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FSM-Guided Adaptive MPC for Robust Fault-Tolerant Control of PV Inverters

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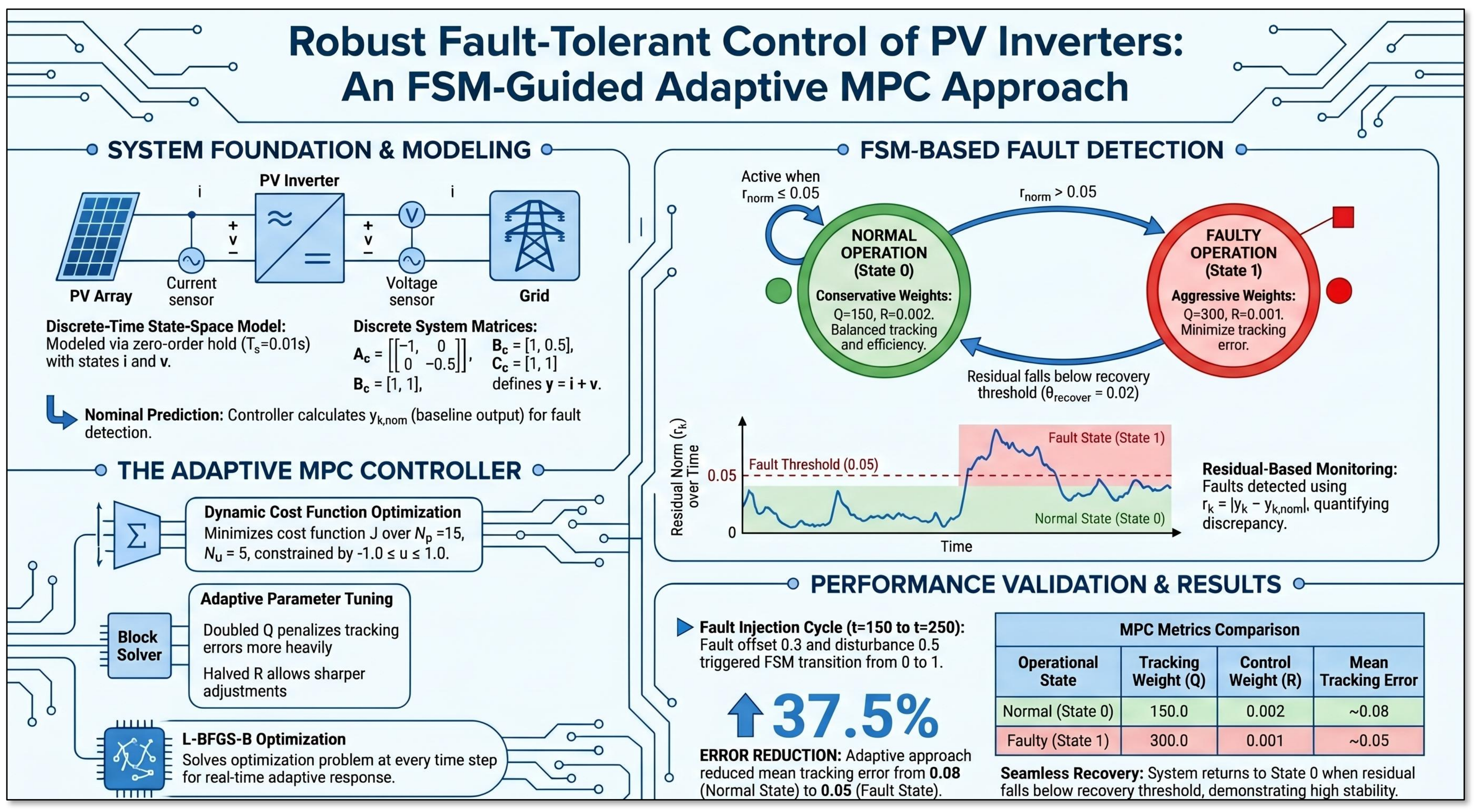
INTRODUCTION & AIM

- ❑ **Background:** Photovoltaic (PV) systems are a cornerstone of renewable energy integration, but PV inverters are highly vulnerable to faults such as sensor offsets, partial shading, and grid-induced disturbances.
- ❑ **The Challenge:** These faults lead to performance degradation, instability, and potential grid disconnection. Traditional PID controllers and standard fixed-parameter Model Predictive Control (MPC) often struggle to dynamically mitigate the impact of these anomalies.
- ❑ **Aim:** To introduce a novel Finite State Machine (FSM)-adaptive MPC framework designed to dynamically detect faults and adjust control strategies, thereby improving the fault tolerance of PV inverters.

METHOD



Discrete-Time State-Space Model: Modeled via zero-order hold (T_s=0.01s) with states **i** and **v**.

Discrete System Matrices: $A_c = \left[\begin{bmatrix} -1, & 0 \\ 0 & -0.5 \end{bmatrix}\right]$, $B_c = [1, 1]$, $B_c = [1, 0.5]$, $C_c = [1, 1]$ defines **y = i + v**.

Nominal Prediction: Controller calculates $y_{k,nom}$ (baseline output) for fault detection.

Dynamic Cost Function Optimization Minimizes cost function J over N_p =15, N_u = 5, constrained by $-1.0 \leq u \leq 1.0$.

Adaptive Parameter Tuning Doubled Q penalizes tracking errors more heavily. Halved R allows sharper adjustments.

L-BFGS-B Optimization Solves optimization problem at every time step for real-time adaptive response.

Conservative Weights: Q=150, R=0.002. Balanced tracking and efficiency.

Aggressive Weights: Q=300, R=0.001. Minimize tracking error.

Residual falls below recovery threshold ($\theta_{recover}$ = 0.02)

Residual-Based Monitoring: Faults detected using $r_k = |y_k - y_{k,nom}|$, quantifying discrepancy.

Fault Injection Cycle (t=150 to t=250): Fault offset 0.3 and disturbance 0.5 triggered FSM transition from 0 to 1.

ERROR REDUCTION: Adaptive approach reduced mean tracking error from **0.08** (Normal State) to **0.05** (Fault State).

MPC Metrics Comparison

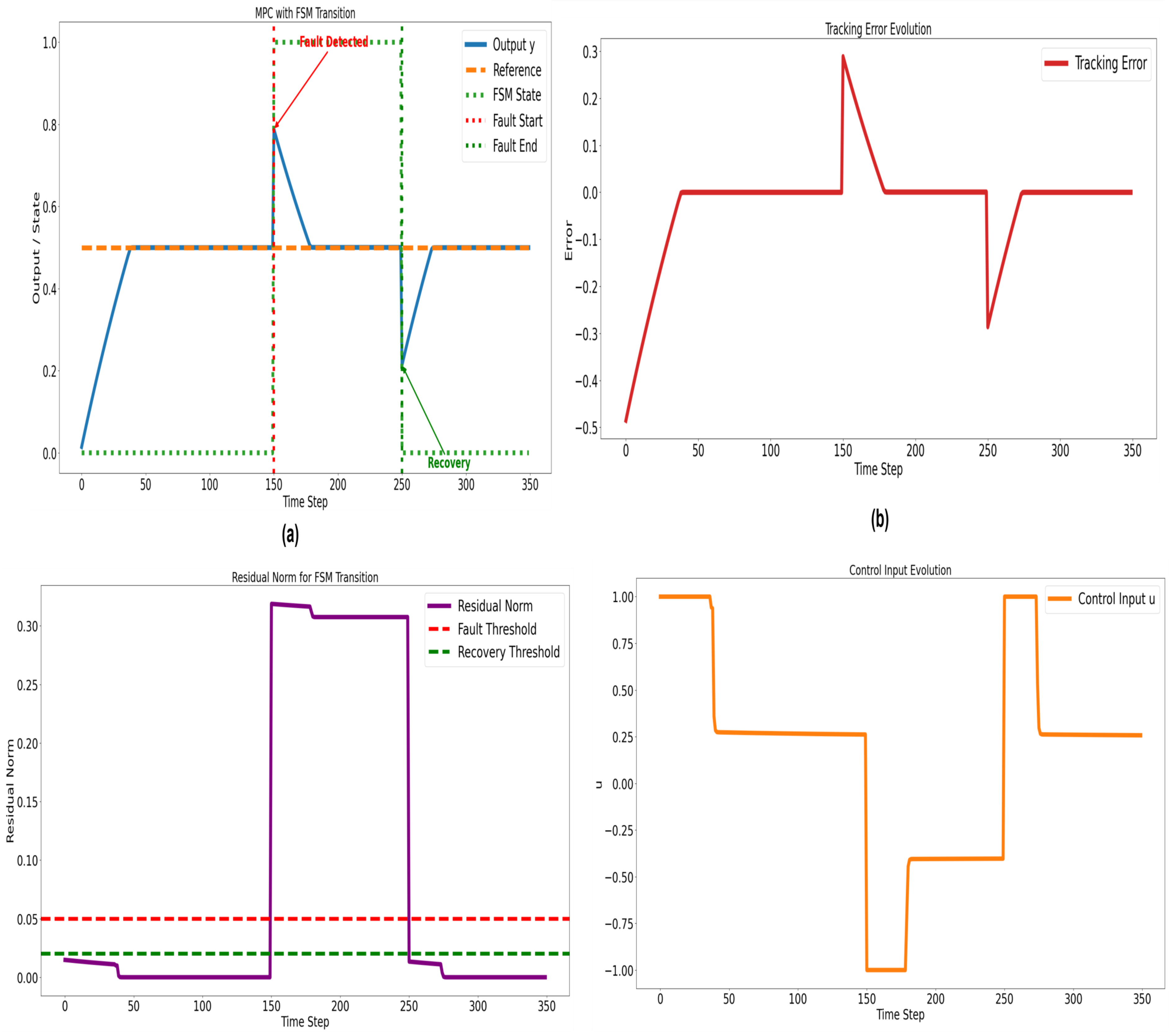
Operational State	Tracking Weight (Q)	Control Weight (R)	Mean Tracking Error
Normal (State 0)	150.0	0.002	~0.08
Faulty (State 1)	300.0	0.001	~0.05

Seamless Recovery: System returns to State 0 when residual falls below recovery threshold, demonstrating high stability.

Fig 1. Proposed architecture for FSM-Guided Adaptive Model Predictive Control for PV Inverters

- ❑ **System Model:** The PV inverter uses a discrete-time state-space model (T_s = 0.01s) that incorporates a potential fault offset, f_k.
- ❑ **Fault Detection:** An FSM monitors the residual norm, $r_k = |y_k - y_{k,nom}|$, transitioning to a faulty state if $r_{norm} > 0.05$ and recovering if $r_{norm} < 0.02$.
- ❑ **MPC Formulation:** The controller optimizes a tracking and control-effort cost function, J, over a prediction horizon of N_p=15 and a control horizon of N_u=5.
- ❑ **Adaptive Tuning:** To maintain performance during anomalies, the MPC dynamically shifts its penalization weights from normal operations (Q=150.0I, R=0.002I) to a more aggressive fault-state tracking (Q=300.0I, R=0.001I).

RESULTS & DISCUSSION



(a) (b)

(c) (d)

Fig 2. FSM-Adaptive MPC performance during a fault-recovery cycle: (a) **Adaptive MPC:** The system successfully tracks the reference, dynamically switching to the fault state between t=150 and t=250. (b) **Tracking Error:** Error minimizes to ~0.05 during the fault due to higher state weighting (Q=300). (c) **Residual Norm:** Fault detection triggers when the norm exceeds 0.05, and recovery triggers when it falls below 0.02. (d) **Control Input:** The controller makes sharper, more aggressive adjustments during the fault due to a reduced control penalty (R=0.001).

The proposed FSM-adaptive MPC enhances PV inverter reliability by using a residual norm to instantly detect faults when they cross a 0.05 threshold. Upon detection, the controller dynamically updates its optimization weights (Q=300, R=0.001) to make sharper, more aggressive control adjustments. This real-time adaptation effectively forces the mean tracking error down from 0.08 to 0.05, maintaining system stability throughout the entire fault and recovery cycle.

CONCLUSION

This work presents an FSM-adaptive MPC framework that significantly enhances PV inverter fault tolerance by using residual-based detection to dynamically tune control parameters and minimize tracking errors during disturbances.

REFERENCES

[1] S. Vazquez, J. Rodriguez, M. Rivera, L. G. Franquelo and M. Norambuena, "Model Predictive Control for Power Converters and Drives: Advances and Trends," IEEE Transactions on Industrial Electronics, vol. 64, no. 2, pp. 935–947, Feb. 2017, doi: 10.1109/TIE.2016.2625238.

[2] N. Muhammad and N. M. Ridzuan, "A Review of Fault Detection and Diagnosis Approaches for Photovoltaic Systems Using Voltage and Current Analysis," in Proceedings of the 2024 IEEE 4th International Conference in Power Engineering Applications (ICPEA), Pulau Pinang, Malaysia, 2024, pp. 25–30, doi: 10.1109/ICPEA60617.2024.10498573.

[3] Y.-H. Zhang and X.-J. Li, "A fault-tolerant model predictive control approach based on deep operator network," Neurocomputing, vol. 651, 131048, 2025, doi: 10.1016/j.neucom.2025.131048.