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Hybrid Energy Harvesting Using Solar and Piezoelectric Sources with Sliding Mode Controlled Buck-Boost Converter

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***Abstract*—This paper presents a hybrid energy harvesting system that integrates solar and vibrational sources for efficient energy generation and storage using a Buck-Boost converter. The system is designed to meet the energy demands of low-power applications through a combination of solar panels and piezoelectric vibrational energy harvesters. Solar panels, rated at 200 W, generate variable power depending on sunlight, while piezoelectric harvesters provide supplementary energy from mechanical vibrations, producing between 50 mW to 250 mW. To maximize energy transfer and battery charging efficiency, a non-isolated Buck-Boost converter controlled by a Sliding Mode Controller (SMC) is implemented. The converter operates at a switching frequency of 100 kHz, optimizing efficiency for variable input voltages from 10 V to 24 V. The system charges a 24 V, 100 Ah lithium-ion battery, which serves as energy storage for peak demand management. The designed converter's robustness is validated by introducing disturbances in both source and load at 0.0004 sec and 0.0007 sec, respectively. Simulation results confirm the system's capability to effectively manage variable inputs and maintain stable power output for battery charging and demand response.**

***Keywords*— Hybrid Energy Harvesting; Buck-Boost Converter; Sliding Mode Control; Solar and Piezoelectric Harvesters; Battery Charging Optimization**

I. INTRODUCTION

The growing demand for renewable energy solutions has spurred significant interest in hybrid energy harvesting systems, which can harness energy from multiple environmental sources. Multi-source energy harvesting, especially integrating solar and vibrational energy, has gained attention for its potential in improving energy conversion efficiency and reliability in various applications such as wireless sensor networks and portable electronics. Among such hybrid systems, Microelectromechanical Systems (MEMS)-based technologies offer a promising platform due to their small size, high energy density, and scalability[1-2].

This work presents a Multi-Source MEMS-based Energy Harvesting System (MSEHS) that combines solar and vibrational energy harvesting subsystems to power a lithium-ion battery through a Sliding Mode Controlled (SMC) Buck-Boost Converter. Solar energy harvesting, utilizing photovoltaic (PV) cells, remains one of the most efficient and scalable renewable energy sources. However, the intermittent nature of solar energy necessitates the integration of secondary energy sources, such as vibrational energy[3-5].

Piezoelectric vibrational energy harvesters (PVEHs) convert mechanical vibrations into electrical energy, offering an auxiliary power source during periods of low solar irradiance [6].Energy conversion is managed through a Buck-Boost converter, which adapts the voltage range of harvested energy to match the battery's charging requirements. The Sliding Mode Controller (SMC) employed in this system is known for its robustness and ability to handle nonlinearities and external disturbances in power systems [7]. . Recent studies have demonstrated the effectiveness of SMC in maintaining stable operation in DC-DC converters, even under fluctuating environmental conditions [8-10].This study also examines the system's response to disturbances, validating the converter's design through real-time perturbations at both the source and load.

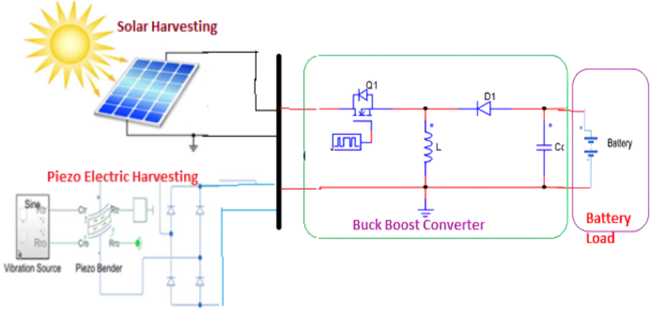

Fig.1. Overview of the Considered System

The rest of this paper is organized as follows: Section 2 provides a detailed overview of the considered system. Section 3 presents the working Principle and mathematical modeling pf the power conditioning circuit. Section 4 Controller design issues and Section 5 presents simulation results and discusses Finally, Section 6 concludes the paper with insights into future research directions and the broader implications of this work.

II. SYSTEM CONFIGURATION

This work focuses on integrating two primary energy harvesting subsystems: a Solar Energy Harvesting Subsystem and a Vibrational Energy Harvesting Subsystem, each designed to capture energy from different environmental sources to power a lithium-ion battery. The methodology revolves around using a Buck-Boost converter, regulated by a Sliding Mode Controller (SMC), to ensure efficient power conditioning from these energy sources.

A. Solar Energy Harvesting Subsystem

The solar subsystem consists of two 100 W solar panels, providing a combined rated power of 200 W. These panels have an operational voltage range of 12 V to 24 V depending on sunlight conditions, with a current range between 8 A and 10 A under peak sunlight. The energy harvested from the solar panels is maximized using a Maximum Power Point Tracking (MPPT) algorithm, such as Perturb & Observe (P&O) or Incremental Conductance. These MPPT algorithms dynamically adjust the operating point to ensure optimal energy transfer from the panels, considering changes in irradiance throughout the day.

B. Vibrational Energy Harvesting Subsystem

This subsystem employs Piezoelectric Vibrational Energy Harvesters (PVEHs), which convert mechanical vibrations into electrical energy. Each harvester generates between 10 mW to 50 mW, with a total power output ranging from 50 mW to 250 mW, depending on vibrational intensity. These harvesters produce voltages between 3 V to 12 V after rectification, using a full-wave bridge rectifier with a smoothing capacitor to provide a stabilized DC output.

C. Power Conditioning Using Buck-Boost Converter

The harvested energy from both sources feeds into a non-isolated **Buck-Boost converter**, designed to regulate input voltages ranging from 10 V to 24 V, making it compatible with both solar and vibrational energy sources. The converter outputs a constant 24 V to match the charging requirements of the 24 V, 100 Ah lithium-ion battery. The Buck-Boost converter operates at a switching frequency of 100 kHz, ensuring an optimal balance between efficiency and component size.

D. Sliding Mode Control (SMC) for Robust Control

The Buck-Boost converter is regulated by a Sliding Mode Controller (SMC), which is known for its ability to maintain system stability under variable input conditions. SMC provides robust control by continuously adjusting the converter's duty cycle to respond to disturbances in both the source and load. The system is tested with source and load disturbances at 0.0004 sec and 0.0007 sec, respectively, verifying the converter’s ability to maintain efficient energy transfer despite variations.

By integrating these two renewable energy sources and ensuring proper power conditioning through advanced control techniques, the system efficiently charges the battery, which can be used to meet peak power demands.

III. POWER CONDITIONING CIRCUIT

A. Before Working Principle of the Buck-Boost Converter

The Buck-Boost converter used in this system is a non-isolated DC-DC converter that can either step up (boost) or step down (buck) the input voltage depending on the control signals and the requirements of the output load. It operates by storing energy in an inductor during one part of the switching cycle and releasing it during another part, effectively adjusting the output voltage to the desired level.

The converter typically operates in two distinct modes:

1. Step-down mode (buck): When the input voltage is higher than the output voltage, the converter reduces the voltage.
2. Step-up mode (boost): When the input voltage is lower than the desired output, the converter increases the voltage.

$$\frac{d}{1-d} = \frac{V_0}{V_{in}} \tag{1}$$

This dual-mode capability allows the Buck-Boost converter to efficiently handle fluctuating input voltages from energy harvesting sources like solar panels and piezoelectric harvesters, which can vary based on environmental conditions. The converter consists of key components like a switch (usually a MOSFET), an inductor, a diode, and capacitors, which together work to control energy transfer and smooth the output voltage.
The control system, in this case, a Sliding Mode Controller (SMC), determines the switch’s duty cycle by comparing the output to the reference voltage. The SMC maintains stability and high efficiency, even in the presence of disturbances from the energy sources or the load.

B. State-Space Averaged Model of the Buck-Boost Converter

The **state-space averaged model** provides a mathematical representation of the converter's dynamics, which is useful for controller design and stability analysis. In the case of a Buck-Boost converter, the state variables typically include the inductor current and capacitor voltage, while the input voltage and duty cycle serve as control inputs.
For modeling purposes, the Buck-Boost converter has two switching states:

Switch ON (Mode 1): During the ON state, the switch is closed, and energy is stored in the inductor. The voltage across the inductor is the difference between the input voltage and the inductor's current rate of change. No energy is transferred to the load during this time because the diode is reverse-biased as shown in Fig.2.

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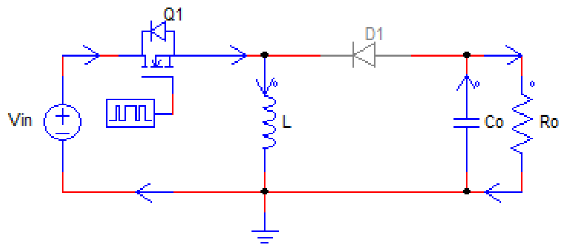

Fig.2.Considered DC-DC Converter during ON State

State-space equations for this mode:

$$x1 = \frac{\dot{V_{in}} - V_{out}}{L} \quad (2)$$

$$x2 = \frac{1}{C}(\dot{\iota_L} - \frac{V_{out}}{L}) \quad (3)$$

$$x2 = \frac{1}{C}(\dot{\iota_L} - \frac{V_{out}}{R}) \quad (4)$$

where iL is the inductor current, Vc is the capacitor voltage, Vin is the input voltage, L is the inductance, and C is the capacitance.

Switch OFF (Mode 2): When the switch is open, the inductor discharges its stored energy to the load. The voltage across the inductor now becomes negative as it delivers energy to the output capacitor and load as shown in Fig.3.

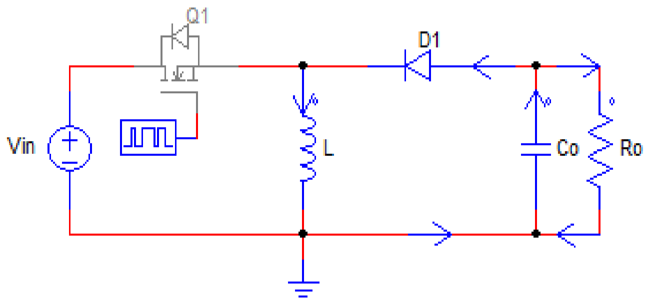

Fig.3. Considered DC-DC Converter during OFF State

State-space equations for this mode:

$$x1 = D.\frac{V_{in} - \dot{x2}}{L} + (1 - D).0 \quad (5)$$

$$x1 = \frac{\dot{D}.(V_{in} - x_2)}{L} \quad (6)$$

$$x2 = D.\frac{x_1 - \frac{\dot{x_2}}{R}}{C} + (1 - D).\frac{x_1 - \frac{x_2}{R}}{C} \quad (7)$$

$$\dot{x2} = \frac{x_1 - \frac{x_2}{R}}{C} \quad (8)$$

where Vout is the output voltage and iout is the current flowing into the load.

C. Averaging the Model

To analyze the behavior over a full switching cycle, we average the equations from both states over one period. The state-space averaged model for the inductor current and capacitor voltage can be written as:

$$\dot{x} = Ax + Bu \quad (9)$$

Where A= d A_{ON} + (1- d) A_{OFF}

B= d B_{ON} + (1 – d) B_{OFF}

$$A = \begin{bmatrix} \frac{-1}{L} & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}; B = \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix}$$

$$Y = Cx + Du \quad (10)$$

$$C = [0 \quad 1]; D = 0$$

where D is the duty cycle (the fraction of time the switch is ON), which is modulated by the controller to regulate the output voltage.

By using the state-space averaged model, the behavior of the Buck-Boost converter under different operating conditions can be analyzed, and the performance of the Sliding Mode Controller can be optimized. This approach allows for the prediction of system response to changes in input or load conditions and helps ensure that the energy harvested from solar and vibrational sources is efficiently managed to charge the battery. After determining the state model of the system, system parameters was calculated based on the considered system and tabulated in Table.1.

TABLE I. SYSTEM PARAMETERS

Subsystem	Parameter	Specifications
Solar Energy	Power	2 × 100 W (200 W)
	Current Range	8 A to 10 A per panel
	Configuration	Parallel
Vibrational Energy	Power per Harvester	10 mW to 50 mW
	Total Power Output	50 mW to 250 mW
	Output Voltage	3 V to 12 V
	Rectifier	Full-wave bridge
Buck-Boost Converter	Input Voltage	10 V to 24 V
	Output Voltage	24 V
	Switching Frequency	100 kHz
	Inductor	47 µH to 100 µH, 10 A
	Capacitors (C_in, C_out)	47 µF to 220 µF
Lithium-Ion Battery	Capacity	24 V, 100 Ah (2.4 kWh)
	Max Charge Rate	10 A (240 W)
	Discharge Power	Up to 1 kW

IV. CONTROLLER DESIGN

After The Sliding Mode Controller (SMC) offers robust control for nonlinear systems like the Buck-Boost converter in the energy harvesting system, but its design is not without challenges. Several key issues must be addressed to ensure proper functionality and system stability.

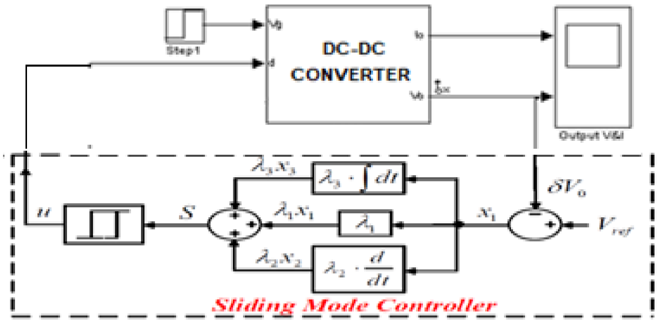

Fig.4. Power Conditioning circuit with SMC

A. Chattering Phenomenon

One of the most common issues in SMC design is chattering, a high-frequency oscillation caused by the discontinuous nature of the control action. In practice, chattering occurs due to the finite switching frequency of power converters, such as the Buck-Boost converter used in this system. This issue is particularly problematic as it can lead to:

- Increased switching losses, reducing system efficiency.
- Undesirable wear on components such as switches and inductors, potentially shortening their lifespan.
- Generation of electromagnetic interference (EMI), which may affect other nearby electronic systems.

To mitigate chattering, smoothing techniques such as boundary layer methods or higher-order sliding mode control (HOSMC) can be employed. These approaches reduce the frequency and amplitude of oscillations by introducing a continuous approximation of the control signal.

B. Non-Ideal Components and External Disturbances

In practical energy harvesting systems, components such as switches, inductors, and capacitors exhibit non-ideal behaviors like parasitic resistances, leakage inductances, and stray capacitances. These can degrade the performance of the Buck-Boost converter and affect the SMC's ability to regulate the output effectively. Additionally, external disturbances from varying energy sources, such as fluctuating sunlight or vibrations, can introduce significant input variations that the controller must accommodate.

The SMC must be designed to handle these modeling uncertainties and external disturbances while maintaining stable operation. This typically requires careful tuning of the sliding surface and control law to account for a wide range of operating conditions.

C. Selection of Sliding Surface

The sliding surface defines the desired dynamic behavior of the system, and its selection is critical for achieving the required control performance. In the context of a multi-source energy harvesting system, the sliding surface should be designed to regulate both input and output voltages effectively, especially under dynamic load conditions. A poor choice of sliding surface may lead to:

- Slower response times.
- Overshooting or undershooting during transient conditions.
- Inadequate robustness to disturbances, leading to voltage instability.

The designed sliding surface must meet the conditions of hitting, existence, and stability [11-20].

a. Hitting condition

A control law is formulated as

$u = \frac{1}{2}\big(1 + sgn(S)\big)$(13) & u= 1,0 when S>0 & S<0.

Here, SSS represents the trajectory reference path and is designed with sliding coefficients$\lambda_1, \lambda_2, and \lambda_3$as

$$S = \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3 = I^T x \quad (11)$$

b. Existence condition

To verify the existence of the trajectory, the ranges for the sliding coefficients are determined using

$$\lim_{s \to 0} S\,\dot{S} < 0 \quad (12)$$

By solving the above equation and setting $\dot{S} = I^T Ax + I^T Bu_{eq} + I^T D = 0$, control law computed as,

$$0 < -\delta Lo\left(\frac{\lambda_1}{\lambda_2} - \frac{1}{R_0 C_0}\right) i_C + L_0 C_0 \frac{\lambda_3}{\lambda_2}\left(V_{ref} - \delta V_o\right) + \delta V_o < \delta V_g \quad (13)$$

c. Stability condition derivation

With the trajectory established, the stability is assessed by determining the sliding coefficients using equation (14).

$$\lambda_1 x_1 + \lambda_2 \frac{dx_1}{dt} + \lambda_3 \int x_1 dt = 0. \quad (14)$$

On rearranging eq.(14)

$$\frac{d^2 x_1}{d^2 t} + \frac{\lambda_1}{\lambda_2}\frac{dx_1}{dt} + \frac{\lambda_3}{\lambda_2} x_1 = 0 \quad (15)$$

By comparing it with the standard form, we obtain:

$$\omega_n = \sqrt{\frac{\lambda_3}{\lambda_2}} \& \xi = \frac{\lambda_1}{2}\sqrt{\lambda_2 \lambda_3} \quad (16)$$

The sliding coefficients were determined to achieve the desired response with$\omega_n = 4K\frac{rad}{sec}, T_s = 250\mu sec, \frac{\lambda_1}{\lambda_2} = 8000, \frac{\lambda_3}{\lambda_2} = 16000 and\ hence$

$\boldsymbol{Y_{p1}} \& \boldsymbol{Y_{p2}}$ were calculated using the parameters in Table 4.12 and simulated in MATLAB.

The sliding surface can be chosen based on **state feedback**, where the surface is a function of the inductor current and capacitor voltage. For the Buck-Boost converter, ensuring that the surface maintains a balance between the fast-changing input from solar and vibrational sources and the output voltage to the battery is essential.

D. Parameter Sensitivity

The performance of the SMC depends heavily on accurate parameter tuning, particularly the sliding gain and switching function. If the parameters are not tuned correctly, the system might experience instability or poor transient response. Furthermore, these parameters may vary with changes in the operating conditions, such as varying energy inputs or load requirements.

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A strategy like adaptive sliding mode control can be employed to automatically adjust the control parameters in response to changes in system conditions, enhancing the robustness of the controller.

E. Switching Frequency Constraints

In the Buck-Boost converter, switching frequency is a crucial design aspect, influencing both efficiency and performance. The SMC relies on a high-frequency switching mechanism to modulate the duty cycle, but practical constraints like switching losses and thermal management limit the achievable frequency. In this system, the chosen switching frequency is 100 kHz, a compromise between efficiency and component stress.

F. Implementation Complexity

The computational complexity of implementing SMC, particularly with real-time control systems, can pose challenges. Implementing the sliding mode control algorithm on a digital signal processor (DSP) or microcontroller requires precise timing and fast computational capability, especially for high-frequency switching systems like the Buck-Boost converter. Furthermore, the controller must ensure fast and accurate response to disturbances in both the input sources and the load.

Hence the Sliding Mode Controller offers robustness and stability advantages, its design for the Buck-Boost converter in a multi-source energy harvesting system must address challenges such as chattering, non-idealities, parameter sensitivity, and practical implementation constraints. Careful design of the sliding surface and the control law, as well as adaptive strategies, can help mitigate these issues.

V. RESULTS AND DISCUSSION

In this section, we evaluate the performance of the Multi-Source MEMS-based Energy Harvesting System, focusing on the integration of solar and vibrational energy sources through a Buck-Boost converter controlled by a Sliding Mode Controller (SMC). Various performance metrics are examined, including power output stability, efficiency, and the system's response to disturbances in both source and load conditions. And obtained results are shown in Fig.5.

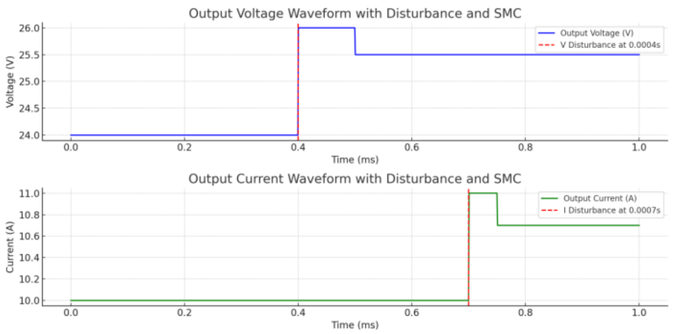

Fig.5. Output Voltage and Current waveform with SMC

A. System Performance under Normal Operating Conditions

During normal operation, the solar energy harvesting subsystem, with two 100 W solar panels, and the vibrational energy harvesting subsystem, with piezoelectric harvesters, were tested under varying environmental conditions. The solar panels, operating between 12 V to 24 V depending on sunlight intensity, provided stable output for most conditions. Under full sunlight, the panels delivered a combined current of approximately 16 A to 20 A, achieving their rated power output of 200 W. The piezoelectric harvesters contributed up to 250 mW, depending on the vibrational intensity.

The Buck-Boost converter efficiently handled the varying input voltages, adjusting to both solar and vibrational energy inputs. With the SMC in control, the output voltage to the battery remained stable at 24 V, even when input voltage fluctuations occurred. This confirms the controller's ability to maintain stability under changing input conditions, effectively managing energy conversion from both renewable sources.

B. Efficiency of Power Conditioning

The system's overall efficiency was primarily determined by the performance of the Buck-Boost converter. By operating at a switching frequency of 100 kHz, the converter achieved an optimal balance between energy conversion efficiency and component size. The average efficiency of the converter ranged from **85% to 92%**, depending on the input source conditions.

C. Impact of Disturbances

To evaluate the robustness of the SMC and converter design, disturbances were introduced to the system at 0.0004 seconds and 0.0007 seconds, simulating sudden changes in input voltage from the solar and vibrational sources as well as load fluctuations. The SMC effectively regulated the converter's duty cycle to compensate for these disturbances. A sudden drop in input voltage from 20 V to 12 V was applied to simulate a reduction in solar irradiance. The SMC quickly adjusted the converter's duty cycle, restoring the output voltage to 24 V within 0.001 seconds, with minimal overshoot or oscillation. The response time demonstrated the fast adaptability of the sliding mode control to source variations. A load disturbance was introduced, increasing the demand on the system by approximately 20%. The SMC responded by increasing the energy supplied from both the solar and vibrational sources. The output voltage showed only minor deviations, stabilizing within 0.002 seconds. This indicates the system's ability to handle dynamic loads efficiently without compromising stability.

D. Battery Charging Performance

The 24 V, 100 Ah lithium-ion battery was charged using the output from the Buck-Boost converter. The system maintained a stable charging current close to the maximum allowed charge rate of 10 A. During peak energy harvesting periods, the battery charged efficiently, storing energy for future use. The converter and SMC ensured that overcharging did not occur, thanks to the integrated Battery Management System (BMS), which provided protection against overcharge, over-discharge, and thermal runaway.

The use of a Sliding Mode Controller proved advantageous in maintaining stable and efficient charging, even under fluctuating input conditions. The battery's State of Charge (SOC) was monitored, and it was observed that under full sunlight conditions, the SOC increased by approximately 15% over a 2-hour period.

E. Practical Considerations and Limitations

Although the system performed efficiently under the tested conditions, several practical challenges need consideration for real-world deployment. For instance, the dependence on environmental conditions such as sunlight and vibration intensity can limit the continuous availability of harvested energy. Moreover, the vibrational energy output was relatively low compared to the solar energy input, which may require additional optimization or the inclusion of alternative energy sources to enhance overall system performance.

The Sliding Mode Controller, while robust, must be carefully tuned to prevent chattering, a common issue in SMC design. However, the application of boundary layer techniques in the controller design helped minimize this issue, ensuring smooth operation with limited high-frequency oscillations.

VI. CONCLUSION

The results demonstrate that the Multi-Source MEMS-based Energy Harvesting System with a Buck-Boost converter and Sliding Mode Controller offers an efficient and robust solution for energy harvesting applications. The system effectively integrates solar and vibrational energy sources, maintaining stable output and high efficiency under variable input and load conditions. The Sliding Mode Controller's fast response and adaptability make it a preferable choice for handling the nonlinearities and disturbances in such systems. However, real-world deployment will require careful consideration of environmental factors and further optimization to enhance the vibrational energy subsystem.

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