Power Quality Control for Data-center Based on QAB-SST System

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***Abstract*— As electrification accelerates across industries to reduce carbon emissions and improve efficiency, the demand for Solid-State Transformers (SSTs) is increasing. In particular, sectors such as manufacturing, data-centers, and railways require stable, high-quality power, exposing the limitations of conventional transformers. This paper proposes a Quad-Active-Bridge(QAB)-based SST system as a solution to improve AC and DC power quality and to respond to rapid load variations in data-centers. The proposed system can be directly connected to the medium-voltage grid, and simulation results verify its capability to control power quality on both sides of the SST.**

***Index Terms*—Solid-State Transformer, Quad-Active-Bridge, Date Center, Power Quality Control, MV/LV Power Converter**

I. INTRODUCTION

The increasing complexity of modern power systems and the rising demand for high-quality electrical energy have made advancements in power conversion technologies a critical priority. In particular, the rapid deployment of smart grids, the growth of electric mobility, and the expanding integration of renewable energy sources have intensified the need for more efficient, flexible, and intelligent power management solutions. Among these emerging technologies, the Solid-State Transformer (SST) has gained significant attention as a key enabler for next-generation power systems [1]–[4].

The accelerating adoption of smart grids and decentralized renewable energy sources further underscores the importance of SST technology. Unlike conventional transformers, SSTs support bidirectional power flow, real-time monitoring, and advanced voltage regulation, thereby facilitating seamless integration of distributed energy resources into the grid. As utilities increasingly transition toward intelligent grid architectures to enhance energy efficiency and demand-response capabilities, SSTs are expected to play a pivotal role in stabilizing power fluctuations and improving overall grid resilience.

These needs are particularly evident in energy-intensive infrastructures such as data-centers. Data-centers require strict voltage regulation, reactive power support, and highly reliable power delivery, while also experiencing rapid and unpredictable load variations driven by dynamic IT workloads. Addressing such characteristics requires power conversion systems capable of fast dynamic response and high-precision power-quality control. SSTs are well suited for this purpose, offering functions such as dynamic voltage regulation, power-factor correction, harmonic mitigation, and improved grid support [5]-[7]. Previous work by our research group has also demonstrated the feasibility of SST-based architectures through the development of a 1MW Quad-Active-Bridge (QAB)-based fast charging system for electric vehicles [8].

Motivated by these trends, this paper proposes a Cascaded H-Bridge (CHB) and QAB-based SST architecture designed to enhance AC and DC power quality for data-center applications. SSTs enable direct medium-to-low voltage conversion through high-frequency operation and provide several advantages, including: (a) a compact footprint through the elimination of bulky line-frequency transformers, (b) improved controllability of power quality, and (c) inherent bidirectional power-flow capability. Additionally, SST integration reduces installation complexity and improves overall conversion efficiency compared with traditional transformer-based configurations [9]-[10].

The proposed SST system adopts a cascaded configuration that integrates a CHB rectifier stage with a QAB DC/DC stage. This topology provides several benefits: (a) direct medium-voltage interconnection without additional conversion stages, (b) simultaneous power delivery to both data-center loads and an energy storage system (ESS), and (c) coordinated bidirectional power-flow management.

System validation was conducted using two approaches. First, a power conversion test was performed to verify rated power handling capability under controlled conditions. Second, performance under practical operating scenarios—such as AC-side voltage fluctuations, rapid DC-side load variations typical of data-center behavior, and harmonic mitigation on the AC grid—was evaluated. The results confirm that the proposed SST architecture maintains stable

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operation across various conditions and effectively improves AC and DC power quality for data-center applications.

II. System Structure of SST System

A. SST System

The proposed SST system illustrated in Figure 1 is directly connected to a three-phase MV grid without any intermediate transformer stage. Five SST submodules are connected in series per phase, resulting in a total of 15 submodules. Each SST submodule consists of a CHB converter for AC/DC conversion and a QAB converter for DC/DC power transfer. This configuration enables direct interfacing with MV-level AC input while simultaneously supporting high-power delivery on the low-voltage DC side. On the DC side, the system includes two independent channels: one dedicated to supplying power to data-center loads and the other interfacing with an ESS for bidirectional charging and discharging. Through this bidirectional interaction among the grid, ESS, and data-center load, the system achieves a high degree of operational flexibility and can actively respond to variations in grid conditions and load demands.

To ensure robust control and protection, the proposed system incorporates a high-speed EtherCAT communication protocol operating at 100 Mbps. EtherCAT communication reliability is enhanced through the adoption of a redundant ring topology. Key advantages of this communication structure include:

(a) minimal control latency consistent with the system control bandwidth,

(b) reliable data exchange among converter submodules,

(c) improved protection coordination, and

(d) precise synchronization between submodules.

The integrated control architecture enables seamless power-flow management among the grid, data-center loads, and ESS while maintaining optimal system performance. Typically, modular SST systems incorporate approximately 10% redundant submodules to ensure continuous operation even under abnormal submodule conditions. However, the current prototype does not include such redundancy, and the implementation of redundant submodules is planned for future work.

The system specifications are summarized in Table I. The converter operates at a rated power of 1 MW with a three-phase 22.9-kV AC input at 60 Hz in a wye configuration. To enable direct connection to the MV grid, the system is designed to satisfy insulation requirements equivalent to 24-kV class operation. The DC output consists of an 800 Vdc (±2%) channel for data-center load supply and a 1,100 Vdc (±10%) channel for the ESS. The 800 Vdc output level reflects voltage levels commonly adopted in modern data-center DC architectures, while the higher ESS-side voltage provides sufficient margin for bidirectional charging and discharging, particularly during transient operating conditions such as voltage sag and rapid load variations.

The efficiency reported in Table I corresponds to the power-conversion efficiency of an individual SST submodule, which is approximately 97% under rated operating conditions. While conventional line-frequency transformers typically achieve efficiencies exceeding 99%, the overall efficiency of an SST system is inherently lower due to the use of multiple power-electronic conversion stages. However, unlike conventional transformers, the proposed SST integrates additional functionalities—including harmonic mitigation, reactive power compensation, voltage regulation, bidirectional power flow, and DC distribution—within a single platform. In traditional data-center power architectures, these functions are often implemented using separate equipment such as STATCOMs, active harmonic filters, rectifiers, and UPS systems, each introducing additional losses. From a system-level perspective, the functional integration enabled by the SST can reduce the total number of conversion stages and auxiliary devices, thereby improving effective energy utilization and operational flexibility.

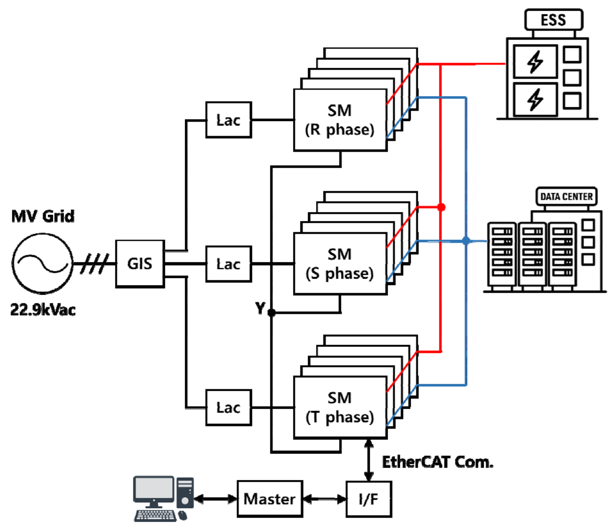

Figure 1 System Configuration of SST System

Table 1 Specification of SST System

Parameter	Unit	Values
Rated Power	MW	1
Phase	-	3Phase
Input Type	-	Wye
Input Voltage	kVac	22.9
Frequency	Hz	60
Data-center Load	Vdc	800(±2%)
ESS Voltage	Vdc	1,100(±10%)
Multi-channel	-	5
Cooling Type	-	Liquid Cooling
SM Efficiency	%	97

B. Submodule Structure

Fig. 2 illustrates the topology of the submodule. On the AC side, the submodule employs a full-bridge structure, enabling efficient AC–DC conversion. On the DC side, the QAB converter connects two bridges in series on the high-voltage port to effectively handle elevated voltage levels. The remaining two bridges of the QAB converter serve as dedicated ports for the data-center and the ESS. This

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configuration reduces voltage stress on the DC-side switching devices while allowing simultaneous connection of the data-center load and the ESS. The integrated design enhances overall system performance and reliability, providing a robust solution for modern data-center applications.

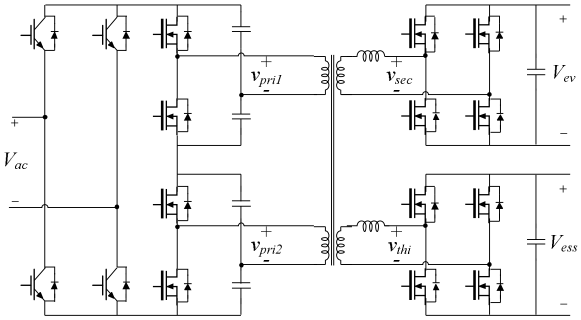

Figure 2 Topology of QAB based SST Submodule

III. Simulation

Modern power systems are increasingly exposed to power-quality disturbances driven by the high penetration of renewable energy resources, the widespread use of power-electronic-based loads, and the growing presence of weak-grid conditions. These factors frequently lead to voltage fluctuations, harmonic distortion, and reactive-power imbalance at the MV distribution level. When such disturbances propagate into data-center facilities, they can induce abnormal behavior in server power-supply units (PSUs), trigger protective actions in UPS rectifiers, degrade cooling-system stability, and ultimately reduce the operational reliability of the entire facility. To mitigate these issues, power-conversion systems interfacing data-centers with the MV grid must provide reactive-power compensation, harmonic suppression, and voltage-regulation capabilities.

In addition to external disturbances, data-centers themselves exhibit highly dynamic load characteristics due to abrupt variations in IT workloads. Rapid changes in compute demand cause sudden load steps at the facility level, resulting in transient voltage deviations, increased current stress on front-end rectifiers, and reduced power-quality margins within the internal distribution network. Consequently, the power-conversion equipment connected to data-centers must also deliver fast dynamic response, stable transient performance, and the ability to maintain voltage and current quality during rapid changes in load conditions.

To address these needs, this paper evaluates whether the proposed QAB-based SST system can satisfy the aforementioned functional requirements through a set of targeted simulation scenarios. The verification focuses on five representative conditions:

(a) voltage fluctuation originating from the MV grid,

(b) harmonic compensation capability under distorted supply conditions,

(c) response to sudden load changes at the data-center side,

(d) the combined case of voltage fluctuation and dynamic load variation, and

(e) severe voltage sag events.

These scenarios collectively demonstrate the SST system's ability to regulate voltage, provide reactive-power support, mitigate harmonics, and sustain stable operation under rapid load transitions—thereby confirming its suitability for data-center applications.

A. *Voltage Fluctuation*

To evaluate the SST system's capability to regulate voltage and provide reactive-power support under grid disturbances, an AC-side voltage fluctuation scenario was considered. In this test, the grid voltage at the AC input was varied from 0.9 pu to 1.1 pu in increments of 0.05 pu, representing typical fluctuations that may occur in medium-voltage distribution networks with high penetration of renewable energy sources or weak-grid conditions.

When the AC voltage deviates from its nominal value, the SST responds by injecting or absorbing reactive power to stabilize the voltage at the Point of Common Coupling (PCC). The reactive-power reference is generated according to a predefined Q–V droop characteristic, enabling smooth and autonomous regulation without the need for external control coordination.

The simulation results shown in the Figure 3 demonstrate that the SST accurately follows the droop curve and provides the required amount of reactive power as the grid voltage changes. As the AC voltage decreases toward 0.9 pu, the SST supplies positive reactive power to support the PCC voltage. Conversely, when the voltage increases above nominal toward 1.1 pu, the SST absorbs reactive power to suppress voltage rise. These results confirm that the proposed SST system effectively mitigates voltage fluctuations and maintains stable PCC voltage levels under varying grid conditions.

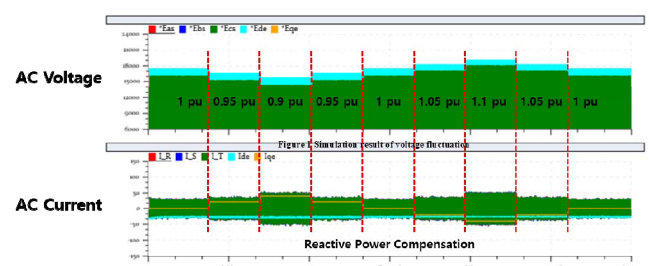

Figure 3 Simulation result of voltage fluctuation

B. *Harmonic Compensation*

To evaluate the harmonic mitigation capability of the proposed SST system, a harmonic-distorted grid condition was simulated. In this scenario, the AC-side grid voltage was intentionally injected with 10% 5th-harmonic and 7% 7th-harmonic components to emulate typical harmonic distortion found in modern power systems with extensive nonlinear and power-electronic loads.

The harmonic compensation controller was then activated to assess its effectiveness in suppressing these distortions. The

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objective of this test was to confirm that the SST can actively cancel harmonic components from the grid current, thereby improving overall power quality at the point of common coupling (PCC).

The simulation results presented in Figure 4 show that, prior to harmonic control activation, the AC-side current contains significant 5th- and 7th-order harmonic components corresponding to the injected distortion. Once the harmonic compensation function is enabled, these harmonic components are substantially reduced, and the AC current waveform transitions to a nearly sinusoidal profile. This demonstrates that the proposed SST system effectively removes harmonic distortion and enhances power quality under distorted grid conditions.

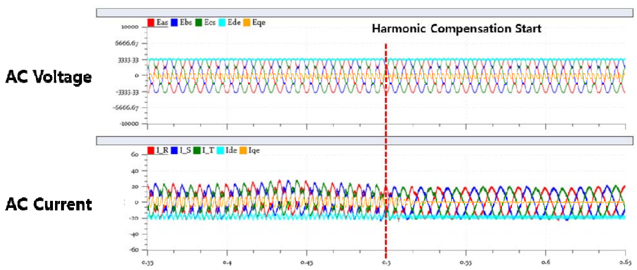

Figure 4 Simulation result of harmonic compensation

C. *Sudden Load Change*

To evaluate the dynamic response of the proposed SST system to the rapid load variations commonly observed in data-center operation, a DC-side sudden load change scenario was analyzed. Data-centers frequently experience abrupt increases in computational demand, resulting in steep power consumption spikes at the DC distribution level. To emulate this behavior, a 0.5 pu load step—transitioning from 0.3 pu to 0.8 pu (or from 0.8 pu to 0.3 pu)—was applied with a frequency of 0.7 Hz over a duration of 40 seconds. The selected frequency was chosen to impose sufficiently frequent load transitions to stress the dynamic performance of the SST under repetitive operating conditions.

This scenario was designed to assess the impact of rapid load transitions on both the AC-side grid interface and the DC-side output ports of the SST. Stability was evaluated in terms of DC output voltage regulation, AC-side current response, and the absence of sustained oscillations following each load transition. For maintaining stable operation of servers, cooling systems, and front-end power-electronic equipment within the data-center, it is essential that the SST preserve stable voltage and current profiles even under such transient conditions.

As shown in Figure 5, the simulation results confirm that the SST responds rapidly to the abrupt DC load variations. Despite the fast 0.5 pu step changes, both AC and DC sources remain stable, exhibiting only minimal deviations in voltage and current. In addition, the DC-side load transients are effectively decoupled from the AC grid, preventing the propagation of sudden power fluctuations to the upstream grid. These results demonstrate that the proposed SST system provides robust dynamic performance and maintains power-quality stability during the rapid load variations typical of modern data-center environments.

Figure 5 Simulation result of sudden load change

D. *Voltage Fluctuation + Sudden Load Change*

In practical data-center operation, voltage fluctuations originating from the AC grid and rapid variations in data-center load demand may occur simultaneously. To evaluate the SST system's capability to handle such combined disturbances, a simulation scenario was constructed in which AC-side voltage fluctuations and DC-side sudden load changes occur concurrently.

In this test, the grid voltage was varied according to the same conditions used in Section A, while a rapid 0.5 pu load step identical to the scenario in Section C was applied on the DC side. Under these conditions, the SST is required to simultaneously provide reactive-power compensation to mitigate grid-voltage deviations and deliver an active-power response to accommodate abrupt changes in DC load demand. This combined scenario represents a more stringent operating condition than individual disturbance tests, as it directly evaluates the coordination capability of the SST control system.

The simulation results presented in Figure 6 confirm that the SST successfully coordinates both control actions. As the AC-side voltage deviates from nominal, the SST injects or absorbs reactive power according to the predefined droop characteristic, while maintaining a stable active-power response to the DC-side load transition. No adverse interaction between the voltage-regulation function and the load-following operation is observed. These results demonstrate that the proposed SST system can handle overlapping grid disturbances and load transients while preserving stable operation and power-quality performance.

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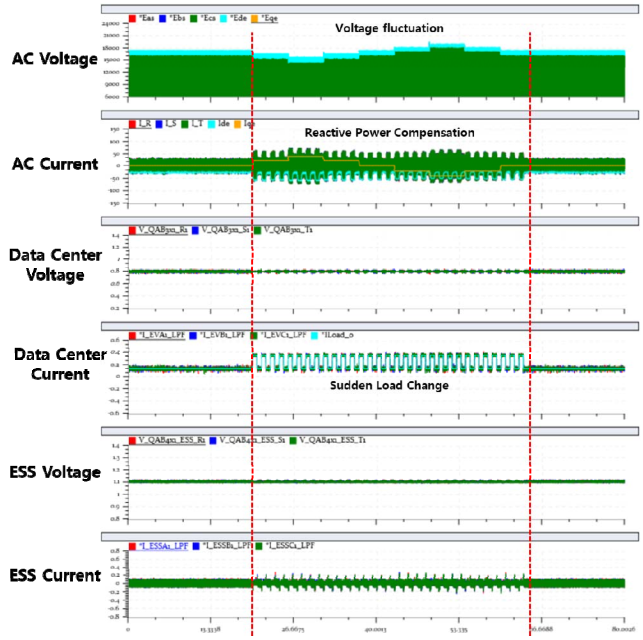

Figure 6 Simulation result of voltage fluctuation and sudden load change

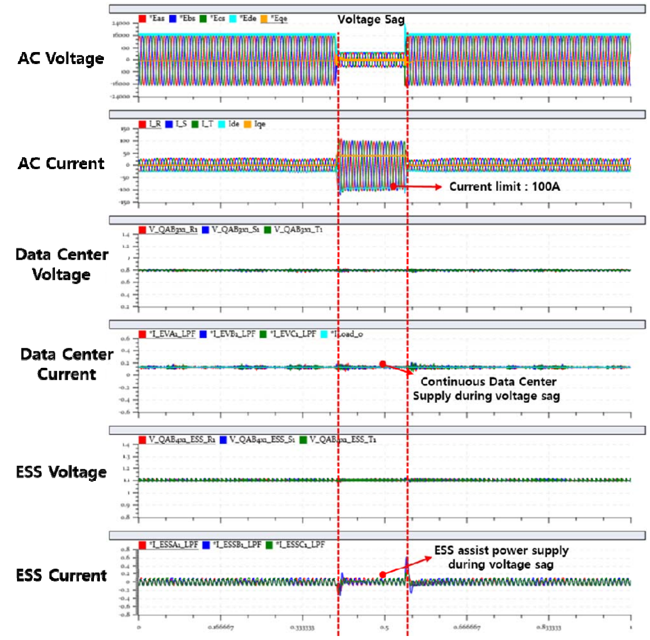

Figure 7 Simulation result of voltage sag

E. Voltage Sag

To evaluate the fault-ride-through capability of the proposed SST system under severe grid disturbances, a voltage sag scenario was examined. When a voltage sag occurs on the AC grid, the magnitude of the grid voltage drops sharply, substantially limiting the amount of active power that can be delivered from the grid to the downstream loads. Under such conditions, the SST must utilize energy from the ESS to support uninterrupted power supply to the data-center load and maintain stable operation.

In this simulation, the AC grid voltage was intentionally reduced to 0.3 pu for a duration of 140 ms, representing a severe sag condition. As shown in Figure 7, when the sag occurs, the SST increases its AC side current output up to the permissible limit in an attempt to deliver as much power as the reduced grid voltage allows. However, the available grid power becomes insufficient to support the data-center demand due to the deep voltage depression. The SST therefore activates ESS support, drawing additional energy from the ESS to compensate for the power deficit.

The simulation results demonstrate that, despite the grid-side voltage collapsing to 0.3 pu, the combined operation of the SST and ESS maintains a stable and continuous power supply to the data-center load with no interruption. This confirms that the proposed SST system provides effective sag-ride-through capability and ensures operational continuity for critical data-center facilities during severe grid voltage disturbances.

IV. Conclusion

In this paper, a QAB–based SST system for data-center applications was proposed and its capability to effectively respond to grid-voltage variations and rapid load fluctuations was validated. The proposed system employs an input serial output-parallel (ISOP) structure, enabling direct connection to medium-voltage grids. This architecture enhances power-conversion efficiency, reduces the overall installation footprint, and significantly improves power density. By integrating the grid, ESS, and data-center load, the SST provides a unified platform for comprehensive power-quality regulation and bidirectional energy-flow management, making it well suited for modern energy-intensive facilities requiring high efficiency, high reliability, and high-quality power. A primary contribution of this work is the demonstration of the SST's capability to deliver reactive-power support and maintain robust dynamic performance under abrupt load changes, confirming its suitability for future data-center applications.

Hyosung is currently establishing a test environment for the validation of MW-class SST systems (Figure 8) and developing a high-capacity SST solution using 300-kW submodules to meet the large-scale load requirements of next-generation data-centers. Furthermore, the system is being designed to achieve 36-kV insulation capability to enable direct interfacing with 34.5-kV MV grids. Once fully developed, such SST technologies are expected to play a pivotal role in advancing the compactness, intelligence, and resiliency of future power-conversion systems—contributing significantly to the digitalization, electrification, and carbon-neutral transformation of the power industry.

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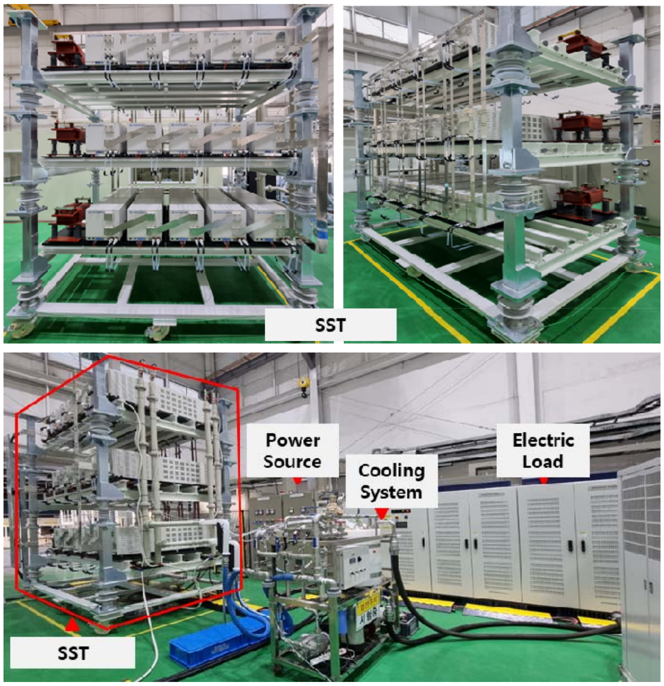

Figure 8 Construction of MW-Class Test Facility

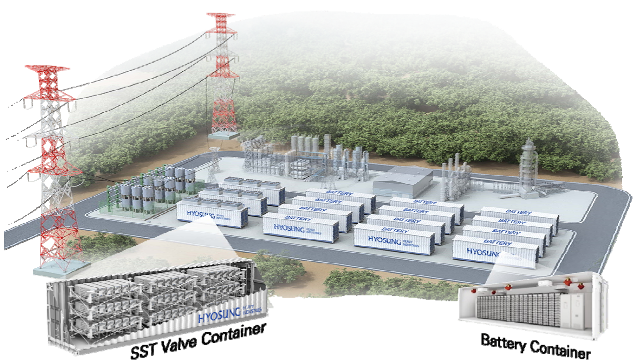

Figure 9 Conceptual Overview of Future SST System

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