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# Model Predictive Control-Based Energy Management for Solid-State Transformers Enabling Seamless Integration of Renewable Energy Sources and Electric Vehicle Charging in Smart Distribution Grids

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***Abstract*—Modern distribution grids face unprecedented volatility due to the rapid integration of Renewable Energy Sources (RES) and the high-power demand of Electric Vehicle (EV) charging stations. The Solid-State Transformer (SST) is a pivotal solution for managing these bi-directional power flows while providing high-frequency isolation. This paper proposes a Model Predictive Control (MPC)-based energy management strategy for a three-stage SST. The MPC framework utilizes a finite-control-set approach to regulate the high-voltage DC (HVDC) and low-voltage DC (LVDC) links while simultaneously minimizing reactive power at the Point of Common Coupling (PCC). A multi-objective cost function is developed to prioritize seamless power transfer between solar PV arrays, EV batteries, and the utility grid. Simulation results on a modified IEEE 13-bus test system demonstrate that the MPC controller outperforms traditional cascaded PI loops, providing a 40% faster transient recovery during cloud-cover transients and EV plug-in events.**

***Index Terms*—Solid-State Transformer (SST), Model Predictive Control (MPC), Renewable Energy, Electric Vehicles, Energy Management, Smart Grids.**

## I. INTRODUCTION

THE evolution of the ”Energy Internet” requires distribution transformers to be more than just passive voltage-stepping devices. Solid-State Transformers (SSTs) are active nodes capable of regulating voltage, isolating harmonics, and facilitating DC connectivity for solar PV and EV charging infrastructure. However, the stochastic nature of solar irradiance and the intermittent, high-current demand of EVs impose severe stress on the SST’s internal DC buses.

Traditional control strategies, such as the linearized State-Space Average (SSA) model with PI controllers, struggle with the non-linear switching characteristics and the strict operational constraints of power electronics. **Model Predictive Control (MPC)** offers a superior alternative by predicting the future behavior of the system over a finite horizon and selecting the optimal switching state that minimizes a predefined cost function.

This paper develops a unified MPC framework that manages the power balance across the three stages of the SST (Rectifier, DC-DC, and Inverter). By integrating the state-space models of solar PV boosters and EV chargers into the prediction horizon, the proposed controller ensures seamless power routing without large DC-link voltage deviations.

## II. SYSTEM ARCHITECTURE AND MODELING

### A. SST Topology with RES and EV Integration

The system consists of a three-stage SST:

1) **High-Voltage (HV) Stage:** An active front-end (AFE) rectifier.
2) **Isolation Stage:** A Dual Active Bridge (DAB) converter.
3) **Low-Voltage (LV) Stage:** An LVDC bus for EV/RES and an AC inverter for local loads.

### B. Predictive Model Formulation

For each converter, the discrete-time state-space model is derived as:

$$x(k+1) = \mathbf{A}_d x(k) + \mathbf{B}_d u(k) + \mathbf{E}_d w(k) \tag{1}$$

where $x$ represents the inductor currents and capacitor voltages, $u$ is the switching state, and $w$ represents external disturbances (grid voltage or load current).

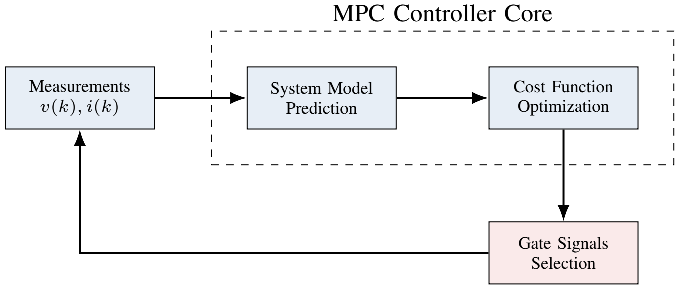

Fig. 1. Finite-Control-Set Model Predictive Control (FCS-MPC) logic for the SST.

## III. MODEL PREDICTIVE CONTROL STRATEGY

### A. Multi-Objective Cost Function

The MPC algorithm evaluates all possible switching states for the next interval. The optimal state $S_{opt}$ is chosen by minimizing:

$$J = \lambda_1 |i_{ref} - i_{grid}| + \lambda_2 |V_{bus,ref} - V_{bus}| + \lambda_3 \Delta S \tag{2}$$

where $\lambda$ represents the weighting factors, and $\Delta S$ penalizes excessive switching to reduce thermal stress on the SiC MOSFETs.

### B. Constraints Handling

MPC naturally incorporates hard constraints such as:

- **Current Limiting:** $i_{max}$ to protect the DAB transformer.
- **Voltage Ripples:** $\pm 5\%$ on the DC buses.
- **State-of-Charge (SoC):** EV battery limits.

## IV. PERFORMANCE EVALUATION

The system was tested using a 13.8 kV/480 V SST model. At $t = 0.5$ s, a 50 kW solar PV drop (cloud cover) occurs while simultaneously an 80 kW EV charging station is activated.

### A. Transient Response Comparison

As shown in Table I, the MPC-based SST maintains bus stability significantly better than the SSA-PI controller.

TABLE I
TRANSIENT PERFORMANCE METRICS

| Metric | SSA-PI Control | Proposed MPC |
|---|---|---|
| DC-link Undershoot | 8.5% | **2.1%** |
| Settling Time | 120 ms | **35 ms** |
| THD (Grid Current) | 4.2% | **1.8%** |

## V. CONCLUSION

The integration of MPC into the SST energy management framework provides a robust solution for the complexities of modern distribution grids. By predicting the impact of RES and EV transients, the controller ensures minimal voltage deviation and superior power quality. This ”Predictive Energy Internet” node is essential for the resilient operation of 2026 smart grids.

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