systems, we propose the following taxonomy based on key characteristics:

Algorithm Type

This criterion classifies PLLs based on their fundamental structure and control approach.

Conventional PLL: The basic PLL architecture typically comprises a phase detector, a loop filter (often a Proportional-Integral (PI) controller), and a Voltage-Controlled Oscillator (VCO) [9]. Its operation relies on minimizing the phase error between the grid voltage and the internally generated signal. A simplified block diagram is shown in Figure 1 [10].



Figure 1: Basic Structure of a Conventional PLL [10].

Modified PLL (MPLL): This type of PLL Emphasize the incorporation of advanced signal processing or control techniques to overcome the limitations of conventional PLLs [11].

Hybrid PLL: This implements the synergistic combination of different PLL structures or enhancement methodologies to achieve superior performance.

Classification Criteria

To provide a structured framework for analysing the diverse landscape of PLL algorithms employed in single-phase grid-connected PV systems, we adopt the following key classification criteria, which will be elaborated upon in the subsequent subsection:

Algorithm Type: This criterion categorizes PLLs based on their fundamental

architecture and control strategy, distinguishing between Conventional PLLs employing basic Proportional-Integral (PI) control, Modified PLLs (MPLLs) that incorporate advanced techniques for enhanced performance, and Hybrid PLLs that combine multiple structures to leverage their complementary advantages [12].

Methodology: This criterion classifies MPLLs based on the specific techniques utilized to enhance their performance under challenging grid conditions. These methodologies include adaptive filtering for dynamic signal conditioning, fuzzy logic for rule-based parameter adaptation, Kalman filtering for optimal state estimation in noisy environments, and the Second-Order Generalized Integrator (SOGI) for accurate fundamental frequency extraction and orthogonal signal generation [12].

Grid Conditions: This criterion categorizes PLLs based on the specific disturbances they are designed to effectively address. These

disturbances commonly encountered in grid-connected systems include harmonics, voltage sags and swells, and frequency deviations, each posing unique challenges to robust synchronization.

Validation Scope: This criterion differentiates studies based on the methodology used to validate the performance of the proposed PLL algorithms, distinguishing between simulation-based analyses that offer flexibility and control, and hardware-implemented prototypes that provide real-world performance assessment.

Review of Existing MPLL Studies Based on the Proposed Taxonomy

Following the establishment of our taxonomy, this section reviews key studies in the field of MPLL algorithms for single-phase PV systems, categorizing them according to the defined criteria.

Table 1: Summary of Modified PLL Studies for Single-Phase PV Systems

Reference	PLL Type	Methodology	Grid conditions addressed	Validation scope	Performance metrics
[12-14]	Conventional	Adaptive Kalman	+ Harmonics and Noise	Simulation	Reduced phase error and improved harmonics rejection
[15-17]	Modified	Least square, SOGI	Harmonics	Simulation	Output current THD <3%
[18-19]	Modified	Fuzzy logic, adaptivr	Frequency/Voltage Deviations	Real world	Improved transient response, enhanced stability
[20]	Hybrid	Hybrid Fuzzy + frequency-locking	Complex Disturbances	Real world	Enhanced tracking, improved stability under various faults
[21]	Modified	Kalman robust	+ Noise, Frequency Variations	Simulation	Reduced settling time, lower phase error

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As evident from Table 1, a diverse range of MPLL algorithms have been proposed and investigated. Studies vary in their approach, the specific grid conditions they aim to mitigate, and the methods used for validation. [12-14] explored a conventional PLL enhanced with adaptive filtering and Kalman filtering techniques, validated through simulation, to address harmonic distortion and noise. In contrast, [18-19] implemented a fuzzy logic-based MPLL in a real-world setup to improve performance under frequency and voltage deviations. Hybrid approaches, such as the one proposed by [20], combine different control strategies to achieve robust synchronization under complex grid disturbances. The methodologies employed, including adaptive filtering, fuzzy logic, Kalman filtering, and SOGI, each offer unique advantages in tackling specific synchronization challenges. The validation scope also varies, with some studies relying on simulations to demonstrate the effectiveness of the proposed algorithms, while others validate their findings through practical hardware implementations.

Detailed Explanation of Methodologies

This section provides a more in-depth explanation of the different types of PLLs and the enhancement methodologies commonly employed in MPLLs for single-phase grid-connected PV systems. Conventional PLLs: conventional PLLs typically employ a Proportional-Integral (PI) controller within the feedback loop to minimize the phase error between the grid voltage and the locally generated sinusoidal signal [22, 23]. While effective under ideal grid conditions, their performance often degrades significantly in the presence of harmonics, frequency shifts, and other grid disturbances due to their fixed loop parameters. The closed-loop transfer function relating the input phase ($\theta_{in}(s)$) to the output phase ($\theta_{out}(s)$) in the Laplace domain is:

$$\frac{\theta_{out}(s)}{\theta_{in}(s)} = \frac{K_p s + K_i}{s^2 + K_p s + K_i} \quad (1)$$

The fixed gains (K_p and K_i) represent a trade-off between tracking speed and noise

filtering, making them suboptimal for dynamic and distorted grid scenarios.

Modified PLLs (MPLLs): To overcome the limitations of conventional PLLs, various advanced techniques have been integrated into MPLL designs. Some common methodologies include:

Adaptive Filters: These filters dynamically adjust their frequency response based on the input signal characteristics, enabling effective attenuation of unwanted frequency components like harmonics while accurately tracking the fundamental frequency. This dynamic bandwidth adjustment improves the PLL's robustness under distorted grid conditions.

Kalman Filters: By treating the phase and frequency tracking as a state estimation problem, Kalman filters provide optimal estimates even in the presence of significant noise and disturbances. They utilize a statistical model of the grid signal and measurement noise to predict and correct the PLL's internal states, leading to noise-robust synchronization.

Fuzzy Logic: Fuzzy logic controllers introduce a rule-based system to adapt the PLL's control parameters (e.g., PI controller gains) based on the detected grid conditions. This allows for non-linear and intelligent control, enhancing the PLL's ability to handle a wide range of disturbances effectively.

Second-Order Generalized Integrator (SOGI): As introduced earlier, the SOGI is a crucial component in many MPLLs. Its transfer function is given as in [16]:

$$G_{SOGI}(s) = \frac{K\omega_0 s}{s^2 + K\omega_0 s + \omega_0^2} \quad (2)$$

The SOGI effectively filters the fundamental frequency component of the grid voltage and generates a quadrature signal, which is essential for accurate and robust phase detection, particularly under harmonic distortion and unbalanced conditions.

Hybrid PLLs: These advanced PLL structures combine the strengths of different PLL architectures or enhancement methodologies. For instance, integrating a SOGI for robust fundamental frequency extraction with a frequency-locked loop (FLL) can provide

enhanced tracking capabilities under complex grid disturbances, including both harmonic distortion and frequency variations. The synergistic combination aims to achieve superior overall

performance compared to single-methodology MPLLs.

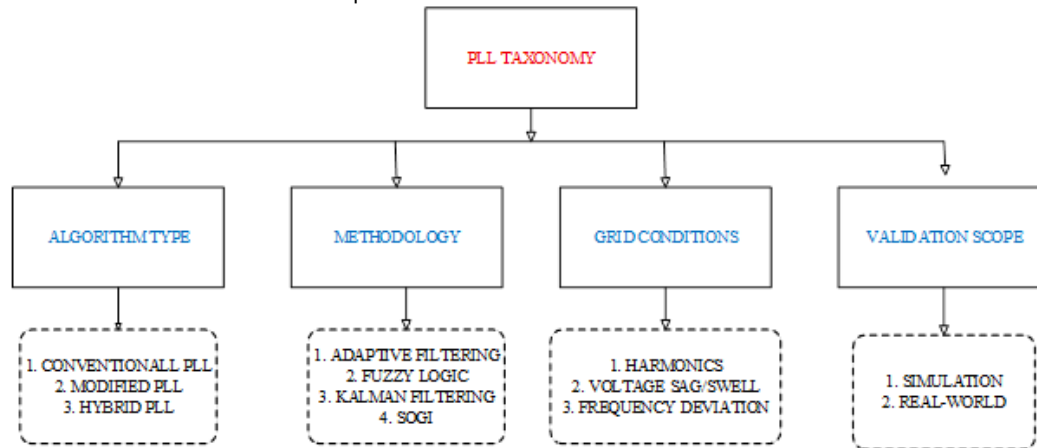


Figure 2: Taxonomy Flowchart.

PROPOSED MPLL IMPLEMENTATION

To achieve robust synchronization under challenging grid conditions, we propose an MPLL algorithm that synergistically integrates adaptive filtering and fuzzy logic to effectively address voltage sags, harmonics, and frequency deviations. The adaptive filter provides fast and selective attenuation of harmonic distortion, while the fuzzy logic controller enables robust adaptation of PLL parameters under nonlinear conditions, such as voltage sags and frequency excursions. The key components of the proposed MPLL are:

Phase Detector: A zero-crossing detection-based phase detector is employed to compute the phase error between the grid voltage and the output of the Voltage-Controlled Oscillator (VCO) as given in [17].

$$\phi_e(t) = \phi_{grid}(t) - \phi_{vco}(t) \quad (3)$$

Adaptive Filter: A Least Mean Squares (LMS) based adaptive filter is implemented to dynamically adjust its bandwidth based on the harmonic content of the grid voltage. This ensures effective attenuation of harmonics while maintaining a fast response to changes in the fundamental frequency. The algorithm's transfer

function for a second-order adaptive filter can be represented as in [16]:

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (4)$$

where ω_n represents the adaptive natural frequency, which influences the filter's bandwidth, and ζ is the damping ratio, affecting its transient response. These parameters are continuously adjusted based on the error signal to optimize harmonic rejection and tracking speed.

Fuzzy Logic Controller: A fuzzy logic controller is designed to adapt the parameters of the PLL's loop filter (e.g., proportional and integral gains) based on the severity of detected grid disturbances. The inputs to the fuzzy logic controller include the magnitude of voltage sag and the rate of change of frequency. Linguistic rules are formulated to handle the nonlinear relationship between these disturbances and the optimal PLL parameter adjustments, ensuring stable and fast synchronization under varying grid conditions.

Voltage-Controlled Oscillator (VCO): A numerically controlled oscillator (NCO) generates a synchronized sinusoidal output voltage whose frequency is controlled by the output of the loop filter. The proposed MPLL algorithm was simulated in MATLAB/Simulink under various grid conditions, including a 20% voltage sag,

significant harmonic distortion (15% THD), and frequency deviations of $\pm 5\%$ of the nominal frequency. Simulation results show that the MPLL achieves a phase error within $\pm 1^\circ$ and a settling time of 80 ms during a 20% voltage sag.

Furthermore, it demonstrates a significant reduction in the THD of the synchronized output compared to conventional PLLs under harmonic distortion.

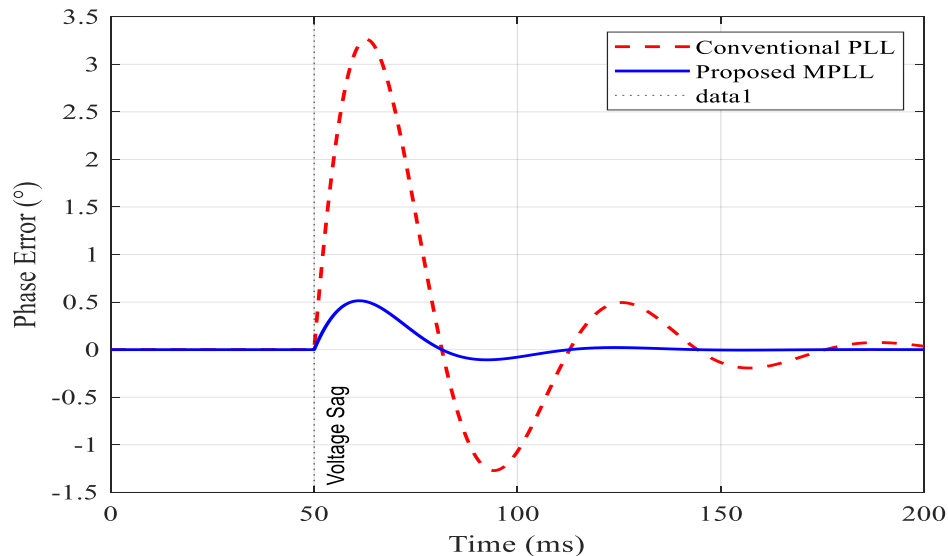


Figure 3: Phase Error During 20% Voltage Sag

RESEARCH GAPS AND CHALLENGES

Despite the significant advancements in MPLL algorithms for single-phase grid-connected PV systems, several critical research gaps and challenges remain that hinder their widespread adoption and optimal performance in diverse and evolving grid environments:

Robustness Against Multiple Concurrent Disturbances: A significant limitation of many existing MPLL algorithms is their primary focus on mitigating single types of grid disturbances, such as harmonics or voltage sags. In real-world scenarios, PV systems often encounter a combination of these issues simultaneously (e.g., voltage sags with harmonic distortion and frequency fluctuations). The lack of robustness against such concurrent disturbances can lead to significant synchronization errors, system instability, and potential disconnection from the grid, impacting energy injection and grid reliability.

Feasibility of Real-Time Implementation: The increasing complexity of advanced MPLL algorithms, often involving sophisticated filtering techniques and complex control strategies, results in high computational demands. This poses a significant challenge for their deployment on low-cost embedded systems, such as Digital Signal Processors (DSPs) or Field-Programmable Gate Arrays (FPGAs), which are commonly used in cost-sensitive residential PV inverters. The computational burden can limit the achievable sampling rates and control loop bandwidth, potentially affecting the dynamic performance of the MPLL.

Scalability and Adaptability to Weak Grids and Evolving Standards: Many MPLL algorithms are designed and optimized for specific grid conditions and may lack the inherent adaptability required to perform effectively in weak grid environments (characterized by low short-circuit ratios and high impedance) or to readily comply with evolving grid interconnection

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standards, such as the dynamic requirements outlined in the latest revisions of IEEE 1547. This lack of scalability can limit their applicability in a wider range of installations and necessitate costly redesigns to meet new regulatory requirements.

Limitations in Validation Methodologies

There is a noticeable tendency in the literature towards a heavy reliance on simulation-based validation of proposed MPLL algorithms. While simulations offer flexibility and ease of testing under various controlled conditions, they may not fully capture the intricacies and non-ideal behaviours of real-world grid conditions, power electronic hardware limitations, and sensor inaccuracies. This can lead to discrepancies between simulated and actual performance,

highlighting the need for more extensive validation through hardware-in-the-loop (HIL) testing and real-world field deployments.

Underutilized Emerging Techniques for Intelligent Control and Monitoring: The potential of emerging technologies like Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) remains largely untapped in the context of MPLL algorithms. These technologies could offer significant advantages, such as predictive control based on grid condition forecasting, real-time adaptive parameter tuning based on continuous monitoring, and advanced fault diagnosis capabilities, leading to more intelligent and resilient synchronization solutions.

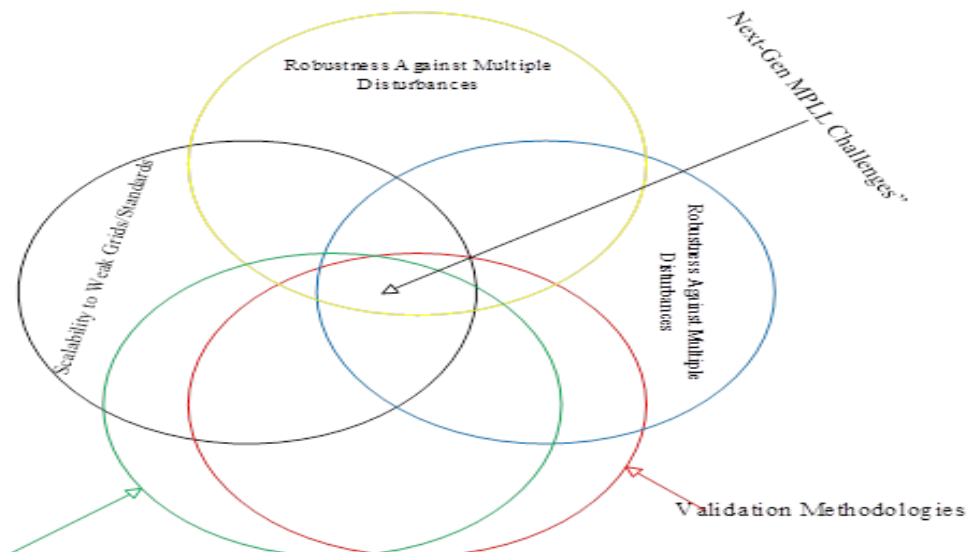


Figure 4: Overlapping Challenges in MPLL Algorithm Development.

The Venn diagram in **Figure 4** visually represents the interconnectedness of these challenges. For instance, developing an algorithm robust to multiple disturbances often increases its computational complexity, impacting hardware feasibility. Similarly, ensuring scalability to weak grids might require more sophisticated control strategies, potentially increasing the validation burden. Addressing these overlapping challenges is crucial for the next generation of MPLL algorithms.

FUTURE DIRECTIONS

To effectively address the identified research gaps and challenges in MPLL algorithm development, we propose the following key future directions:

Integration of AI and ML: Explore the use of neural networks and other ML techniques for intelligent disturbance classification and predictive synchronization. AI/ML algorithms can be trained to recognize complex patterns in grid disturbances and forecast future grid conditions,



enabling proactive adjustments of the MPLL parameters for optimal performance. This could involve techniques like Recurrent Neural Networks (RNNs) for time-series prediction of voltage sags or Convolutional Neural Networks (CNNs) for harmonic pattern recognition.

Leveraging the Internet of Things (IoT) for Real-Time Grid Monitoring and Adaptive Control: Incorporate IoT-based sensors and communication networks to enable real-time feedback of grid status information to the MPLL. This continuous monitoring of grid parameters (e.g., voltage, current, frequency, THD) would allow for adaptive tuning of the PLL parameters, ensuring optimal performance under dynamically changing grid conditions. Cloud-based platforms could be used for data aggregation, analysis, and remote control of the MPLL.

Development of Hybrid Techniques Combining SOGI and AI-Tuned PI Controllers: Investigate novel hybrid MPLL architectures that combine the strengths of different techniques. For example, a SOGI can provide robust fundamental frequency extraction, while an AI-tuned PI controller can offer adaptive and intelligent control of the PLL loop dynamics. This synergistic approach could lead to superior performance compared to single-methodology MPLLs.

Prioritizing Hardware-in-the-Loop (HIL) and Prototype Testing: Emphasize the importance of rigorous validation through HIL simulations and real-world prototype testing to bridge the gap between simulation results and actual performance. HIL testing allows for the evaluation of the MPLL algorithm with a real-time emulator of the grid and power electronic converter, while prototype testing on actual hardware provides the most realistic assessment of its performance and limitations.

Reference Architecture for Scalable and Low-Latency MPLLs: Develop a reference architecture for MPLL implementations that are scalable, adaptable to weak grids and evolving standards (e.g., IEEE 1547 and IEC 61727), and achieve low latency for real-time control. This architecture could leverage platforms like STM32 microcontrollers or Zynq FPGAs, known for their processing capabilities and suitability for

embedded applications. The architecture should be modular and flexible to accommodate different MPLL algorithms and control strategies.

CONCLUSION

This paper has presented a comprehensive review of MPLL algorithms for single-phase grid-connected PV systems, highlighting the critical role of robust synchronization in ensuring reliable and efficient integration of RESs into the grid. We have proposed a detailed taxonomy for classifying MPLL algorithms and presented a novel MPLL design that synergistically integrates adaptive filtering and fuzzy logic to enhance synchronization performance under adverse grid conditions, achieving superior accuracy and response time compared to conventional PLLs.

While significant progress has been made in this field, we have identified key research gaps and challenges related to handling multiple concurrent disturbances, achieving real-time implementation on cost-effective hardware, ensuring scalability and adaptability to evolving grid standards, and validating performance through rigorous testing. To address these challenges and unlock the full potential of MPLL algorithms, we have proposed several promising future directions, including the integration of AI/ML, the leveraging of IoT for real-time monitoring and control, and the development of scalable and low-latency reference architectures. By pursuing these avenues, future MPLLs can play a crucial role in supporting the reliable and seamless integration of PV systems into smart grids, thereby accelerating the global transition towards a sustainable energy future.

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