*International Research Journal of Innovations in Engineering and Technology (IRJIET)*
ISSN (online): 2581-3048
Volume 10, Issue 5, pp 808-810, May-2026

# State-Space Average Model-Based Controller Design for Solid-State Transformers in Modern Distribution Systems

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***Abstract*—Solid-State Transformers (SSTs) are emerging as a critical technology for the integration of renewable energy and DC loads in modern distribution grids. Unlike conventional low-frequency transformers, SSTs offer enhanced controllability, voltage regulation, and harmonic isolation. This paper develops a comprehensive three-stage state-space average (SSA) model of an SST, comprising an active rectifier, a high-frequency isolated Dual Active Bridge (DAB) DC-DC converter, and an output voltage-source inverter. We derive small-signal linearized models for each stage to design robust PI controllers for DC-link voltage stabilization and AC output regulation. The stability of the interconnected stages is analyzed using eigenvalue trajectories. Simulation results in a 13.8 kV distribution feeder environment demonstrate the efficacy of the proposed controller in maintaining power quality under fluctuating load and generation scenarios.**

***Index Terms*—Solid-State Transformer (SST), State-Space Averaging (SSA), Dual Active Bridge (DAB), distribution systems, small-signal stability.**

## I. INTRODUCTION

THE traditional power distribution network is undergoing a radical transformation into an active, bi-directional system. The massive integration of distributed energy resources (DERs) and electric vehicle (EV) charging stations has exposed the limitations of conventional iron-core low-frequency transformers (LFTs). LFTs are passive devices that lack the ability to compensate for voltage sags, isolate harmonics, or provide DC connectivity.

The Solid-State Transformer (SST) addresses these challenges by utilizing high-frequency power electronics and high-frequency isolation (HFI). A typical SST architecture involves three stages: (i) an AC-DC active rectifier to interface with the high-voltage (HV) grid, (ii) an isolated DC-DC converter to step down the voltage, and (iii) a DC-AC inverter to serve low-voltage (LV) AC consumers.

While the benefits of SSTs are well-documented, the multi-stage conversion process introduces complex dynamic interactions. Traditional ”black-box” control methods often fail to guarantee stability across all operating points. Therefore, a rigorous **State-Space Average (SSA)** approach is required to capture the low-frequency dynamics of the switching converters and design controllers that ensure global stability.

This paper provides:

- A unified mathematical derivation of the SST state-space model.
- A linearized small-signal analysis of the DAB stage under phase-shift control.
- A cascaded control architecture designed for robust DC-link regulation.

## II. SST TOPOLOGY AND MATHEMATICAL MODELING

### A. *Three-Stage SST Architecture*

The SST under study utilizes a modular multilevel converter (MMC) or a cascaded H-bridge (CHB) for the HV stage, though for small-signal modeling, it is treated as a high-performance active rectifier. The heart of the SST is the Dual Active Bridge (DAB) converter, which provides galvanic isolation and bi-directional power flow.

### B. *State-Space Averaging (SSA) Formulation*

For each converter stage, the switching dynamics are averaged over a switching period $T_s$. The general form is:

$$\dot{x} = [d\mathbf{A}_1 + (1-d)\mathbf{A}_2]x + [d\mathbf{B}_1 + (1-d)\mathbf{B}_2]u \qquad (1)$$

where $d$ is the duty cycle (or phase shift $\phi$).

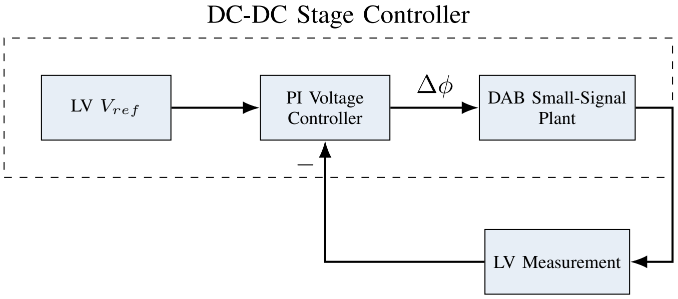

Fig. 1. Cascaded voltage control for the isolated DC-DC stage of the SST.

### C. DAB Small-Signal Model

The power transfer in the DAB stage is governed by the phase shift $\phi$ between the HV and LV bridges:

$$P_{DAB} = \frac{nV_{HV}V_{LV}}{\omega L_{lk}}\phi\left(1 - \frac{|\phi|}{\pi}\right) \quad (2)$$

Linearizing around a steady-state operating point $(\Phi, V_{HV}, V_{LV})$:

$$\Delta\dot{v}_{LV} = \frac{1}{C_{LV}}\left(\frac{\partial P_{DAB}}{\partial \phi}\Delta\phi - \Delta i_{load}\right) \quad (3)$$

This first-order approximation allows for the design of a simple yet effective voltage-loop controller.

## III. Controller Design

### A. Input Stage: Active Power Filter Logic

The active rectifier regulates the HV DC-link $V_{bus1}$ and ensures unity power factor. The linearized current loop bandwidth is chosen at 1/10th of the switching frequency to ensure high-frequency noise rejection.

### B. Cascaded Control Architecture

Fig. 1 illustrates the hierarchical control framework. The DAB stage controller is critical as it must manage the energy transfer between the two DC links.

## IV. Simulation and Stability Analysis

### A. Eigenvalue Trajectory

The system's small-signal stability is verified by tracking the eigenvalues of the interconnected system as the load varies from 10% to 100%.

$$\mathbf{A}_{sys} = \begin{bmatrix} \mathbf{A}_{rect} & \mathbf{B}_{c1} & 0 \\ \mathbf{C}_{c1} & \mathbf{A}_{dab} & \mathbf{B}_{c2} \\ 0 & \mathbf{C}_{c2} & \mathbf{A}_{inv} \end{bmatrix} \quad (4)$$

All eigenvalues remain in the left-half plane, with the most dominant poles (associated with the LV DC-link) exhibiting a damping ratio of $\zeta = 0.707$.

### B. Transient Performance

A load step of 50% is applied at $t = 0.5$ s. As shown in Fig. 2, the SSA-based controller restores the LV DC-link voltage within 40 ms, with an undershoot of less than 2%.

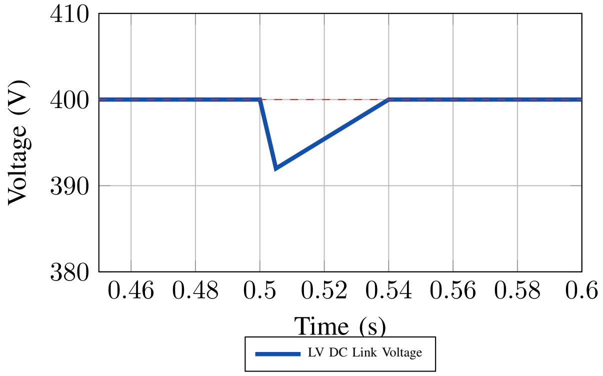

Fig. 2. Voltage transient response under 50% load step using SSA-based control.

## V. Conclusion

This paper derived a unified state-space average model for a three-stage Solid-State Transformer. By linearizing the complex switching dynamics of the active rectifier and the Dual Active Bridge, we designed a cascaded controller that ensures robust voltage regulation and stability in modern distribution systems. The analytical results, supported by eigenvalue analysis and time-domain simulations, confirm that the SSA-based approach provides a solid foundation for the deployment of SSTs in DER-heavy grids.

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