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Centralized Load Shedding and Restoration for Future Sustainable Power Systems

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ABSTRACT

The evolving modern power systems are integrating increased number of renewable energy sources, these introduced challenges related to frequency stability and system inertia. Traditional underfrequency load shedding schemes which rely on fixed thresholds and decentralized relays, are becoming insufficient in addressing the rapid dynamics of modern smart grids. This thesis investigates the implementation of a centralized Load Shedding and Restoration strategy utilizing the ABB SSC600. Which is an intelligent IED compatible with IEC 61850 and has the possibility to carry out protection and control up to 30 feeders within a medium voltage substation environment.

The study involves the design, configuration and testing of LS&R logic using ABB's PCM600 engineering tool. Two primary scenarios are evaluated under the thesis, a frequency only disturbance caused by a drop in RES generation, and secondly combined frequency and Rate of Change of Frequency event under low-inertia conditions. A five step load shedding strategy is implemented and validated. The results demonstrate that the SSC600 provides accurate and quicker response times. By effectively prioritizing of loads and smooth staged restoration once frequency stability is established.

Furthermore, the thesis proposes recommendations on how the existing load shedding and restoration functionality can be enhanced to be best suited for the future power grids. These adaptive enhancements including ROCOF threshold adjustments based on system inertia, voltage stability margin monitoring, and the integration of smart loads for flexible response. A comparative analysis against traditional distributed protection systems highlights the operational, technical, and economic advantages of the SSC600's centralized architecture. The findings confirm that the SSC600 is a robust and scalable solution for futureproof power systems, particularly in grids with high renewable penetration and the need for intelligent, coordinated protection.

This thesis was conducted in collaboration with ABB and includes a business case evaluating the deployment of SSC600 in real-world substations. The analysis highlights benefit such as reduced hardware complexity, lower capital and operational costs, and improved scalability compared to traditional protection schemes. With the possibility of integrating multiple protection and control functions into a single intelligent unit, SSC600 offers both technical and long term economic advantages, supporting efficient modernization of substations aligned with smart grid and renewable integration goals.

KEYWORDS: Load Shedding, Restoration, ABB SSC600, Renewable Energy Integration, Smart Grids, Frequency Stability, ROCOF, Centralized Protection.

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Abbreviations

ABB	Asea Brown Boveri (ABB Group, manufacturer of SSC600 and PCM600)
AC	Alternating Current
AI	Artificial Intelligence
AND	Logical AND (used in function block logic)
ARM	Alarm Relay Module
BESS	Battery Energy Storage System
CPU	Central Processing Unit
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DFT	Discrete Fourier Transform
FBD	Function Block Diagram
FMMXU	Frequency Measurement Logical Node (IEC 61850)
GOOSE	Generic Object-Oriented Substation Event (IEC 61850 message)
GPS	Global Positioning System
HMI	Human-Machine Interface
HSR	High-availability Seamless Redundancy
Hz	Hertz (unit of frequency)
IED	Intelligent Electronic Device
IEC	International Electrotechnical Commission
IRIG-B	Inter-Range Instrumentation Group time code B
LED	Light-Emitting Diode (indicator)
LS&R	Load Shedding and Restoration
MU	Merging Unit
MMS	Manufacturing Message Specification (IEC 61850 client/server communication)
PCM600	Protection and Control Manager 600 (ABB’s configuration software)
PMU	Phasor Measurement Unit
PRP	Parallel Redundancy Protocol
PTOC	Protection Time Overcurrent Function Block
RES	Renewable Energy Source

REX615	ABB Feeder Protection Relay
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SMV	Sampled Measured Value
SSC600	Smart Substation Control and Protection Device by ABB
SV	Sampled Values (IEC 61850-9-2)
TON	Timer ON Delay Function Block
UFLS	Underfrequency Load Shedding
WHMI	Web-based Human-Machine Interface
XCBR	IEC 61850 Logical Node for Circuit Breaker

1 Introduction

The global energy sector is experiencing a significant transformation driven by the demands of increasing energy consumption due to new technologies and the requirement for sustainability. The integration of Renewable Energy Sources (RES) is becoming more and more important where at the center of this transition is smart grid technology with renewable energy sources, including most common solar and wind power and other developing RES technologies. These technologies seek to improve grid flexibility, optimize energy use, reduce operational expenses, and enable consumers increased interaction and energy availability. Integrating energy storage systems with renewable energy sources has created novel possibilities for a more efficient, sustainable, and reliable energy future.

1.1 Centralized Protection and Load Shedding

To ensure the safety and reliability of electrical networks, protection systems deploy various devices such as relays and circuit breakers to detect and isolate faults. Centralized protection methods in protection engineering present an integrated strategy by combining control functions into an individual intelligent unit. This centralized system oversees the entire network, identifies anomalies, and manages protective measures with enhanced speed and precision relative to conventional, distributed approaches.

The ABB SSC600 provides significant advancements in protection and control. A centralized protection and control unit capable of controlling multiple IEDs, SSC600 integrates real-time monitoring, fault detection, and easy visualizing capabilities into a single device. By replacing the need for multiple individual protection relays, SSC600 simplifies substation architecture, enhances reliability, reduces hardware requirements, and supports streamlined grid automation through IEC 61850-compliant communication.

In the context of modern power systems characterized by high RES penetration and dynamic demand profiles, the role of centralized protection combined with intelligent load shedding and restoration (LS&R) strategies is critical. These strategies enable the controlled disconnection of non-essential loads during disturbances, preventing overloads and aiding the swift restoration of services. When integrated into centralized systems like SSC600, LS&R substantially enhance system resilience, improve infrastructure reliability, and maximize the use of renewable resources. In addition, intelligent load shedding is crucial for maintaining grid stability despite unpredictable or rapidly fluctuating operational conditions.

With RES often introducing variability and intermittency into power systems, intelligent LS&R mechanisms can preemptively shed selected loads to avoid cascading failures. When supported by centralized protection and control units, such as SSC600, these actions can be automated based on real-time data, thus ensuring a stable and balanced power system. This approach also allows optimal use of auxiliary assets like battery energy storage systems (BESS), addressing common challenges associated with RES integration such as voltage fluctuations and unpredictable generation output.

1.2 Research Problems

Smart grids' use of renewable energy sources adds new operational complexity because of its naturally unpredictable and intermittent character. In systems where reliability and responsiveness are essential traditional grid management solutions sometimes poorly address the challenges posed by such fluctuations. In this context, intelligent load shedding managed through centralized protection systems is necessary to ensure uninterrupted and stable power supply.

Centralized protection platforms, such as ABB's SSC600, are particularly well-suited to address these challenges on load shedding and restoration. Through functions such as underfrequency and Rate of Change of Frequency (ROCOF) detection, SSC600 enables rapid and adaptive load shedding responses. However, the seamless integration of such systems into smart grids presents several technical challenges, including issues of interoperability, communication latency, and compatibility with dynamic RES outputs.

This thesis investigates the implementation of ABB SSC600 in smart load shedding and restoration applications. The objective is to assess how the device enhances protection coordination, grid stability, and operational efficiency in environments characterized by high RES penetration. Emphasis is placed on how predictive analytics, real-time data acquisition, and adaptive control thresholds can contribute to improved load shedding framework.

Open communication protocols, such as IEC 61850, improved cybersecurity measures are necessary to ensure the secure and seamless operation of SSC600 within modern smart grid environments. The device's visualization features which offer advance graphical displays of grid conditions, faults and protection functions. Further support operators in identifying the fault conditions, behaviors during fault and to make informed decisions during disturbances. These Human Machine interfaces (HMI) have the capability to access via onsite and remote locations providing the possibility to modify and update using tools such as ABB's PCM600.

By investigating these questions through simulation, functional logic design, and case analysis, this thesis aims to develop and recommend a more intelligent, responsive, and futuristic approach to load shedding and restoration using centralized digital protection systems.

1.3 Objective

To analyze the operational functionality of the ABB SSC600 default underfrequency and ROCOF based load shedding logic (LSHDPFRQ) within a medium voltage substation environment.

Analyze and investigate the capabilities of SSC600 load shedding, communication and visualization techniques

To identify limitations in current SSC600 load shedding schemes and to propose adaptive enhancements to SSC600 protection

To assess the operational benefits through a business case for implementing centralized load shedding using SSC600 in smart grid environments, with respect to grid stability, cost efficiency, and integration readiness for RES.

2 Literature Review

2.1 Load Shedding and Restoration in Smart Grid

Load shedding and restoration are pivotal operations in ensuring the stability and reliability of modern power systems, particularly in smart grids. As the complexity of power networks increases with the integration of renewable energy sources, distributed generation, and more dynamic demand patterns, traditional methods of grid management have proven insufficient. Smart grids that are inclusive of advanced communication, real-time monitoring, and automation can provide more possibilities to implement new methods of load shedding and restoration strategies improving operational efficiency and reliability.

2.1.1 Load Shedding in Smart Grids

Load shedding is defined as the intentional, controlled disconnection of electrical loads during conditions where supply cannot meet demand or when system stability is threatened. In traditional power grids, load shedding was typically performed based on fixed thresholds for frequency or voltage. Smart grids can leverage real time data acquisition from intelligent control mechanisms to make dynamic and precise load-shedding decisions. The incorporation of technologies such as sensors, smart meters, Phasor Measurement Unit (PMU) and communication strategies allows for continuous monitoring of the grid, enabling faster detection of imbalances and disturbances (Phadke, 2008). These systems independently initiate load-shedding measures in response to real-time situations, including underfrequency incidents or rapid rate of change of frequency (ROCOF), thereby decreasing the response time to grid imbalances and mitigating the risk of cascade failures.

A critical aspect of load shedding in smart grids is the ability to prioritize loads based on their criticality. Essential services such as hospitals, emergency services, and communication systems must remain powered during grid disturbances. Therefore, modern smart grids implement prioritization schemes that ensure non-essential loads are shed first, while vital infrastructure continues to receive power. This approach reduces impacts on critical loads and provides continuous power to essential areas and services. And load shedding helps preserve public safety during emergencies (Lobos & Rezmer, J., 2005). Furthermore, intelligent systems can predict and prevent grid instability by analyzing both historical and real-time data. Systems integrated with intelligent LS&R mechanisms can become proactive for load shedding by forecasting future disturbances and it will reduce the likelihood of significant failures. (Xu & Liu, 2011).

2.1.2 Restoration in Smart Grids

Restoration refers to the process of re-energizing the loads that were disconnected during a load-shedding event. Once system stability is restored typically through the reestablishment of sufficient generation capacity or the resolution of faults loads are gradually brought back online. However, this process must be managed carefully to avoid reintroducing instability. Reconnecting too many loads at once can cause further frequency or voltage fluctuations, potentially triggering additional load shedding. Therefore, restoration in smart grids is typically performed in phases, with critical loads being restored first, followed by non-essential loads as the system continues to stabilize (Xu & Liu, 2011).

Automated control systems are crucial to this process, as they ensure that the restoration sequence is both systematic and optimized for stability. These systems can dynamically adjust the restoration strategy based on the current state of the grid, considering factors such as grid health, the load demand, and the available generation (Kezunovic, Meliopoulos, & Madani, 2004). Moreover, restoration decisions are made with real-time data inputs, allowing for adaptive strategies that respond to the evolving grid conditions and help prevent further disruptions.

2.1.3 Predictive and Adaptive Strategies for Load Shedding and Restoration

A significant improvement in LS&R in smart grids is the implementation of predictive and adaptive techniques. Predictive techniques will use historical and real-time data to predict possible disruptions in the grid such as underfrequency occurrences due to faults and changes in generation and start preemptive measures. This method provides the possibility to initiate load shedding before system instability becomes critical, thus mitigating the risk of large-scale outages and even complete system backouts. On the other hand, adaptive control systems can adjust operational thresholds dynamically responding to the changing conditions of the grid conditions and generation making it perfect for integrating RES. These systems optimize both LS&R strategies based on variables, such as frequency, voltage, load demand, and power generation availability (Kezunovic et al., 2004).

The integration of these advanced strategies enables smart grids to become more resilient to disturbances, improving both their reliability and ability to recover quickly from faults. By implementing predictive forecasting and adaptive control smart grids can enhance load shedding and restoration efficiency to maintain power supply stability even in adverse situations.

2.1.4 Load shedding strategies

Load shedding is a critical strategy employed in power systems to maintain stability and prevent total system collapse during periods of imbalance between electricity supply and demand. As power systems grow more complex with the integration of renewable energy sources, electric vehicles, and dynamic loads, the need for efficient, automated, and intelligent load shedding strategies has intensified. The literature reveals a wide range of approaches developed to optimize load shedding, including frequency-based, priority-based, event-driven, and predictive strategies.

Early load shedding methods were primarily frequency-based, relying on underfrequency relays to trigger disconnection of loads when system frequency dropped below a certain threshold. These traditional schemes are simple and widely adopted but lack adaptability to modern grid dynamics (Phadke & Thorp, 2008). Static threshold used in LS&R can either overreact or respond too late, especially in systems with high penetration of renewables due to the intermittent nature of generation.

To address these limitations, priority based load shedding strategies were developed. These methods assign priority levels to different loads, ensuring that critical loads are maintained while noncritical ones are shed first. Priority based schemes have been shown to reduce the social and economic impacts of load shedding events by preserving essential services (Elmitwally & Alolah, 2008).

Another approach is event driven load shedding, proposed by Xu and Liu (2011) showcase a more advanced and flexible strategy. Load shedding will be based on real-time system events rather than static thresholds. Their model monitors network parameters and executes load shedding only when specific stability criteria are breached. This approach improves grid resilience and reduces unnecessary interruptions maintaining the optimal power availability and balance between generation and consumption.

More recent advancements incorporate predictive and adaptive load shedding strategies. Predictive models use historical data and real-time inputs to forecast potential grid instability, enabling pre-emptive actions before conditions become critical. For example, machine learning techniques and time-series analysis are now being used to anticipate underfrequency or overload conditions and proactively shed loads in a more optimized fashion (Kundur et al., 2010).

Adaptive strategies adjust load shedding thresholds dynamically based on the current state of the grid. These strategies have become increasingly important with the integration of variable renewable energy sources, which introduce higher uncertainty in generation. Adaptive ROCOF based methods have shown promising results in detecting fast disturbances and improving the responsiveness of protection systems (Rudner et al., 2017).

Moreover, distributed and hierarchical load shedding frameworks have been introduced to improve scalability and coordination. In such systems, local controllers shed loads based on local measurements, while a central coordinator oversees global system stability. This decentralized approach improves fault tolerance and scalability, especially in large and complex grids (Moeini-Aghtaie et al., 2013).

Literature clearly demonstrates a shift from static, threshold-based schemes to intelligent, data driven strategies. When integrated of real-time monitoring, communication technologies, and advanced analytics to the system it enabled more accurate, and responsive load shedding mechanisms. These developments are crucial for ensuring the reliability of future power systems that must operate under increasing uncertainty and complexity.

2.1.4 Load restoration strategies

Load restoration is a crucial function in power system operation like the Load shedding. recovering the electrical service to consumers following a partial or complete load shedding. The process is generally complex due to the need to balance system stability and operational priorities while gradually re-energizing the grid. As the architecture of modern power systems evolves toward smart grids characterized by the integration of renewable energy sources, advanced communication technologies, and distributed generation restoration strategies have become more sophisticated.

Traditionally, load restoration was guided by operator experience and static preset values generally was the main cause of delayed recovery and potential overloading during the re-energization process. However, modern power systems use more dynamic and automated methodologies. Priority-based restoration is one of the basic strategies that are used. Where loads are restored in a hierarchical sequence based on criticality. Essential services such as hospitals, water treatment facilities, and communication infrastructure. (Zhu et al., 2013).

A significant advancement in restoration methodology is the use of optimization algorithms to determine the best sequence and timing for reconnecting loads. Many researchers provide solutions and techniques such as mixed integer programming, particle swarm optimization and genetic algorithms to address the complexities of load restoration planning (Ding et al., 2014). These models consider various limitations including generator availability, load priorities, network topology, and voltage or frequency limits.

In the context of smart grids, model predictive control (MPC) has emerged as an effective framework for real-time decision-making during restoration. MPC-based strategies use a predictive model of the grid to anticipate future states and compute control actions that can steer the system toward a stable operating point while gradually restoring load (Nguyen & Flueck, 2010). The adaptability of MPC facilitates responsive management in uncertain situations, especially in the presence of renewable energy generation.

Decentralized and multi-agent systems (MAS) have also gained attention for their application in load restoration. In MAS based restoration platforms operate autonomously in different parts of the grid communicating locally and cooperate to achieve system wide goals. This methodology improves the flexibility and fault tolerance of restoration processes, particularly in distribution networks. (Ghosh et al., 2014).

Fast load restoration using phasor measurement units (PMUs) and real-time wide-area monitoring has also been explored. Phadke and Thorp (2008) highlight the role of synchrophasor in enabling fast detection of system conditions, supporting rapid restoration decisions based on accurate, time-synchronized data. PMU Based measurement techniques reduce the use of manual decision making and improve the reliability of the restoration process.

Integrating RES and BESS for restoration planning provide both opportunities as well as many challenges. While these resources can support localized restoration and reduce dependency on central generation. Their variability requires adaptive control strategies and reliable forecasting technologies (Fang et al., 2012). Effective restoration requires proper coordination between distributed resources and central control systems.

The literature thus reveals a transition from manual, rule-based approaches to automated, intelligent, and optimization driven restoration strategies. The addition of real-time monitoring, adaptive algorithms, and decentralized coordination indicates the continuous advancement of restoration methodologies in line with the smart grid structure.

2.1.5 Load Shedding and Restoration with Renewable Energy Sources

The increasing integration of RES such as solar photovoltaic (PV) and wind power into modern electrical grids has introduced many challenges in managing grid stability and reliability. LS& R usually needs to be re-evaluated regarding RES because of its intermittent nature greatly complicating real-time power system operations and energy availability.

Wind and solar output are highly dependent on weather conditions and are inherently less predictable than conventional energy sources. Rapid frequency changes caused by this instability indicate rapid and adaptable load shedding actions to prevent cascading failures. In systems with high RES integration, traditional underfrequency load shedding (UFLS) depending on preset criteria may be insufficient or badly coordinated (Huang et al., 2014).

To address these issues, adaptive and ROCOF-based load shedding methods have gained prominence. These approaches utilize real-time data to adjust shedding thresholds based on system inertia, frequency trends, and RES output variability. For example, Rudner, Chatzivasileiadis, and Andersson (2017) proposed a ROCOF-based UFLS strategy that dynamically adapts to wind power variability, improving the responsiveness and selectivity of load shedding in high-RES grids.

In addition to grid wide load shedding strategies, distributed energy resources (DERs) including rooftop solar and community scale wind or storage systems have enabled localized responses to grid instability. Decentralized or islanded load shedding where local microgrids shed load independently based on local frequency or voltage deviations has become a feasible strategy with advanced inverters and grid-forming controls (Lasseter, 2011). These methods contribute to faster stabilization and reduce reliance on centralized coordination, especially in distribution networks with high RES penetration.

The role of RES in load restoration is also evolving. While conventional restoration strategies relied on thermal plants and synchronous generators for grid re-energization, RES systems particularly when combined with battery energy storage systems (BESS) can support black start capabilities and phased restoration in microgrids and remote areas (Oudalov et al., 2009). The main challenge is the lack of inertia in RES, which complicates synchronization and voltage control during restoration process. During past years, much research indicates that coordinated use of RES and storage, combined with smart inverters, can facilitate stable and timely reconnection of loads after an outage or load shedding (Bayati et al., 2020).

Forecasting and predictive control techniques have been integrated into modern restoration strategies to better manage increased RES in energy generation. By combining weather forecasting with grid state estimation, operators can plan restoration sequences that avoid instability due to sudden changes in RES power output. The most used frameworks are model predictive control (MPC) and multi-agent systems which provide flexibility and adaptability for load restoration. (Rohden et al., 2016).

The integration of RES is an essential shift from traditional energy generation techniques. Adaptive and centralized load shedding and restoration strategies which ensure compatibility with RES require the incorporation of advanced forecasting, control algorithms, and communication infrastructure capable of responding to the dynamic behavior of RES. Identified research and techniques provide proven and new techniques to be utilized.

2.2 ABB SSC600

The current power system is moving towards digitalization incorporating flexible, reliable, and efficient substation automation solutions for P&C. ABB's SSC600 Centralized Protection and Control (CPC) device significantly advances this direction. SSC600 has the power to combine protection, control, monitoring, and communication functionalities into a single centralized unit. Replacing the traditional approach of using multiple individual protection relays at each bay. This change in P&C system architecture supports a more streamlined and cost effective substation design while enhancing operational performance and adaptability.

Engineered to fit IEC 61850 requirements, the SSC600 guarantees compatibility and simple interaction with other IEDs in the substation. Standardization facilitates straightforward system integration, quick communication, and interoperability. The gadget has a modular software architecture that lets users choose and change functionalities depending on changing system requirements. This futureproof design allows utilities to change and update the functionality without equipment replacement or system redesign. Its implementation of web based HMI is capable of supporting operators in efficiently controlling and managing the system by optimizing access to data, diagnostics, and configuration.

Studies and practical deployments have demonstrated the effectiveness of SSC600 in managing a wide range of substation applications, including feeder, transformer, motor, and busbar protection. In pilot projects, such as those conducted in Finland, SSC600 has proven its ability to handle real-time fault detection and clearing, including short circuits and earth faults. These demonstrations have confirmed its reliability, precision, and readiness for real-world implementation in medium voltage networks. The centralized approach also allows for reduced engineering time, easier maintenance, and lower total cost of ownership due to fewer physical devices and hard wiring. (ABB, 2021)

A key concern with the SSC600 system is that it relies on a single device for centralized protection, which means if it fails, the entire protection setup could be at risk. To reduce this vulnerability, it's important to design redundancy into the system either by pairing SSC600 with a backup unit or integrating it as part of a hybrid protection scheme. As more substations move toward digital operations, cybersecurity also becomes increasingly important. Since the SSC600 plays a central role and connects with various communication interfaces, it needs to be well protected against potential cyber threats that could disrupt grid operations.

To follow the digitalization in the energy sector, ABB has developed a software-based version of its SSC600, called SSC600 SW. This software based version can run on standard customers server hardware, making it easier to adapt to different system designs. It also allows for smoother integration with other digital components in modern substations, offering greater flexibility and scalability for utilities looking to future-proof their infrastructure.

The ABB SSC600 is at the cutting edge of centralized, software driven control and protection in modern electrical power networks and industrial sectors. The strong performance, flexible configuration options, and seamless integration with other systems provide the advancement in protection and control environment that can handle the growing complexity and digital requirements of today’s power networks.

2.2.1 Load Shedding and Restoration Strategies in ABB SSC600

Effective fault visualization and analysis are fundamental in supporting the operational decision-making required for LS&R in modern power systems. Modern systems are becoming more complex with RES integrations and real-time control requirements, which can visualize and interpret fault data accurately.

Historically, fault detection and localization were manual or semi-automated processes, often delayed by limited data resolution and non-standardized communication. The emergence of smart grid technologies, however, has enabled the deployment of synchronized phasor measurement units (PMUs), intelligent electronic devices (IEDs), and high-speed communication protocols, such as IEC 61850, that support real-time fault data collection and visualization (Phadke & Thorp, 2008). These advancements provide the basis for both automated fault detection and human-in-the-loop situational awareness, which are essential for initiating timely and accurate load shedding during disturbances.

Visualization tools display system parameters such as voltage profiles, frequency variations, and fault locations through intuitive graphical interfaces. These interfaces help operators rapidly assess the severity and extent of faults, identify affected areas, and determine appropriate corrective actions. Zhao et al. (2010) demonstrated that PMU-based fault visualization systems significantly reduce the time needed for system operators to assess cascading outages, which directly impacts the speed and effectiveness of load shedding strategies.

In centralized protection architectures, such as those utilizing ABB’s SSC600, fault data from distributed sources is aggregated and presented via a centralized HMI. This HMI typically includes real-time event lists, waveform records, and graphical network views that display fault zones and device status. Visualization and easy access for the HMI over remote server enhances operational situational awareness, enabling informed decisions for isolating faulted segments and initiating load shedding while protecting critical infrastructure (ABB, 2021).

The Possibility to measure and analyze the faults is vital in planning and optimization of LS&R in modern power systems. The historical fault records and system responses, utilities can refine restoration sequences, avoid re-energizing unstable parts of the network, and prioritize critical loads. Fahimi et al. (2016) used machine learning algorithms to automate the interpretation of transmission line fault records, improving both fault classification accuracy and restoration planning.

Because SSC600 is software based it opens the door to Artificial intelligence (AI) and machine learning (ML) techniques to be integrated into fault identification platforms to enhance their predictive capabilities. Fan et al. (2019) proposed a hybrid framework combining AI-driven analysis and visual interfaces for fault location and restoration planning. These intelligent systems are particularly valuable in large-scale, high-density networks where data volume and complexity exceed human processing capacity.

Real-time fault visualization is further supported by geographic information systems (GIS), which link electrical asset data with spatial locations. This allows restoration crews and operators to coordinate responses more efficiently, especially in geographically dispersed grids with mixed urban and rural infrastructures.

2.3 Importance of Fault Visualization and Analysis in Load Shedding and Restoration

The possibilities provided by SSC600 for fault visualization and analysis are fundamental in supporting the operational decision making required for load shedding and restoration (LS&R) in modern power systems. As the power grid complexity increased due to distributed generation, renewable energy sources, and real-time control systems the ability to accurately visualize and interpret fault data is essential for enhancing the reliability, speed, and precision of LS&R operations.

Historically, fault detection and localization were manual or semi-automated processes, often delayed by limited data resolution and non-standardized communication. The emergence of smart grid technologies, however, has enabled the deployment of synchronized phasor measurement units (PMUs), intelligent electronic devices (IEDs), and high speed communication protocols, such as IEC 61850, that support real time fault data collection and visualization (Phadke & Thorp, 2008). These advancements provide the basis for both automated fault detection and human-in-the-loop situational awareness, which are essential for initiating timely and accurate load shedding during disturbances.

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In centralized protection architectures, such as those utilizing ABB’s SSC600, fault data from distributed sources is aggregated and presented via a centralized human-machine interface (HMI). This HMI typically includes real-time event lists, waveform records, and graphical network views that display fault zones and device status. Such visualization enhances operational situational awareness, enabling informed decisions for isolating faulty segments and initiating load shedding while protecting critical infrastructure (ABB, 2020).

Fault analysis is an important area in the planning and optimization of load restoration. Fahimi et al. (2016) used machine learning algorithms to automate the interpretation of transmission line fault records, improving both fault classification accuracy and restoration planning.

Artificial intelligence (AI) and machine learning (ML) have been increasingly integrated into fault visualization platforms to enhance their predictive capabilities. Fan et al. (2019) proposed a hybrid framework combining AI driven analysis and visual interfaces for fault location and restoration planning. These intelligent systems are particularly valuable in large scale, high density networks where data volume and complexity exceed human processing capacity.

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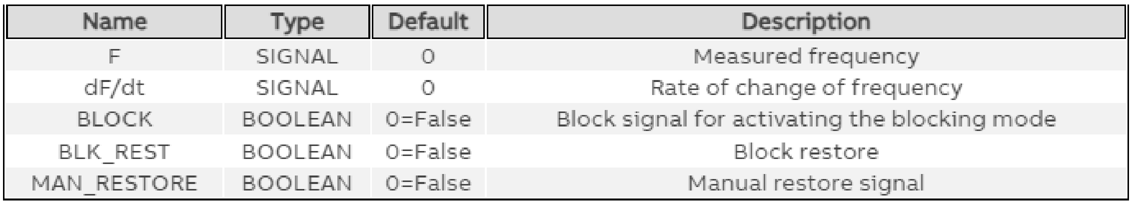
3 ABB SSC600 Load Shedding and Restoration

3.1 Functionality and Operation

The load-shedding and restoration function LSHDPFRQ can perform load-shedding based on underfrequency and the rate of change of the frequency. The load that is shed during the frequency disturbance can be restored once the frequency has stabilized to the normal level.

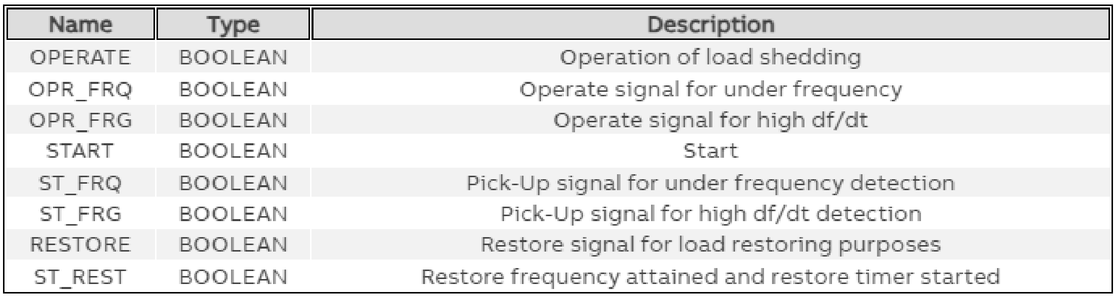
Figure 1 - ABB SSC600 Loadshedding and Restoration Function Block (ABB SSC600 Technical Manual)

Input Signals



Name	Type	Default	Description
F	SIGNAL	0	Measured frequency
dF/dt	SIGNAL	0	Rate of change of frequency
BLOCK	BOOLEAN	0=False	Block signal for activating the blocking mode
BLK_REST	BOOLEAN	0=False	Block restore
MAN_RESTORE	BOOLEAN	0=False	Manual restore signal

Figure 2 - LSHDPFRQ Input signals (ABB SSC600 Technical manual)



Name	Type	Description
OPERATE	BOOLEAN	Operation of load shedding
OPR_FRQ	BOOLEAN	Operate signal for under frequency
OPR_FRG	BOOLEAN	Operate signal for high df/dt
START	BOOLEAN	Start
ST_FRQ	BOOLEAN	Pick-Up signal for under frequency detection
ST_FRG	BOOLEAN	Pick-Up signal for high df/dt detection
RESTORE	BOOLEAN	Restore signal for load restoring purposes
ST_REST	BOOLEAN	Restore frequency attained and restore timer started

Figure 3- LSHDPFRQ output signals (ABB SSC600 Technical manual)

To find the underfrequency condition, the observed system frequency is compared to the fixed value. A high frequency reduction rate is detected by comparing the measured rate of change of frequency (df/dt) to the predefined value. Load-shedding is activated using the combination of the detected underfrequency and the high df/dt. The detection of the underfrequency and high df/dt and the activation of LSHDPFRQ are separated by a clear time delay. One can select this time lag to stop undesired load-shedding activities when the system frequency returns to the regular level.

LSHDPFRQ function can bring back the load shed during the frequency disturbance once the frequency has steadied. Restoration can be done either manually or mechanically. The function has a blocking feature. Should you choose, you can disable function outputs, timers, or even the function itself.
The function can be enabled and disabled with the operation setting. The corresponding parameter values are "On" and "Off".

The operation of LSHDPFRQ can be described using the following module diagram.

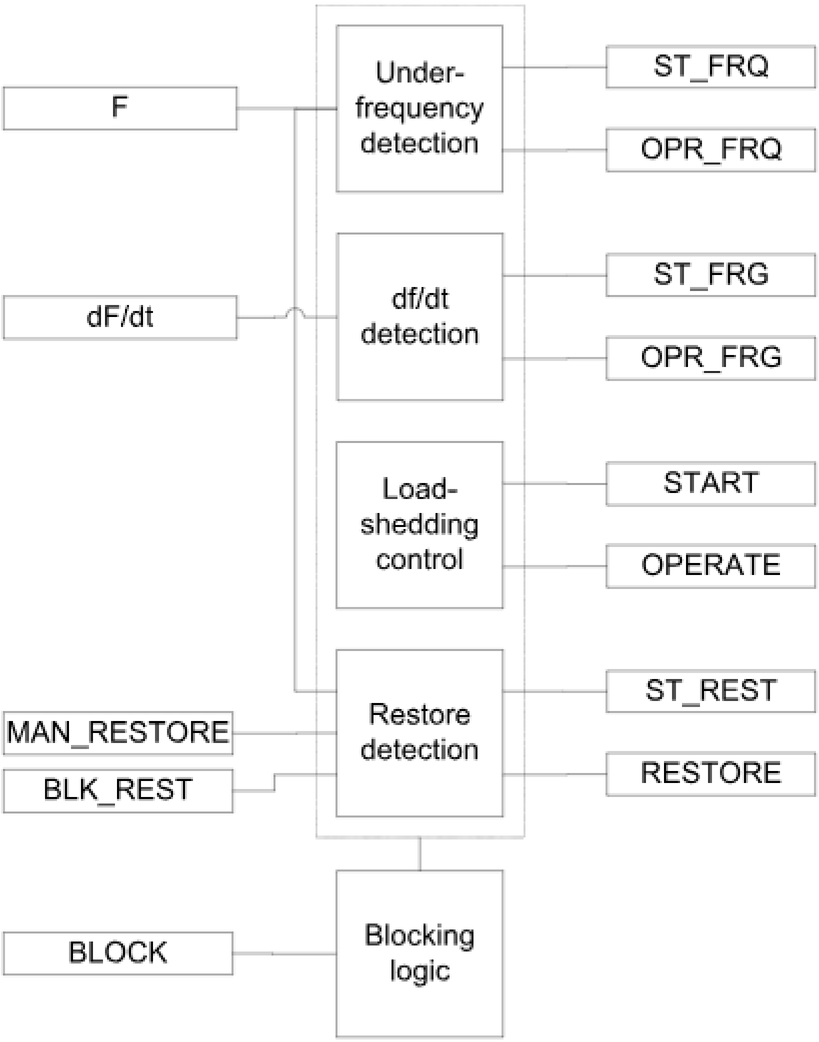


Figure 4 - ABB SSC600 Loadshedding and Restoration Functional module diagram Block (ABB SSC600 Technical Manual)

3.1.1 Detection of Underfrequency and the ROCOF

Underfrequency detection

The underfrequency detection assesses the input frequency derived from the voltage signal. When the measured frequency falls below the set value of the Start Value Freq parameter, an underfrequency is detected.

The underfrequency detection system has a timer with definite time (DT) qualities. Underfrequency detection causes the operation timer to turn on the ST_FRQ output. The OPR_FRQ output is turned on if the underfrequency condition still exists when the underfrequency timer has reached the value specified by Operate Tm Freq. The reset timer is turned on should the module run before the frequency returns to normal. The timer resets and the ST_FRQ output is turned off if the reset timer hits the value specified by Reset delay time.

ROCOF Detection

The df/dt detection computes the gradient of the input frequency derived from the voltage signal. Comparing the gradient to the Start value df/dt setting reveals a high df/dt condition. The df/dt detector is turned on when the frequency gradient drops at a quicker pace than the specified Start value df/dt.

The df/dt detection system has a timer matching the DT characteristics. Operation timer turns on the ST_FRG output on df/dt detection. The OPR_FRG output is turned on if the df/dt condition still exists when the timer has reached the value set by Operate Tm df/dt. The reset timer is turned on if df/dt normalizes before the module runs. The timer resets and the ST_FRG output is turned off if the reset timer equals the Reset delay time setting.

3.1.2 Load-shedding control

Load shed mode user setting defines the mechanism of load-shedding: whether to run based on underfrequency or high df/dt or both. The allowed operating modes for the Load shed mode settings are "Freq<", "Freq< AND df/dt" and "Freq< OR df/dt". The START and OPERATE output signals are turned on once the chosen operating mode criteria are met.

START_DUR, which is accessible as monitored data, allows one to track the percentage of the elapsed delay time when the START output is active.

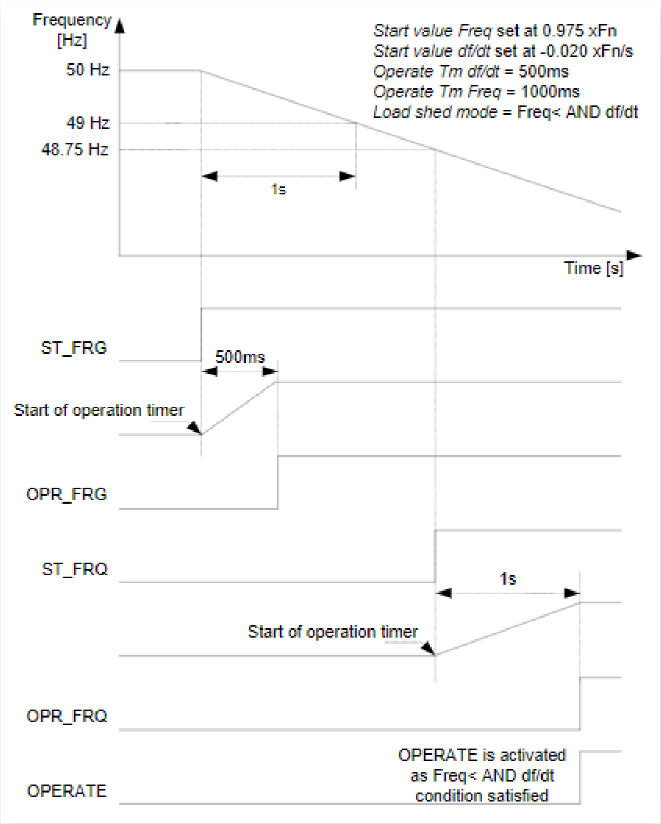


Figure 5 Load-shedding operation in the "Freq< AND df/dt>" mode when both Freq< and df/dt conditions are satisfied (ABB SSC600 Technical manual)

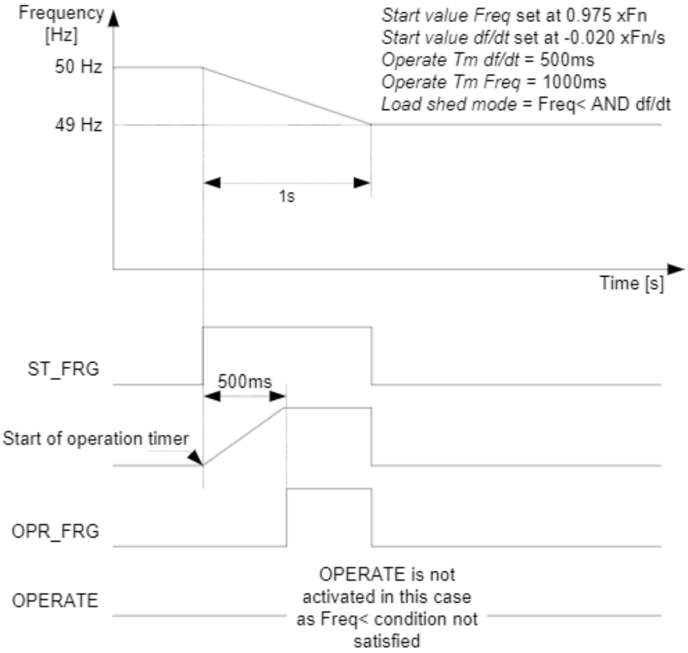


Figure 6- Load-shedding operation in the "Freq< AND df/dt>" mode when only the df/dt condition is satisfied (SSC600 Technical Manual)

3.1.3 Restoration Mode

The RESTORE signal output is active if after the OPERATE input activation the frequency returns to a level above the Restore start Val setting. For 100 ms, the RESTORE output stays active. The Restore mode option lets you choose the restoring mode to be "Disabled", "Auto" or "Manual".

Disabled

Load restoration is disabled.

Auto

Input frequency is constant compared to the Restore start Val setting in the "Auto" mode. The restoration detection system has a timer matching the DT traits. Restoring detection triggers the ST_REST output via the operation timer. The RESTORE output is turned on should the restoring condition still exist when the timer has reached the value of the Restore delay time setting. The reset timeout is activated should the frequency fall below the Re-store start Val before the RESTORE output is turned on. The timer resets and the ST_REST start output is turned off if the reset timer equals the Reset delay time setting.

Manual

Manual restoration is possible in the "Manual" mode either via the MAN_RESTORE input or via communication. Should the MAN_RESTORE command be available and the frequency exceed the Restore start Val setting, the ST_REST output is enabled. The manual restoration comprises a timer with the DT qualities. The RESTORE output is activated if the restoring condition still exists when the timer reaches the specified value of the Restore delay time setting. The reset timeout is activated should the frequency fall below the Restore start Val setting prior to the RESTORE output being engaged. The timer resets and the ST_REST start output is turned off if the reset timer equals the Reset delay time setting.

3.1.4 Application

Depending on the area, an AC power system is meant to run at a nominal frequency, usually 50 Hz or 60. Under normal circumstances, the actual operating frequency stays quite near this nominal number, often within a narrow range of ±0.5 Hz. Maintaining this frequency is vital since even little changes may compromise the stability of the whole power grid. Particularly to safeguard frequency-sensitive devices like motors, generators, and industrial equipment, frequency stability is a key issue in the operation and control of transmission and distribution networks.

To keep the system frequency, an increase in the connected load has to be matched by a matching rise in actual power generation. Any imbalance between generation and load creates frequency changes, the rate of change of frequency (ROCOF) shows how fast this imbalance is happening. The frequency falls and ROCOF turns negative when the load surpasses generation; conversely, the frequency rises with a positive ROCOF when generation exceeds load. Quick decision-making in load shedding activities depends on this measure. Load-shedding systems trigger underfrequency to cut off non-essential loads, hence assisting with system stabilization. Loads are given precedence such that lower-priority consumers are shed first, hence preserving the integrity of essential infrastructure and guaranteeing that key services stay unbroken.

The electricity grid might break into smaller, isolated parts called islands during some protective activities or system crises. Often, these islands are out of balance between load and generation, which causes changes from the nominal operating frequency. Sensitive power system components like turbines and motors might be harmed by such off-nominal frequency circumstances, so they must be handled immediately. A frequency-based load shedding plan is used to restore system stability and prevent harm. This means quickly detaching chosen loads to restore generation and consumption balance, therefore returning the system frequency to its usual range.

Multiple load shedding relays must be strategically placed close to several load centers since the emergence of system islands during disturbances is not always foreseeable. A single site's excessive load shedding might lead to instability; so, the load shedding procedure is most efficient when it is spread and discretely carried out in stages across several sites. This method gradually lowers the load until the system frequency falls back to acceptable range. The formerly shed loads may be safely restored once stability is regained and the frequency nears its nominal value. To prevent the system from returning to an emergency condition, this repair must also be done in stages. Depending on the system configuration, this procedure can be either manual or automated.

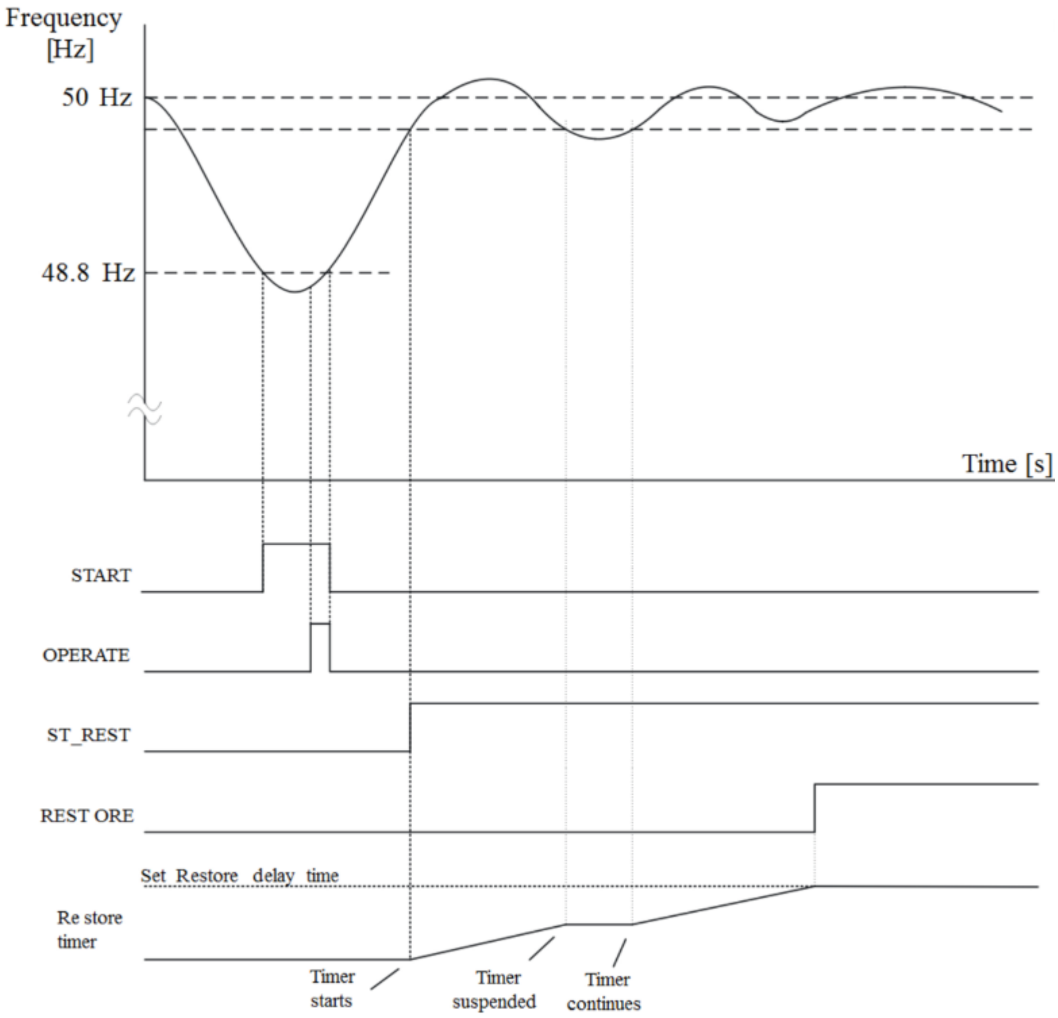


Figure 7 - Operation of the load-shedding function (ABB SSC600 Technical manual)

3.1.5 Power system protection by load-shedding

Frequency and the rate of change in frequency (df/dt) are used to determine the required load shedding. Based on several frequency and df/dt requirements, several load-shedding stages can be specified at a single location. Usually, six or four steps of load-shedding are carried out, each shedding raising the load part from five to twenty-five percent of full load in a few seconds. The system frequency is read back after every shedding; more shedding activities are done only if required to have an impact of any transient, a significant time delay should be established.

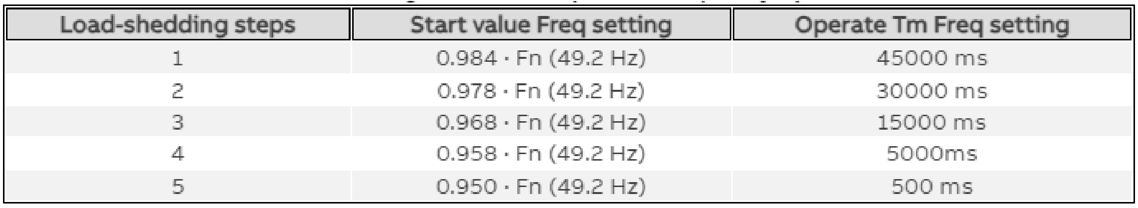
The value of the setting must be far below the lowest normal frequency and far over the lowest permitted frequency of the system. The features of the power system under consideration determine the setting level, the number of steps and the distance between two steps (in time or in frequency). A key factor is the size of the highest loss of generation in relation to the size of the power system. In big systems, the load-shedding can be set at a high frequency level, and the time delay is usually not important. Small systems require a low frequency starting level and a quick time delay.

A small system running at 50 Hz calls for an underfrequency for various steps from 49.2 Hz to 47.5 Hz in increments of 0.3 to 0.4 Hz. From a higher frequency value to a lower frequency value, the operating duration for the underfrequency can be varied sequentially from a few seconds to a few fractions of a second. The frequency function's rate of change is not instantaneous as it requires time to provide a steady value. A time delay sufficient to handle the signal noise is advised.

A single event can cause small industrial systems to experience the rate of change of frequency as high as 5 Hz/s. When major faults or combinations of faults are removed, even huge power networks can create small islands with significant load-generation imbalance. When a small island separates from a big system, up to 3 Hz/s has been felt. The frequency rate of change is far lower for typical severe disruptions in big power systems, often only a fraction of 1.0 Hz/s.

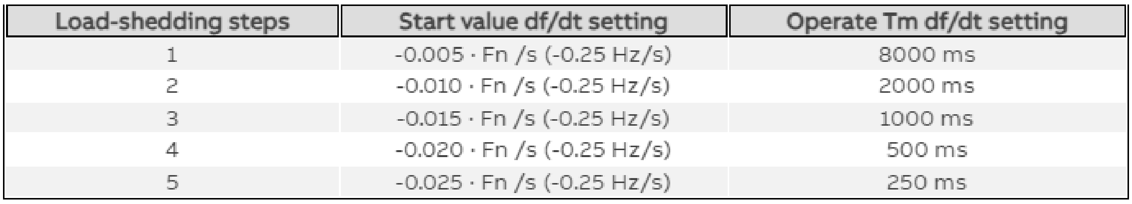
For large, distributed power networks, the df/dt option can likewise range from 0.1 Hz/s to 1.2 Hz/s in increments of 0.1 Hz/s to 0.3 Hz/s, with the operation time ranging from a few seconds to a few fractions of a second. The higher df/dt configuration should be maintained in the last operating time.

The shed load can be restored once the frequency has steadied. Restoring operations should be done incrementally, with caution that it does not return the system to the emergency state.



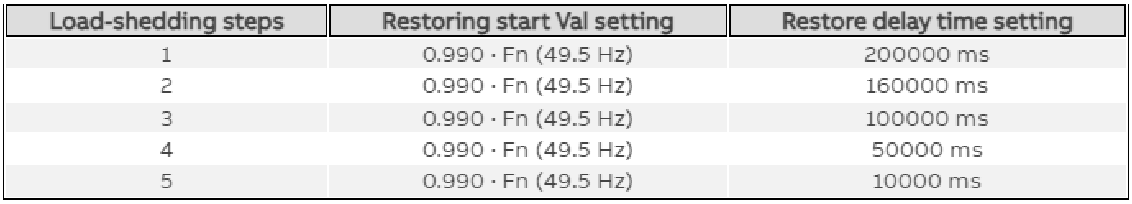
Load-shedding steps	Start value Freq setting	Operate Tm Freq setting
1	0.984 · Fn (49.2 Hz)	45000 ms
2	0.978 · Fn (49.2 Hz)	30000 ms
3	0.968 · Fn (49.2 Hz)	15000 ms
4	0.958 · Fn (49.2 Hz)	5000ms
5	0.950 · Fn (49.2 Hz)	500 ms

Figure 8 - Setting up a five-step underfrequency operation (ABB SSC600 Technical Manual)



Load-shedding steps	Start value df/dt setting	Operate Tm df/dt setting
1	-0.005 · Fn /s (-0.25 Hz/s)	8000 ms
2	-0.010 · Fn /s (-0.25 Hz/s)	2000 ms
3	-0.015 · Fn /s (-0.25 Hz/s)	1000 ms
4	-0.020 · Fn /s (-0.25 Hz/s)	500 ms
5	-0.025 · Fn /s (-0.25 Hz/s)	250 ms

Figure 9- Setting for a five-step df/dt< operation (ABB SSC600 Technical Manual)



Load-shedding steps	Restoring start Val setting	Restore delay time setting
1	0.990 · Fn (49.5 Hz)	200000 ms
2	0.990 · Fn (49.5 Hz)	160000 ms
3	0.990 · Fn (49.5 Hz)	100000 ms
4	0.990 · Fn (49.5 Hz)	50000 ms
5	0.990 · Fn (49.5 Hz)	10000 ms

Figure 10 - Setting up a five-step restoring operation (ABB SSC600 Technical Manual)

3.2 PCM600

ABB PCM600 (Protection and Control Manager) is a powerful and user friendly software tool designed for configuring, commissioning, monitoring, and maintaining ABB protection and control IEDs such as the Relion® series and the SSC600 centralized protection and control unit.

Developed as a unified platform, PCM600 provides a consistent interface for working with various ABB devices, streamlining engineering workflows across substation automation systems.

ABB PCM600 is highly compatible with a broad range of ABB protection and control devices, including the Relion® 615, 620, 650, and 670 series, as well as the centralized SSC600 unit. SSC600 is designed to seamlessly integrate with any device based IEC 61850 based with wide range of manufacturers in substation automation systems which support communication, configuration, and data exchange in modern digital substations. PCM600 is regularly updated to maintain and improve the latest developments and to be compatible with the latest IED firmware versions and functional upgrades. That ensure smooth operation across various device oner the time, this wide range compatibility makes it a versatile and essential tool for both new installations and management of existing ABB substation assets.

Key Features

- Graphical Function Block Editor- Develop and modify security and automation logic via user friendly graphical tools.
- Parameter Configuration- Effortlessly adjust relay protection functions, thresholds, delays, and logical conditions.
- IED Connectivity - Facilitate communication with devices using IEC 61850, Ethernet or serial interfaces.
- Signal Monitoring and Diagnostics - Observe real-time status of protective functions, measurements, binary signals and event logs.

- IED File Management - Transfer settings, logic, and firmware to and from the IEDs.
- Electrical Network Topology Visualization - Design and illustrate the configuration of the electrical network and its components.
- Support for SSC600 - PCM600 serves as the primary engineering tool for customizing the centralized ABB SSC600 unit.

ABB PCM600 facilitates the configuration and execution of automated load shedding and restoration protocols within ABB protection and control IEDs, including the centralized SSC600. Engineers can utilize the Function Block Diagram (FBD) editor in PCM600 to create logic predicated on real-time system characteristics, including frequency and the ROCOF. For functions such as load shedding and restoration including 81LSH (Underfrequency Load Shedding) can be used to disconnect non-essential loads when the frequency falls below established thresholds, thereby aiding in the stabilization of the grid amid generation deficits or disturbances. Similarly, the restoration logics can be programmed utilizing frequency supervision blocks (e.g., 81F), timers, and logical gates to incrementally reconnect loads after the system frequency stabilizes above predetermined thresholds for a set time as required.

4 Methodology

This section outlines the step by step methodology employed to design and implement, centralized load shedding and protection scheme using the ABB SSC600 in a typical medium voltage substation configuration. The methodology involves designing the network topology, implementing protection schemes, configuring communication protocols, and setting up a visualization interface using ABB Relay engineering tool PCM600.

4.1 Substation Configuration Design

This thesis considers a model substation that effectively demonstrates the capabilities of the ABB SSC600 in implementing advanced load shedding and restoration strategies. The proposed network configuration includes two incomer feeders and six outgoing feeders, a common topology in medium voltage distribution substations that require high reliability and flexibility.

The proposed methodology model substation configuration integrating two incomer feeders, one from traditional power generation (e.g., utility grid or thermal plant) and the other from a RES such as a solar PV or wind farm. This hybrid configuration represents a modern distribution network and allows for the testing of advanced protection and control strategies under dynamic generation conditions.

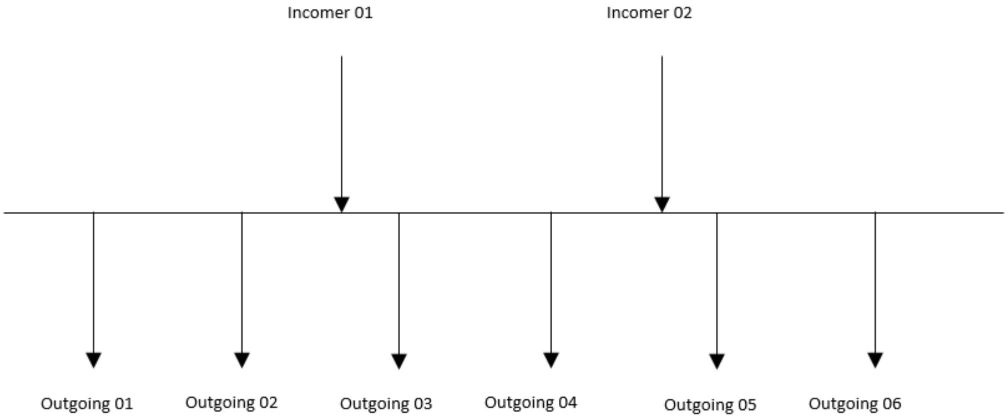


Figure 11- System SLD

The feeders use ABB REX615 relays as the merging units to collect and communicate data in the network. This strategy of using relays in merging units provides an additional level of protection on top of the primary SSC600 protection improving redundancy and system reliability. Both ABB REX615 and SSC600 are fully capable of utilizing IEC61850 communication protocols for seamless and fast responses during protection.

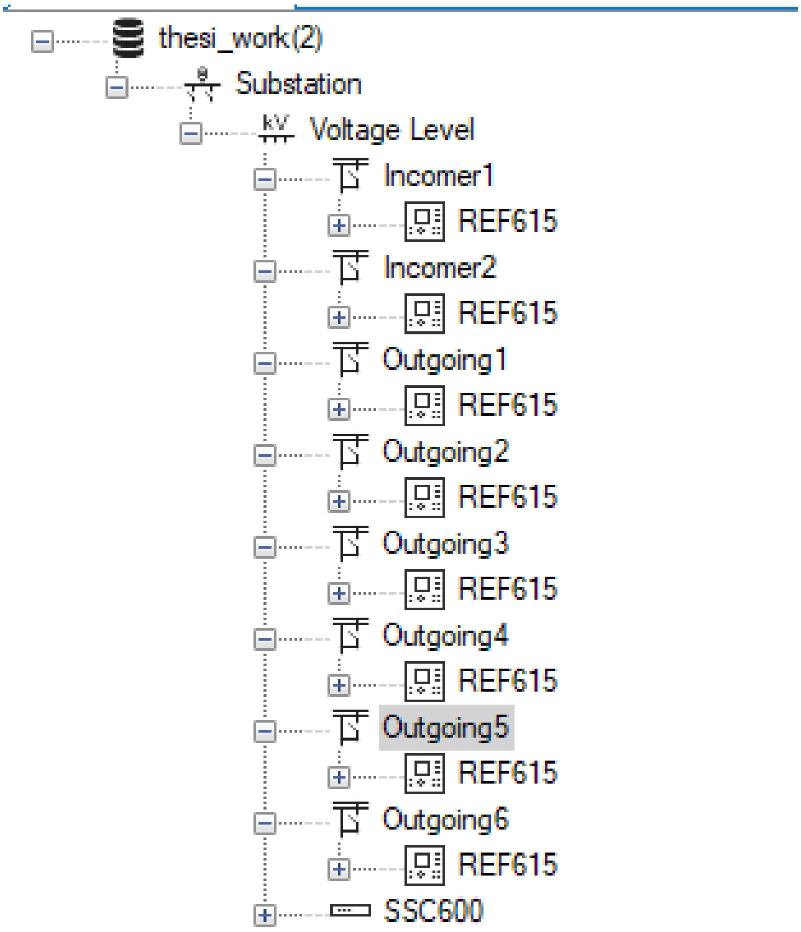


Figure 12- main substation setup in PCM600

The ABB SSC600 is engineered to provide real time supervision of voltage, frequency, and current parameters across all incomers and feeders. To handle the fluctuating nature of RES, the SSC600 leverages its high speed communications with primary merging units in this case REX615 relays continuously monitoring the,

- Voltage amplitude and symmetry on each phase

- Frequency and Rate of Change of Frequency (ROCOF)
- Current magnitude and direction, which helps detect reverse power flow or faults

4.2 Input measurements

The REX15 relays used as the merging units at each bay can measure the analog current and voltage values through its connected analog inputs. The Three phase current, residual current, three phase voltage and residual voltage can be measured. Using this measurement the single phase current and voltage, frequency and power is calculated for all protection functions.

As shown below the measurement can be set up with PCM600 function blocks.

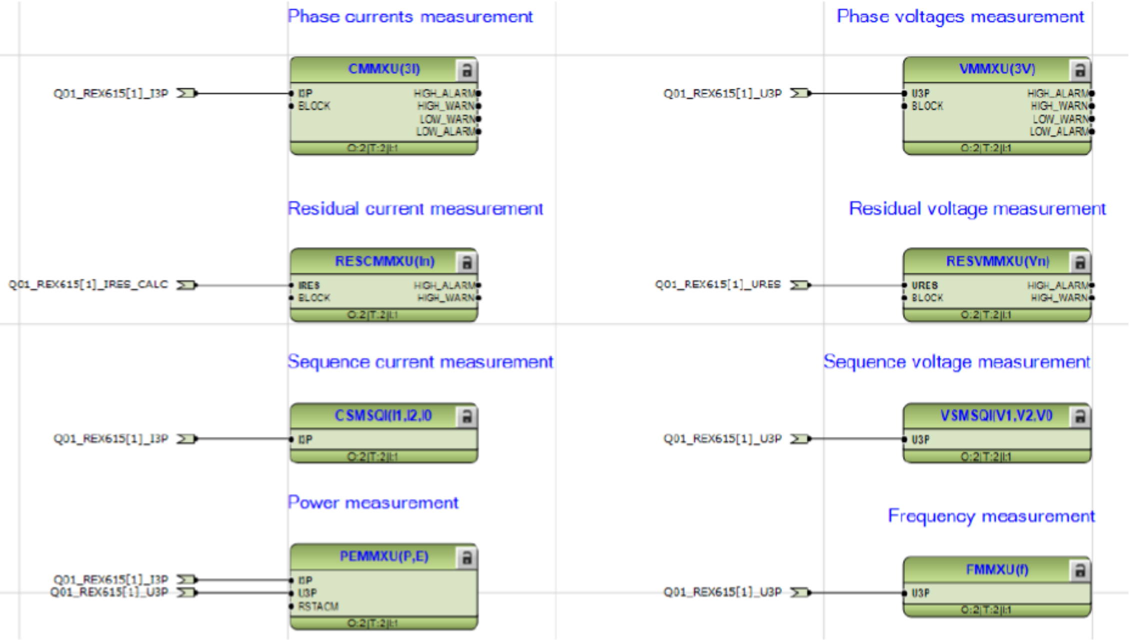


Figure 13-measurement function blocks

4.2.1 The REX615 frequency calculation

The ABB REX615 protection relay determines system frequency using its internal frequency measurement function, designated as FMMXU (Frequency Measurement Logical Node). This function processes voltage and current inputs to calculate the frequency of the power system.

The REX615 utilizes digital signal processing techniques to analyze the input waveforms. Specifically, it employs the Discrete Fourier Transform (DFT) method to extract the fundamental frequency component from the measured signals. This approach allows for accurate frequency estimation even in the presence of harmonics and noise.

4.2.2 The REX615 ROCOF Calculation

Once the frequency is measured over successive sampling windows, ROCOF is computed using the basic numerical derivative.

$$\mathrm{ROCOF} = \frac{f(t) - f(t - \Delta t)}{\Delta t}$$

f(t) is the current frequency value
Δt is the sampling interval

The frequency measurement function operates effectively within a frequency range of 20 Hz to 70 Hz, accommodating various system conditions. The accuracy of the frequency measurement is maintained within ±2 Hz of the nominal system frequency, ensuring reliable operation of frequency-dependent protection functions.

4.3 Implementation of communication between REX615 and SSC600

The measured voltage and current signals need to be communicated to SSC600 for measurements and control and protection functions.

The SMVSENDER and SMVRECEIVER function blocks are used to send the measured values from REX615 to the SSC600.

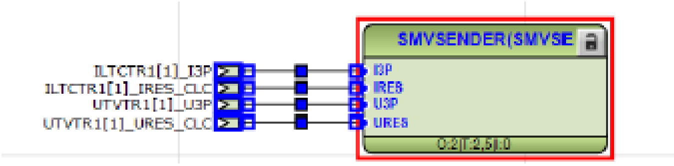


Figure 14- SMV sender function block

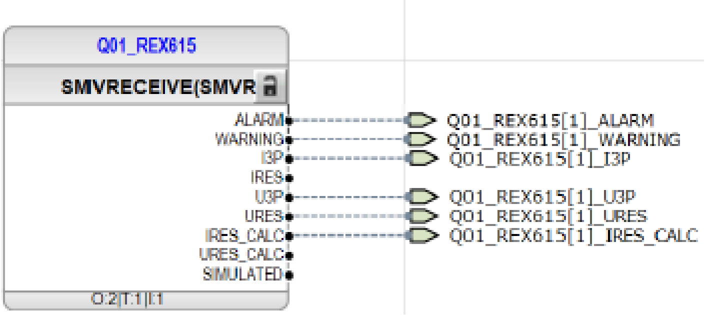


Figure 15- SMV Receive function block

Additionally, to the current and voltage values all other control and protection function, and indication signals can be sent to via SV via process bus communication. Inbuilt SMV alarms and warning functions are capable to identify the SV transmitted and received and if any error it will indicate the issue.

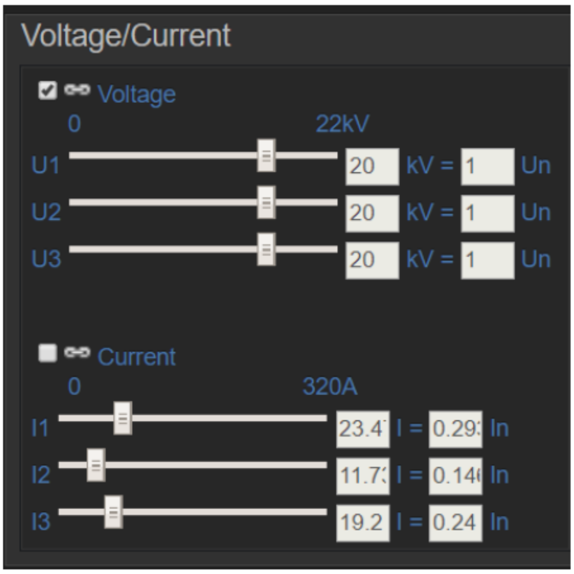
4.3.1 Process bus communication

ABB's SSC600 is relying heavily on high-speed, fiber-optic-based bus communication. The process bus, defined under IEC 61850-9-2, replaces traditional hardwired connections between instrument transformers (CTs and VTs), protection relays and control units with a fully digital architecture.

The core communication over the process bus consists of two major types of messages, Sampled Measured Values (SMV) and GOOSE (Generic Object-Oriented Substation Event) messages. SMVs are time-synchronized digital representations of voltage and current measurements, typically sent from merging units or intelligent bay level devices in this case REX615 configured as SMV senders. These SMVs are critical for real-time protection and monitoring functions within SSC600. The SSC600 can subscribe to multiple SMV streams, with support for up to four protection zones, each receiving sampled values from up to six merging units.

In parallel, GOOSE messaging defined under IEC 61850-8-1 enables high-speed exchange of binary signals between devices, typically used for transmitting breaker status, trip signals, interlocking commands, and other fast protection-related events. SSC600 both sends and receives GOOSE messages, facilitating coordination with bay-level IEDs, circuit breakers, and control interfaces. This allows for instantaneous protection actions, with deterministic communication latencies typically below 4 milliseconds, which is critical in fast protection schemes like busbar differential protection or adaptive load shedding.

For this Thesis, to test the function and visualization the Protection relay simulator connected to the relay panels at the training and testing facility can be used. The Simulator can be accessed virtually via the HMI, and it has the possibility to control the Circuit Breaker and the disconnector and control the voltage and the current levels.


Voltage/Current

☑ Voltage
0 22kV
U1 20 kV = 1 Un
U2 20 kV = 1 Un
U3 20 kV = 1 Un

☐ Current
0 320A
I1 23.4 I = 0.29 In
I2 11.7 I = 0.14 In
I3 19.2 I = 0.24 In

Figure 16- SSC600 virtual simulator control

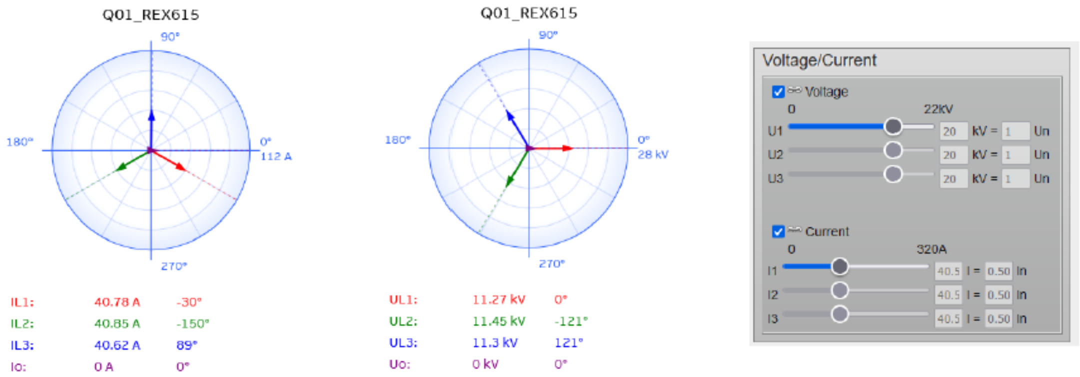
4.3.2 SSC600 Web HMI

The ABB SSC600 Web-based Human-Machine Interface (WHMI) is a powerful interface can be accessed from web browser, that enables real-time monitoring, control, and diagnostics of the centralized protection and control system. Unlike conventional local HMI displays on bay-level relays, the WHMI in SSC600 is accessed via a secure web browser (using HTTPS), making it available both locally and remotely, depending on system configuration and access rights can be assigned and modified at ease.

The SSC600 WHMI continuously displays real-time measurement data acquired via the IEC 61850 process bus from merging units or IEDs (REX615) for example,

- Phase voltages and line voltages
- Phase currents
- Frequency and Rate of Change of Frequency (ROCOF)
- Power (active, reactive, apparent)
- Power factor and harmonics
- Trip and status indications
- Protection function states and outputs

Measurements are graphically visualized in the WHMI using gauges, trend plots, and numerical values. This allows operators to assess system conditions easily. The visualization can be done during fault conditions or post event diagnostics. The interface supports refresh rates aligned with real-time process bus data (4000 samples/s from SMV streams), ensuring accuracy and reliability.



IL1:	40.78 A	-30°
IL2:	40.85 A	-150°
IL3:	40.62 A	89°
Io:	0 A	0°

UL1:	11.27 kV	0°
UL2:	11.45 kV	-121°
UL3:	11.3 kV	121°
Uo:	0 kV	0°

U1 20 kV = 1 Un
U2 20 kV = 1 Un
U3 20 kV = 1 Un
I1 40.5 I = 0.50 In
I2 40.5 I = 0.50 In
I3 40.5 I = 0.50 In

Figure 17 - SSC600 WHMI

4.4 Implementation of Load Shedding and Restoration

The Load shedding and restoration in PCM600 is associated with the LSHDPFRQ function block. The system measured three phase voltage is used as the input signal and the required measurements for Frequency and ROCOF are obtained from that. The measured system frequency is compared to the set value to detect the underfrequency condition. The measured rate of change of frequency (df/dt) is compared to the set value to detect a high frequency reduction rate. The function block will send its output signals to operate the load shedding and restoration as described in section xx.

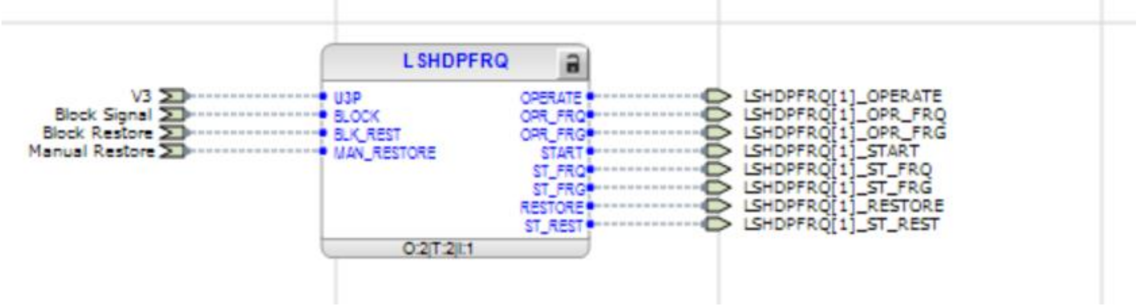


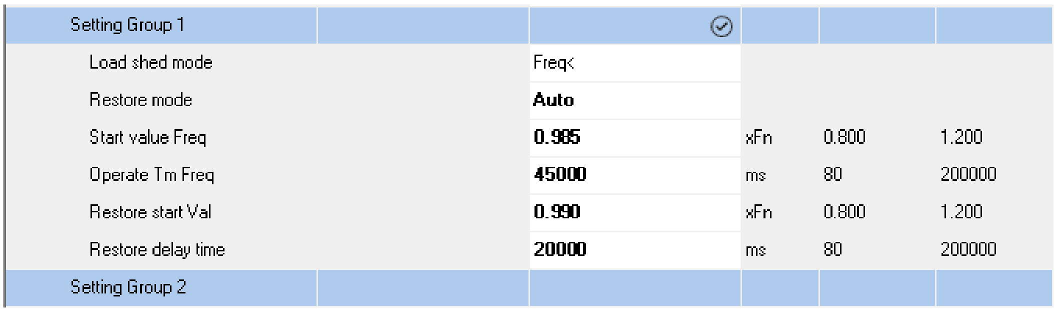
Figure 18- Load shedding and restoration (LSHDPFRQ) function block

The SSC00 has the possibility to set the loadshedding based on three options,

- Frequency-based (Freq<)
- Frequency or ROCOF (Freq< OR df/dt)
- Frequency and ROCOF (Freq< AND df/dt)

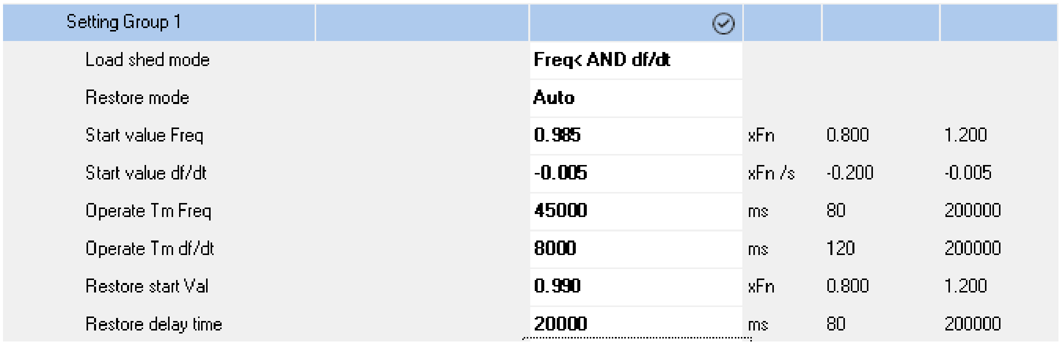
Using the parameter setting tool the frequency, ROCOF, time to check and delay time for restoration can be adjusted accordingly and can fine tune the system as required.

- **Start Value Frequency** - Set the frequency threshold for initiating load shedding (e.g., 0.95 × fn)
- **Start Value df/dt** - Set the ROCOF threshold (e.g., -0.2 × fn/s).
- **Operate Time Frequency -** Define the delay before load shedding activates after frequency drops below the threshold.
- **Operate Time df/dt -** Define the delay before load shedding activates after ROCOF exceeds the threshold.
- **Restore Mode** – Auto, Manual, Off
- **Restore Start Value** - Set the frequency threshold where load restoration begins
- **Restore Delay Time** - Set the delay initiating load restoration frequency recovers.



Setting Group 1	✓			
Load shed mode	Freq<			
Restore mode	Auto			
Start value Freq	0.985	xFn	0.800	1.200
Operate Tm Freq	45000	ms	80	200000
Restore start Val	0.990	xFn	0.800	1.200
Restore delay time	20000	ms	80	200000
Setting Group 2				

Figure 19- Frequency only LS&R Parameter setting



Setting Group 1	✓			
Load shed mode	Freq< AND df/dt			
Restore mode	Auto			
Start value Freq	0.985	xFn	0.800	1.200
Start value df/dt	-0.005	xFn /s	-0.200	-0.005
Operate Tm Freq	45000	ms	80	200000
Operate Tm df/dt	8000	ms	120	200000
Restore start Val	0.990	xFn	0.800	1.200
Restore delay time	20000	ms	80	200000

Figure 20- Frequency and ROCOF LS&R Parameter setting

4.4.1 Breaker control with LS&R

To enable the Circuit breaker operation for load shedding and restoration using ABB SSC600, the OPERATE and RESTORE outputs from the LSHDPFRQ function block can be transmitted via GOOSE messaging. The OPERATE signal is typically linked to a virtual binary output, which is then published through a GOOSE message and subscribed to by the corresponding bay level IED (REX615). On the receiving device, the GOOSE input is mapped to the breaker control interface via the BCXCBR.OpnTrg input, to trigger load disconnection. Similarly, the RESTORE output is mapped to another virtual signal and GOOSE message, which can be connected to the ClsTrg (close trigger) input of the bay breaker IED to perform staged reconnection once system frequency stabilizes. With the aid f GOOSE messaging the protection can ensure low latency enabling SSC600 to issue fast, coordinated commands across the substation without the need for direct wiring, enhancing flexibility and scalability in smart grid deployments.

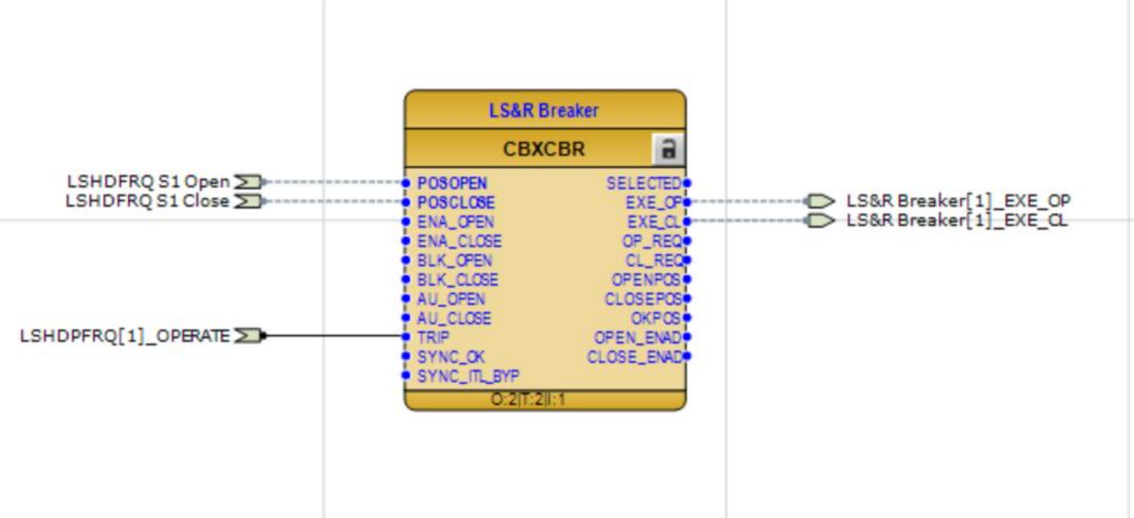


Figure 21- Breaker control function block

4.4.3 Visualization of the function

Using the visualization tools in SSC600 the breaker conditions can be continuously monitored. The virtual LED's can be set up to identify if the function is activated or not. As well the current system Frequency, voltage and current can be displayed in the HMI.

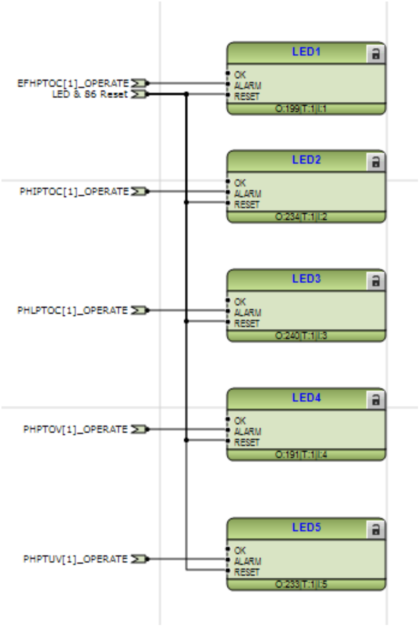
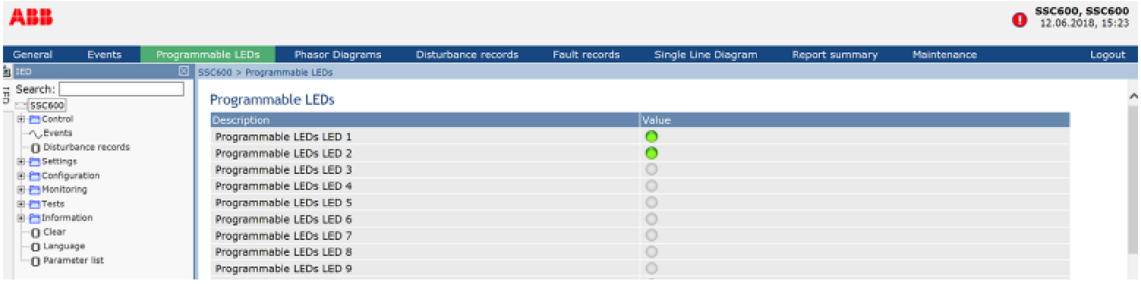


Figure 22- LED and alarm config for LS&R function



Programmable LEDs

Description	Value
Programmable LEDs LED 1	●
Programmable LEDs LED 2	●
Programmable LEDs LED 3	○
Programmable LEDs LED 4	○
Programmable LEDs LED 5	○
Programmable LEDs LED 6	○
Programmable LEDs LED 7	○
Programmable LEDs LED 8	○
Programmable LEDs LED 9	○

Figure 23- SSC600 WHMI LED indications

In the SSC600, LED indicators and alarm outputs can be configured to provide visual and audible signals whenever a load shedding or restoration event occurs. Using ABB's PCM600 engineering tool, logical outputs from the LS&R function block OPERATE, RESTORE, or individual stage triggers can be mapped to specific virtual LED channels. These LEDs can be labeled, color-coded, and set to indicate different operating states, such as an active shedding stage, restoration in progress, or system reset. Similarly, the same logic signals can be routed to physical digital outputs or virtual alarm relays to activate sirens, alarm lights, or SCADA event alerts. This setup ensures that operators are immediately notified when SSC600 initiates protective actions, enhancing situational awareness and facilitating quicker manual intervention or diagnostics.

In the WHMI’s Measurements tab, users can view live system parameters such as phase voltages, currents, frequency, and calculated ROCOF. These values are sourced from the SMVs received via the process bus or from directly connected IEDs. The frequency and ROCOF thresholds configured in the LSHDPFRQ function block are monitored here, and their violation can be tracked through time-aligned trend plots.

5 Results and Analysis

This section of the thesis presents the outcomes of implementing centralized load shedding and restoration strategy in ABB SSC600 in a model medium voltage substation which was designed and in the previous chapter configured through PCM600. The performance of the LS&R strategy in SSC600 is evaluated under various simulated conditions, including normal operation, underfrequency events, and high ROCOF scenarios.

5.1 Scenario 1 – Underfrequency Event Triggered by RES Fluctuation

Objective

To observe the performance of SSC600's frequency-only load shedding logic during a renewable generation drop those results in frequency deviation.

Test Conditions

- Nominal frequency -50 Hz
- Simulated frequency dip to- 49.2 Hz over 3 seconds
- Load shedding threshold (start value)- 49.5 Hz
- Number of steps- 5
- Restoration threshold- 49.6 Hz for 5 seconds
- ROCOF logic- Disabled

Observation

Once frequency fell below 49.5 Hz, SSC600 triggered Stage 1 load shedding after a configured operate delay of 0.5 seconds. Additional steps were activated in intervals of 0.4 Hz as frequency continued to drop. The lowest point reached was 49.2 Hz, after which the system stabilized.

Table 1 - Results from test scenario 1

Step	Threshold (Hz)	Delay (s)	Shed Load (%)	Trigger Time (s)
1	49.5	0.5	10%	0.5
2	49.2	0.4	10%	1.2
3–5	Not triggered	—	—	—

Results

The system successfully stabilized at 49.6 Hz, and automatic restoration was initiated after 5 seconds. SSC600 restored the previously disconnected loads in 3 staggered steps without any further dips and signs of overcompensation or secondary instability were observed.

Discussion

The frequency-only logic proved effective in low-rate frequency deviation scenarios. SSC600's centralized design enabled sub-second decision making and prioritized feeder disconnections. Response times averaged around 600 ms for Stage 1 and 1.2 seconds for Stage 2, which is significantly faster than typical distributed relays (2–3 seconds per literature: Phadke & Thorp, 2008). The staggered restoration logic was effective in preventing overload upon recovery.

5.2 Scenario 2 – Combined Frequency and ROCOF Event Under Low-Inertia Conditions

Objective

To evaluate SSC600's dual-condition logic when both underfrequency and ROCOF events occur, particularly in low-inertia systems with high RES penetration.

Test Conditions

- Frequency drop from 50 Hz to 49.1 Hz in 1.5 seconds

- ROCOF threshold- >1.0 Hz/s
- Load shedding mode- Freq< AND df/dt
- Operate delay for ROCOF- 0.3 seconds
- Load shed per step- 10%
- Number of stages- 5

Observation

The system detected a rapid ROCOF of 1.5 Hz/s early during the frequency deviation and preemptively triggered Stage 1 and Stage 2 shedding almost simultaneously, even before the frequency fell below 49.5 Hz. This proactive response effectively slowed the rate of frequency decline and prevented system collapse.

Table 2- Results from test scenario 2

Step	Trigger Basis	Delay (s)	Shed Load (%)	Trigger Time (s)
1	ROCOF	0.3	10%	0.3
2	ROCOF	0.3	10%	0.5
3	Frequency	0.5	10%	1.2
4–5	Not required	—	—	—

Result

The ROCOF-based early shedding enabled SSC600 to stop the frequency drop at 49.1 Hz, after which frequency recovered. Restoration began when the system crossed the 49.6 Hz mark and remained stable for 5 seconds. The system restored loads in two stages with no relapses.

Discussion

Compared to Case 1, the combined logic provided a significantly faster response in more severe dynamic conditions. Stage 1 was activated within 300 ms, much faster than the typical reaction time for distributed systems (⩾2.4 s) noted in Moeini Aghtaie et al.,

2013. This case demonstrates SSC600’s suitability in modern grids with high RES penetration, where low inertia results in steeper frequency declines.

The ROCOF function's high sensitivity and combined logic structure showed increased protection selectivity and system resilience. It prevented cascading failures that could have occurred had only frequency logic been used.

5.3 Output Visualization and Diagnostics Using PCM600

5.3.1 Visualization

The integrated HMI and fault diagnostics available in SSC600 provided clear, real-time insights during all test conditions. Operators could observe live system values, including frequency, ROCOF, output signals, and relay status. Fault logs and event recordings were immediately available, showing the timeline of system responses with millisecond precision.

The WHMI serves as the central point for real-time monitoring of measurement values including frequency, voltage, current, and breaker position. For load shedding operations, outputs such as LSHDPFRQ.OPERATE, RESTORE, and stage-wise triggers are displayed clearly under the relevant function blocks. The interface also allows system operators to observe real-time logic outputs and confirm whether a trip or restore action is currently active. In systems configured with a single-line diagram (SLD) view, the WHMI can graphically represent the condition of feeders, showing color-coded states (e.g., red for disconnected, green for active) to indicate the real-time status of load shedding.

In addition to real-time display, SSC600 logs every event such as frequency threshold violations, stage triggers, and breaker operations using its event recorder. These logs are time-stamped down to the millisecond, making them ideal for post-event analysis and validation of protection settings. Operators can retrieve logs either through WHMI or via

PCM600's data reading tools. These logs can further be exported in CSV format for analysis in tools such as Excel or MATLAB.

For advanced measurement visualization, SSC600 also supports trend views. These can plot key parameters like frequency and voltage over time. If activated, this feature allows users to view the progression of frequency during a load shedding scenario, giving insight into how each step contributed to system stabilization. For example, a trend graph could show a frequency dip to 49.2 Hz, followed by stabilization after shedding Stage 2 load.

Table 3 - Visualization features

Visualization Feature	Interface	Description
Real-time signal monitoring	WHMI	Live values for frequency, voltage, current, trip logic
Event logs	WHMI / PCM600	Time-stamped records of LS&R stages and breaker trips
Single Line Diagram (SLD)	WHMI	Graphical view of feeder/breaker states and trip status
Logic outputs (LEDs, ARMs)	PCM600 + Device Panel	LED/alarm activation mapped to trip signals
Trend graphs (time series)	WHMI / PCM600 (optional)	Plots of frequency, voltage, and ROCOF during events
SCADA visualization	IEC 61850 MMS / GOOSE	Centralized monitoring of SSC600 logic and grid status

5.3.2 Event recording and diagnostic

A key benefit on ABB SSC600 is its integrated high resolution event recording and fault analysis. This functionality provide critical role in verifying protection logic performance, analysing system behaviour during disturbances, and supporting maintenance or post fault review activities. The SSC600 continuously monitors and logs all relevant operational and protection events, ensuring that no critical transition or action is missed.

Every significant event such as frequency threshold crossings, ROCOF triggers, activation of load shedding stages, load restoration attempts, breaker trips, and command responses. These are recorded with precise time stamping down to the millisecond. This high resolution time tagging is enabled by the device’s synchronization to a global time source via the Precision Time Protocol (PTP/IEEE 1588) or IRIG-B, ensuring that all entries in the event log are consistent and can be accurately correlated with data from other devices in the system.

Operators and engineers can access these logs in real time through the SSC600 WHMI, where events are displayed in a chronological, searchable format under the “Events” or “Alarm and Log Viewer” sections. Each log entry includes the event description, triggering signal, status change, and precise timestamp.

In addition to on screen viewing, detailed event and fault records can also be accessed using ABB’s PCM600 software. The data can be downloaded for archival or diagnostic use or exported in standard formats such as CSV or COMTRADE. These files can then be analysed using third party tools like Microsoft Excel, MATLAB, or specialized power system analysis software. Engineers can plot system response curves, investigate the timing between protection logic activations, and validate whether the configured thresholds and delays performed as expected during a real disturbance.

SSC600 also supports disturbance recording, capturing waveforms and system values during abnormal events. This includes pre-fault, fault, and post-fault data, which can be configured to trigger on specific conditions. The resulting COMTRADE files provide a complete snapshot of the system now of disturbance, enabling root cause analysis and detailed fault interpretation.

Together, these diagnostics empower operators and protection engineers with full visibility into the device’s operation and the electrical system's condition. This helps to ensure the reliability of protection schemes, identify errors or delayed responses. And that can be used to refine load shedding and restoration logic for improved future performance.

5.4 Comparative Performance: Centralized vs. Distributed Protection

Although the test environment developed in this thesis focused exclusively on the ABB SSC600’s centralized protection architecture, numerous published studies provide real-world insights into the performance limitations of traditional distributed load shedding systems. These conventional schemes typically consist of independent underfrequency relays installed on feeders or substations, each configured to act on predefined frequency thresholds. Because these relays operate autonomously without centralized coordination, the system’s response tends to be slower, less precise, and less selective.

Empirical data shows that traditional underfrequency load shedding (UFLS) schemes often exhibit average reaction times between 2 to 5 seconds from the onset of frequency deviation to the activation of load shedding (Moeini-Aghtaie et al., 2013; Zhao et al., 2010). These delays are primarily due to the reliance on local relay measurements and the absence of a global view of system frequency dynamics. Additionally, due to their fixed threshold logic and lack of real-time prioritization, distributed systems frequently shed 20–35% more load than necessary, including essential services that could otherwise be preserved (Elmitwally & Alolah, 2008; Rudner et al., 2017). In cascading failure scenarios, this imprecision may even exacerbate grid instability instead of mitigating it.

In contrast, the ABB SSC600—designed for centralized protection and control—demonstrated a sub-second response in simulation, initiating corrective action within 1.2 seconds of detecting an underfrequency event (from 50 Hz down to 49.2 Hz). When operating in ROCOF-sensitive mode, it triggered load disconnection in as little as 0.6–0.8 seconds, depending on the severity of the disturbance and inertia settings. Its logic-based priority scheme allowed the disconnection of only 25% of the total connected load across three stages, each based on load criticality and feeder assignment, thereby maintaining continuity for vital infrastructure.

Furthermore, the SSC600's use of IEC 61850 GOOSE and MMS protocols enables high-speed peer-to-peer communication and system-wide awareness, reducing inter-device latency and ensuring that all load shedding decisions are both synchronized and situationally informed. Unlike traditional relay-based systems that may trip feeders indiscriminately based on local conditions, SSC600 orchestrates disconnections centrally, executing optimal decisions using real-time voltage, frequency, and ROCOF data from across the network.

These performance gains faster response, less unnecessary disconnection, and better system stabilization highlight the superiority of SSC600 in the context of modern smart grid demands, especially where high renewable penetration and low inertia make rapid and adaptive protection critical.

Table 4- Results comparison from traditional Table 5- advantages of centralized vs distributed protectionand centralized load shedding and restoration

Parameter	Traditional Distributed UFLS	ABB SSC600 Centralized LS&R	Source(s)
Response Time (Typical)	2.0 – 5.0 seconds	0.6 – 1.2 seconds	Zhao et al., 2010; Moeini-Aghtaie et al., 2013
Trigger Method	Local frequency relay thresholds	Central logic via frequency + ROCOF + priority	ABB SSC600 Simulations; ABB, 2021
Coordination Method	Independent relays (no global coordination)	Centralized controller (30 feeders max)	ABB SSC600 Manual; IEC 61850 GOOSE Messaging
Load Shedding Amount (Typical)	30–50% of connected load	20–30% (based on dynamic prioritization)	Elmitwally & Alolah, 2008; Rudner et al., 2017
Prioritization Capability	Limited to fixed stages	Dynamic load ranking based on feeder configuration	ABB SSC600 Technical Manual; PCM600 Implementation

Restoration Method	Manual or fixed-timer-based	Staged auto/manual restoration via logic	SSC600 Simulation Results; ABB SSC600 Manual
Resilience to Low-Inertia Grids	Low – Fixed thresholds not suited to fast ROCOF	High – Adaptive response logic possible	Rudner et al., 2017; Thesis Scenario 2 Results
Communication Protocol	Hardwired or SCADA delay	High-speed IEC 61850 (GOOSE, MMS)	ABB SSC600 Architecture Documentation
Visualization and Diagnostics	Relay-level basic trip history	Real-time HMI + event logs + waveform analysis	ABB PCM600 Platform; Simulation Test Logs

6 Recommendations for Improving SSC600 Load Shedding Techniques

This section offers recommendations to improve the load shedding and restoration mechanisms of the ABB SSC600. The suggested improvements are based in recent research results and address current issues in smart grids, microgrids, renewable energy source integration, and low inertia environments.

6.1 Adaptive Load Shedding Based on System Inertia

The current load shedding technique in ABB SSC600 relies on preset underfrequency and Rate of Change of Frequency thresholds to initiate protective actions. This is generally more effective in traditional high inertia power systems. This setup is becoming insufficient in modern networks characterized by high penetration of RES, inverter based distributed generation and partially islanded microgrids. In these low inertia power systems frequency deviations are rapid, which reduces the time available for corrective responses. Hence these fixed frequency thresholds can lead to delayed shedding or unnecessary shedding which is not the optimal result expected.

As a solution for these limitations in SSC600, it can be enhanced with real time system inertia estimation capabilities. This will enable dynamic adjustment of load shedding and restoration parameters. Adaptive functionality is essential in high RES penetrated systems, where generation fluctuate continuously because of its intermittent nature.

6.1.1 Inertia Estimation Techniques for SSC600

Two well established techniques have emerged in recent research for estimating system inertia in real time which can be utilized to improve performance on SSC600.

6.1.1.1 Swing Equation-Based Estimation

This method derives the equivalent system inertia by analyzing the relationship between active power imbalance and the rate of frequency change during a disturbance of the power system. It is required to have highly accurate frequency data which is typically obtained from PMUs. Studies by Zhao et al. (2019) confirm the suitability of this approach for large scale grid applications with improved results compared to traditional Frequency based LS&R.

Swing Equation

The swing equation is a fundamental mathematical model used in power system dynamics to describe the rotational motion of a synchronous generator's rotor during disturbances during faults or sudden changes. It provides parameters to analyze how the generator responds to imbalances between mechanical input power and electrical output power.

$$\frac{2H}{\omega_s} \cdot \frac{d^2\delta}{dt^2} = P_m - P_e$$

δ: Rotor angle (in radians) — the angular position of the generator relative to a reference.

H: Inertia constant (in seconds) — measures the kinetic energy stored in the rotating mass at rated speed.

ω_s- Synchronous angular speed (rad/s).

P_m - Mechanical power input to the generator (per unit or MW).

P_e - Electrical power output from the generator (per unit or MW).

$d^2\delta \backslash dt^2$ - Angular acceleration of the rotor.

If $P_m>P_e$, the rotor accelerates.

If $P_m<P_e$, the rotor decelerates.

For protection function s the swing equation can be simplified,

$$\frac{df}{dt} \approx \frac{P_m - P_e}{2H \cdot f}$$

This expression indicates that the rate at which frequency changes is directly proportional to the power imbalance and inversely proportional to the inertia of the system. The lower the inertia, the more rapidly the frequency will change for the same disturbance.

6.1.1.2 Kalman Filter-Based Estimation

This technique uses iterative estimate methods to extract inertia from noisy or missing measurement data. It is especially efficacious in microgrid environments or regions high in RES, where system dynamics show more variation. Song et al. (2020) established that Kalman filters provide dependable and rapid inertia tracking, which may be directly used to inform adaptive load shedding strategies.

Kalman Filter

A Kalman Filter delivers the best estimations of system variables (such as voltage, frequency, or inertia) by forecasting their future states and refining those forecasts with actual measurements, so decreasing error over time.

Prediction,

$$\hat{x}_{k|k-1} = A\hat{x}_{k-1|k-1} + Bu_{k-1}$$
$$P_{k|k-1} = AP_{k-1|k-1}A^T + Q$$

$\hat{x}_{k|k-1}$: Predicted state at time k

P: Error covariance

A: State transition matrix

B: Control input matrix

Q: Process noise covariance

Update,

$$K_k = P_{k|k-1}H^T(HP_{k|k-1}H^T + R)^{-1}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H\hat{x}_{k|k-1})$$

$$P_{k|k} = (I - K_kH)P_{k|k-1}$$

K_k: Kalman gain

H: Observation matrix

R: Measurement noise covariance

z_k: Actual measurement at time k

6.1.1.3 Adaptive Load Shedding Logic in SSC600

SSC600 functionality and logic can be improved to establish communication with PMU via IEC61850 and calculate accurate system inertia. With the availability of the accurate system inertia SSC600 can dynamically modify the following parameters for improved load shedding.

ROCOF Setpoints - Lower inertia systems require more sensitive ROCOF thresholds to initiate timely load shedding.

Shedding Step Sizes and Delays - Development of logic based on adaptive inertia can reduce time delays between shedding stages and adjust the percentage of load shed on each step. For instance, faster shedding may be necessary when inertia is low to prevent frequency collapse. Nguyen et al. (2021) proposed similar adaptive load shedding schemes in their centralized protection framework.

Restoration Thresholds and Timing - Following a load shedding, SSC600 currently must delay restoration until system stability is confirmed. Traditional high inertia systems recover quickly and allow quicker reconnection of loads. While low inertia grids may require additional time to recover. Hossain et al. (2017) emphasizes the importance of aligning restoration timing with system dynamics to prevent oscillations or secondary trips due to load restoration.

The proposed adaptive load shedding enhancement based on system inertia can be realistically implemented in the ABB SSC600 using its existing digital infrastructure, logical control and engineering tools. The configuration process can primarily be carried out through ABB PCM600.

6.1.2 Implementation of Adaptive Load Shedding Logic in SSC600

Real-Time Data Acquisition

PMU/IED Integration- Set up the SSC600 to acquire high-resolution frequency, voltage, and power data from PMUs or high-speed IEDs via IEC 61850 Sampled Values (SV) and GOOSE messaging. And to map the incoming data to new input signals to access in improved function blocks.

Inertia Estimation Logic Deployment

Custom Function Block can be designed utilizing PCM600's Graphical Function Block Editor (GFBE) to run a streamlined inertia estimation model. For instance, it can simulate the swing equation or implement Kalman filter logic using mathematical and logical blocks. The developed function block will be able to calculate and provide the output of the estimated inertia.

Adaptive ROCOF Logic Block Implimentation

The following block diagram illustrates a logical flow for implementing Adaptive Rate of Change of Frequency trigger logic within ABB PCM600 for the SSC600 device. The system begins with two predefined ROCOF threshold constants. One for high inertia conditions and another for low inertia scenarios. A selector block (SEL) dynamically chooses between these thresholds based on a binary input signal representing the current grid condition or mode such as a low inertia flag. The chosen adaptive threshold is then compared against the actual measured ROCOF signal using a greater than (GT) comparator. If the ROCOF exceeds the selected threshold, the output activates a timer on delay (TON) block to filter out transient spikes and ensure stability. Once the delay elapses, a final trip condition output is activated. This output can be routed to a load shedding function, breaker trip logic, or alarm trigger. The diagram demonstrates how logic components in PCM600 can be arranged to make the ROCOF based protection scheme responsive to real-time system conditions, allowing for smarter and more reliable protection in variable inertia power systems

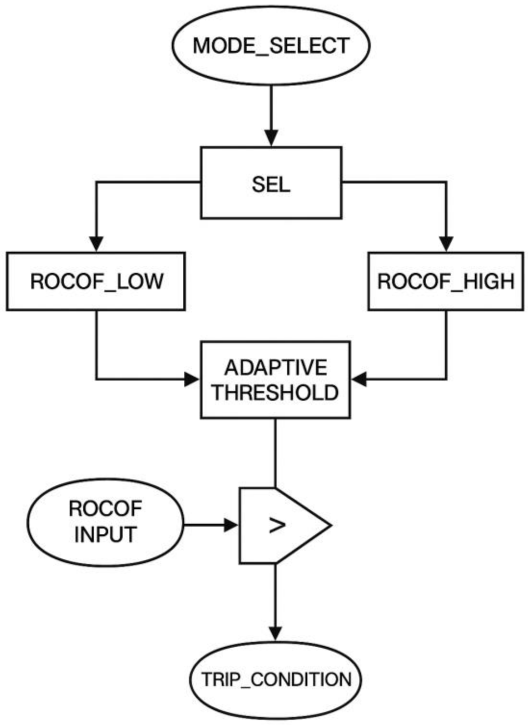


Figure 24- adaptive function block flow diagram

SWING Equation Implementation

Although ABB PCM600 does not support differential equations directly, a simplified approximation of the swing equation can be implemented using standard function blocks. The approach involves estimating the system's ROCOF based on the power imbalance between generation and load. Within PCM600's Function Block Diagram editor, summing blocks and logical Not are used to compute the difference between measured or simulated mechanical power input and electrical load demand. This result is then divided by the product of the inertia constant and real-time frequency, calculated using multiplication and division blocks. The resulting ROCOF estimate can be fed into a comparator to trigger load shedding when it exceeds a dynamic threshold. Timers and logical gates can be added to refine this trigger signal, creating an adaptive ROCOF-based protection mechanism that responds to real-time grid conditions. This method allows SSC600 to emulate the swing equation's behavior and enhance its responsiveness in low-inertia power systems, improving overall system stability.

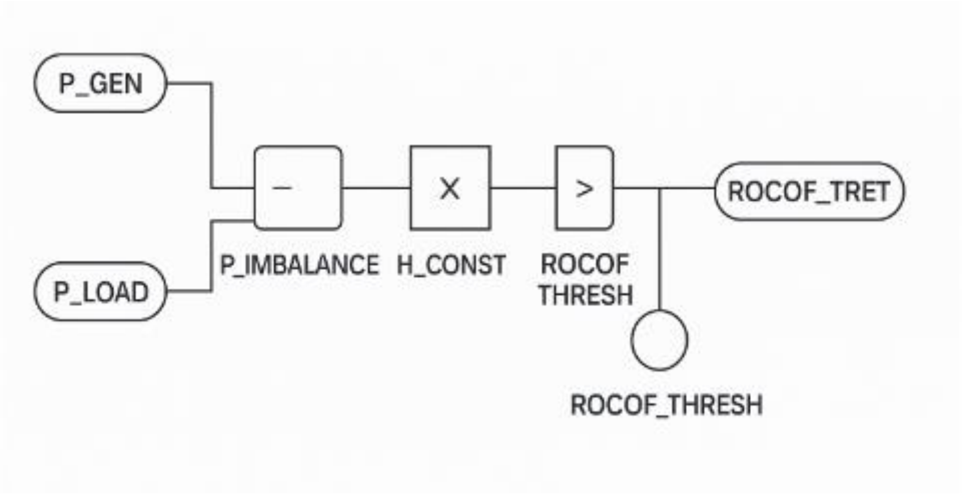


Figure 25- Swing equation function

Adaptive Threshold Control

Dynamic Setpoint Adjustment - Based on the real time inertia value gathered from the new function block it can design conditional logic that adjusts the following.

- ROCOF thresholds
- Underfrequency thresholds
- Shedding time delays and step sizes

This can be implemented using comparator blocks, lookup tables, or PID-based scaling mechanisms within PCM600's logic editor.

Load Shedding Logic Extension

Modification of the existing LSHDPFRQ function in SSC600 or to develop a new function that provide accurate LS&R in RES environment to reference the dynamically calculated threshold values.

Monitoring and Visualization

Additionally, a useful function of SSC600 is the visualization and data recording possibilities. Using it the following can be visualized and identify

- Estimated inertia value
- Active ROCOF/frequency setpoints
- Shedding status and active step

These variables can be displayed on the SSC600's HMI or can be communicated SCADA interface via IEC 61850 MMS or Web UI for operator situational awareness.

6.1.3 Expected Benefits of Inertia Adaptive Load Shedding in SSC600

1. Faster and Accurate Protection Response

By adjusting ROCOF and frequency thresholds in real time, SSC600 can detect and react to disturbances more precisely. Especially in low inertia systems where traditional fixed settings may respond too late. Which is a positive development in improving the integration of RES to modern power grids.

2. Reduced Risk of Cascading Failures

Early detection of instability allows the system to shed just enough load to stabilize frequency before it collapses further which significantly reducing the likelihood of system wide blackouts.

3. Minimized Over or Under Load Shedding

Adaptive thresholds prevent unnecessary load disconnection improving power quality and customer satisfaction.

4. Improved Integration of Renewable Energy Sources

The strategy accommodates the variable inertia introduced by inverter-based renewables, making SSC600 more effective in managing future grids with dynamic generation characteristics.

5. Cost Efficient Upgrade Path

with SSC600 it provides the possibility to upgrade newly implemented features without the requirement no new hardware. New functions can be implemented via PCM600 and update to the system. This solution provides to power system operators an affordable solution and the possibility to upgrade the systems remotely with minimal effort.

6. Improved Situational Awareness and Operator Control

With SSC600 visualization tools real time visualization of inertia, shedding status, and thresholds helps operators better understand system behaviour and, improve decision making process during emergencies or restoration. Additionally, with the communication techniques the data can be centrally viewed and monitored when integrated with SCADA.

6.2 Integration of Voltage Stability Margin Monitoring

The existing load shedding algorithms in the ABB SSC600 predominantly depend on underfrequency and ROCOF detection to preserve system integrity. This method fails to consider voltage instability, which may arise independently of frequency irregularities, particularly in grids with significant RES integration and inadequate voltage support. Voltage collapse, sometimes caused by inadequate reactive power or overloaded transmission lines, can initiate cascading failures prior to the detection of frequency deviations.

Recent research literature emphasizes the essential function of including voltage stability indicators into centralized load shedding mechanisms. In the research Nguyen et al. (2021) indicates that centralized adaptive shedding, based on real time voltage stability margins, significantly improves system reliability during weak conditions. And Hossain et al. (2017) highlighted the application of voltage sensitivity indices (VSIs) to evaluate the of actual voltage compared to voltage instability. Integrating these insights into SSC600 would provide protective measures that are more voltage sensitive that is adapted to changing grid conditions.

6.2.1 Implementation in SSC600

Incorporation of Real Time Voltage Sensitivity Indices - Enhance SSC600's measuring functionalities to continually calculate VSI by utilizing real-time voltage and reactive power data from PMUs and IEDs through IEC 61850, GOOSE, and Sampled Values protocols. These indicators measure the impact of minor fluctuations in reactive power demand at a node on voltage magnitude, facilitating dynamic identification of vulnerable grid areas.

Dynamic Load Shedding Triggers - Adjust the SSC600 LSHDPFRQ logic block to include voltage sensitivity criteria. When the VSI for a feeder or node surpasses a critical threshold, SSC600 must activate a load shedding signal to the corresponding load prior to the violation of conventional frequency limitations. This method aids in mitigating the progression of voltage instability at an early stage.

Including Voltage Stability Margins into load shedding setpoints - Implement new customizable parameters inside SSC600's protection framework that enable operators to establish crucial VSI or Q-margin values as setpoints. These can be utilized in combination with frequency and ROCOF thresholds, providing the device with a multi-criteria foundation for preventive measures.

6.2.2 Expected Benefits of Integration of Voltage Stability Margin Monitoring

The integration of VSI, dynamic load triggers to identify voltage sensitivity and including voltage stability margins into SSC600 will improve its effectiveness in managing modern grid with higher penetration of RES. The following benefits outline how the above discussed improvements can benefit a more reliable, efficient, and intelligent load shedding and restoration system.

1. Proactive Voltage response

Integrating VSI and V-Q curve monitoring into the SSC600 enhances its capacity to identify early stage voltage instability prior to the activation of conventional frequency-based triggers. This resulted in a strategy for control centers implementing preventive load shedding in situations where reactive power shortage or line congestion would cause a voltage collapse. SSC600 visualization tools and measurements can interface with SCADA to activate alarms. The intermittent nature and reduced inertia in renewable energy source integrated systems make voltage interruptions more frequent and unexpected. The potential for early identification will reduce the probability of cascade tripping and blackouts.

2. Random Load Shedding

Instead of implementing section-wide disconnections, VSI-based load shedding allows precise control. This focused strategy reduces unnecessary load disconnection and helps to maintain electricity supply to essential facilities such as hospitals, data centers, and industrial areas which are dependent on the electricity availability. As SSC600 has the possibility to control 30 feeders it can create scenarios that would randomly select the weak feeders rather than pre identified feeders tripping as standard.

3. Improved Coordination with Reactive Power Support Devices

The above proposed methods allow SSC600 to interface with Flexible AC Transmission Systems (FACTS) which provide reactive power support. Equipment, such as shunt capacitor banks, STATCOMs, and on-load tap changers (OLTCs). Communication, especially with STATCOM, can create logic that load shedding would only be triggered if these devices are operating near their limits or are unable to restore voltage within acceptable thresholds. FACTs devices are becoming more popular in Wind energy applications and the generation variation triggered load shedding can be identified and eliminated.

4. Enhanced Suitability for Smart Grid and RES-Enriched Environments
Modern smart grids are demanding protection and control systems that have the capability to include adaptable, data driven, and resilient to fluctuations caused by RES. With the improvements made in voltage stability margins into SSC600's it can improve situational awareness. And it enables the device to handle increased dynamic impacts of intermittent generation and localized voltage problems that are inadequately addressed by frequency based logic.

6.3 Integration of Smart Loads for Underfrequency Load Shedding in Low-Inertia Grids

6.3.1 Identified Limitation

ABB SSC600's current load shedding logic considers all loads as static and lacks the differentiation between conventional passive loads and smart loads that can be controlled. The new approach focusses on the potential of smart loads such as HVAC systems, electric vehicle (EV) chargers, and industrial appliances that can adjust their power consumption dynamically with response to grid conditions. In low inertia grids where frequency deviations occur rapidly due to high penetration of RES leveraging smart loads for frequency stabilization can lead to improved load shedding and efficient power systems.

6.3.2 Proposed Enhancement

To improve SSC600 current effectiveness in modern grid environments, it is recommended to integrate smart load management into its UFLS scheme. This integration via wide communication methodologies in SSC600 enables to interact with demand side controllable loads. The power grid today is heavily investing in smart grid and communication between loads and control centres to provide the optimal balance between generation and consumption maintain the network conditions.

- Load Modulation Signals - By producing signals that can be sent to smart loads to temporarily lower power use during frequency drops, the by which the SSC600 can helps to eliminate the need for fast load disconnection.
- Device-Level Frequency Response - SSC600 can be integrated with Distributed Energy Resource Management Systems (DERMS) or Energy Management Systems (EMS) locally to coordinate frequency response for smart appliances, ensuring a combined demand side response for frequency events.

There is increasing number of research carried out on how to utilize smart loads in UFLS schemes to enhance frequency stability in low-inertia grids. In a similar research Darbandsari and Amraee (2022) propose a multistage UFLS plan activated by smart loads, demonstrating improved frequency response and reduced load shedding requirements that lead to improved results in grid availability.

6.3.3 Implementation in SSC600

Smart loads can be integrated to SSC600 in following method,

1. Communication Infrastructure: Establishing reliable communication channels between SSC600 and smart loads. The device has already built up from Native IEC61850 helps in improving the capabilities beyond traditional protection and control. GOOSE message can be used for fast and reliable data transmission.
2. Load Identification and Classification: The connected load and feeders can be classified by the characteristic of its connected loads. The possibility control 30 feeders with once SSC600 device provide the capability monitor more loads and to develop customize targeted load shedding function.
3. Integration with DERMS/EMS: Communication and coordinating with higher level monitoring and management systems to ensure that load control actions align with broader grid management objectives and industry practices.

6.3.4 Expected Benefits from Integration of Smart Loads for Underfrequency Load Shedding in Low-Inertia Grids

The integration of smart loads into SSC600 for LS&R introduces a futuristic shift for frequency stability and demand side flexibility managed in modern power systems. This approach not only modernizes protective functions but also creates key benefits that are outlined below,

1.Reduced Service Disruption
Traditional load shedding strategies often affect large numbers of customers during load shedding. With the incorporation of controllable smart loads such as HVAC systems, EV charging stations, and commercial appliances SSC600 can implement targeted highly efficient demand reductions. This approach can ramp down or cycle offloads temporarily without fully disconnecting. Will lead to service availability and improving customer satisfaction during uncontrollable grid events.

2. Improved Grid Resilience
Particularly in low-inertia or isolated grids where system stability can decline quickly, smart load integration improves the overall resilience of the power system. The capacity to regulate demand in reaction to frequency changes lowers dependence on slower generation reactions.

3. Facilitation of Renewable Integration
High levels of RES penetration introduce both power fluctuations and reduced system inertia. Smart loads act as fast acting, flexible balancing assets, helping to support the volatility of RES output. When the load is dynamically adapted based on frequency or forecasted generation changes it improves the hosting capacity of renewables and reduces curtailment events. SSC600 integration with DERMS or EMS will be supporting this cause.

7 Business Case for SSC600

The current energy sector is growing towards smart grid and more RES integration, in that context maintaining power system stability has become increasingly complex and arises the need for improved grid resilience. Traditional protection schemes, often decentralized and static struggle to respond efficiently to these new dynamic grid conditions. Due to these requirements, it is required to have smarter, faster and more coordinated protection solutions. The ABB SSC600 centralized protection and control unit offers a next-generation future proof approach to managing critical protection and control functions such as load shedding and restoration. With the centralized decision-making and enabling intelligent control logic to SSC600 allows utilities and industrial operators to enhance power system reliability and optimize operational efficiency. This chapter will focus on business cases that outline the value proposition, technical benefits, and financial impact of implementing SSC600 based centralized load shedding and restoration schemes in modern power systems.

7.1 Advantages of SSC600 in Load Shedding and Restoration

Centralized Decision-Making

The ABB SSC600 provides faster and more coordinated actions through centralized protection and control and having the possibility to control up to 30 feeders with one device. In other hand traditional power systems rely on distributed protection relays at each feeder, which may result in delayed responses and coordination issues during grid disturbances. The SSC600 consolidates multiple protection functions into a single device and this centralization of P&C ensures that load shedding and restoration decisions are made in real-time which significantly improve the response time to disturbances caused by underfrequency and ROCOF events.

SSC600 can integrate multiple protection functions into one device. And the product is designed as a way it can combine multiple protection packages. For instance, frequency based load shedding (81LSH) can be combined with protection functions like busbar differential protection (87B) which will allow disturbances to be quickly detected and isolated, minimizing the potential for cascading failures and system wide outages. The LS&R protection function in SSC600 prioritizes less critical loads for shedding and maintaining essential loads. The time between fault identification and implementation of corrective actions is significantly reduced in SSC600 which improves grid stability and enhances the overall reliability of the power system.

Protection System	**Response Time (Seconds)**	**Key Advantages**
Distributed Protection	2-5	Relays respond independently, leading to potential delays in coordination.
Centralized SSC600	<1	Real-time monitoring and synchronized actions for faster system stability.

Table 6- comparison between distributed protection vs centralized SSC600

Simplified System Architecture

The ABB SSC600 simplifies protection system design by consolidating multiple protection, control and communication functions into a single integrated device. In traditional protection schemes each feeder is connected to a dedicated protection relay for its functionality leading to a complex and costly system with extensive wiring and installation. But the SSC600 system can manage up to 30 feeders from a single central unit, significantly reducing the number of devices required and simplifying the overall infrastructure. The system can gather measurements via merging units at each end of the feeder and all the measurements are communicated to SSC600 and the protection functions are carried out centrally and the trip functions are communicated which will reduce the overall response time in the system.

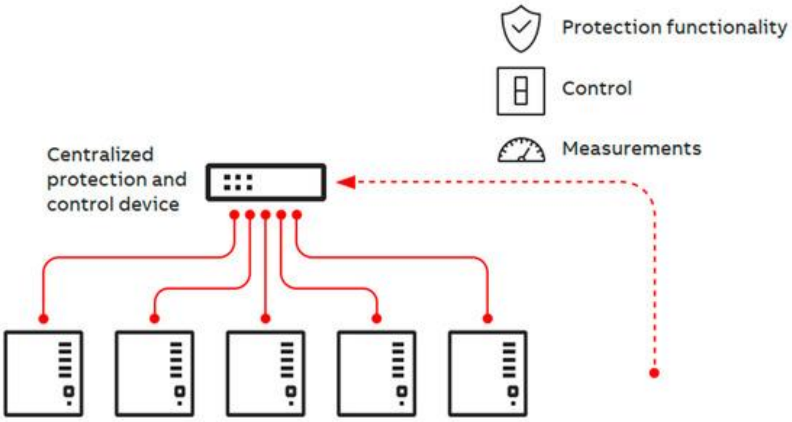


Figure 26 - SSC600 system architecture

This centralized approach not only reduces capital expenditure (CAPEX) but also lowers operational expenditure (OPEX) due to fewer components and simplified maintenance. The modular design of SSC600 enables easy scalability as the system evolves, without the need for major hardware upgrades. The SSC600 can start with few feeders and evolve up to 30 feeders in the future as the network grows. Additionally, the system supports remote configuration and diagnostics via ABB's own Engineering tool PCM600 software. This allows operators to modify settings, simulate events, and troubleshoot remotely, reducing the need for on-site interventions. And it has the possibility to upgrade any additional protection function in the future such as motor protection or differential protection.

Overall, SSC600 provides simplified architecture that enables long term cost savings, reduces system complexity and ensures easy maintenance.

Table 7- Comparison and benefits

Criteria	**Traditional Distributed Protection Systems**	**SSC600 Centralized Protection System**
CAPEX (Capital Expenditure)	High due to the need for multiple relays, wiring, and separate devices for each feeder.	Low due to the consolidation of multiple protection functions into a single device.

OPEX (Operational Expenditure)	High due to higher maintenance costs, more components to manage, and potential for greater system failures.	Low due to fewer components, integrated functions, and reduced system downtime.
Maintenance Complexity	High complexity, requiring individual inspection and maintenance of each relay and device.	Low complexity, with fewer components to manage and easier diagnostics via PCM600 software.
Installation Time	Long due to extensive wiring, installation of multiple protection relays, and testing each feeder independently.	Short, as fewer physical components need to be installed, and the central unit manages all feeders.
Scalability	Difficult and costly to scale, requiring additional relays and equipment for each new feeder or protection function.	Easy to scale, with the ability to add more feeders or protection functions without significant hardware changes.
System Reliability	Lower reliability due to the increased number of components that can fail.	Higher reliability due to reduced number of components and centralized control.
Fault Detection & Response	Slower response time due to possible coordination delays between distributed relays.	Faster response time with coordinated load shedding and fault isolation from a centralized unit.
System Flexibility	Limited flexibility as each relay operates independently with fixed settings.	High flexibility with modular software, allowing remote updates and reconfigurations.
Integration with Other Systems	Difficult and costly to integrate with other protection systems or substation automation due to decentralized nature.	Easy integration with existing automation systems through IEC 61850 and centralized control.

Table 8 - Comparison of benefits between traditional and centralized protection

Integrated Protection Schemes in SSC600

The ABB SSC600 is designed to support advanced protection function packages that can be flexibly combined offering a highly integrated and efficient solution for power system protection. Single SSC600 can manage multiple protection functions which significantly simplifies the overall system architecture. For instance, frequency-based load shedding (81LSH) can be implemented alongside busbar differential protection (87BB), overcurrent protection (50/51), earth fault protection (50N/51N), and breaker failure protection (BFP).

The combination of these protection functions in a single device enhances operational transparency by reducing the number of devices that need to be monitored and maintained. It also improves coordination among protection elements, which minimizes the risk of faults propagating and causing more severe system disturbances. One critical issue in using a centralized single device for protection is that it will introduce a single point of failure to the system. This can be overcome by introducing redundancies to the system as defined below.

Method 01

The primary data collection points for merging units can be replaced with basic protection relays. The SSC600 is used as the main complex protection function and other relays as the secondary protection device.

Redundant communication with PRP Time synchronization via the IEEE 1588 v2 GPS master or a relay acting as backup time master.

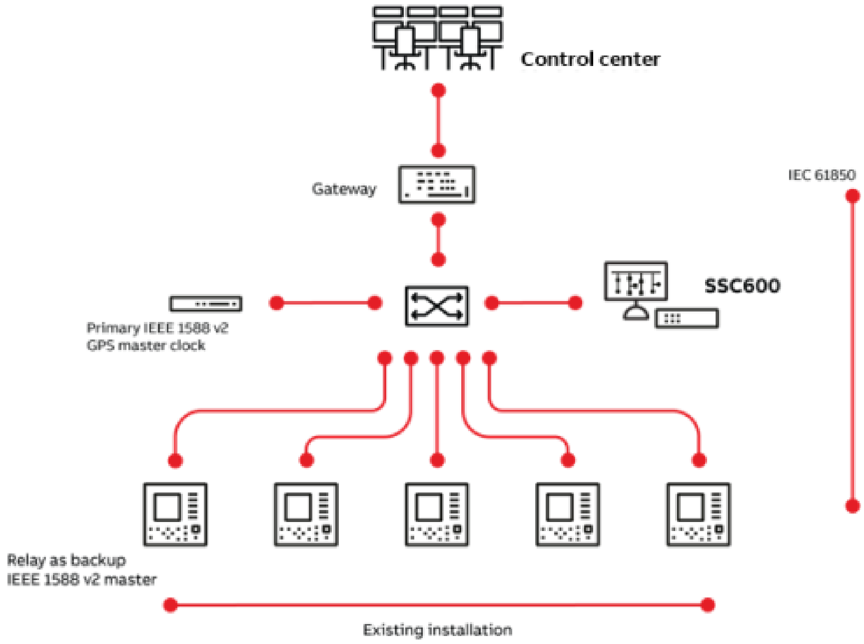


Figure 27- SSC600 connected via protection relays for backup

Method two

Two SSC600 devices and one gateway to the SCADA system

- Redundant power supply in SSC600
- Both SSC600 devices in hot-hot redundancy mode
- Redundant communication with PRP
- Time synchronization via the IEEE 1588 v2 GPS master and backup time master from MU or secondary GPS master

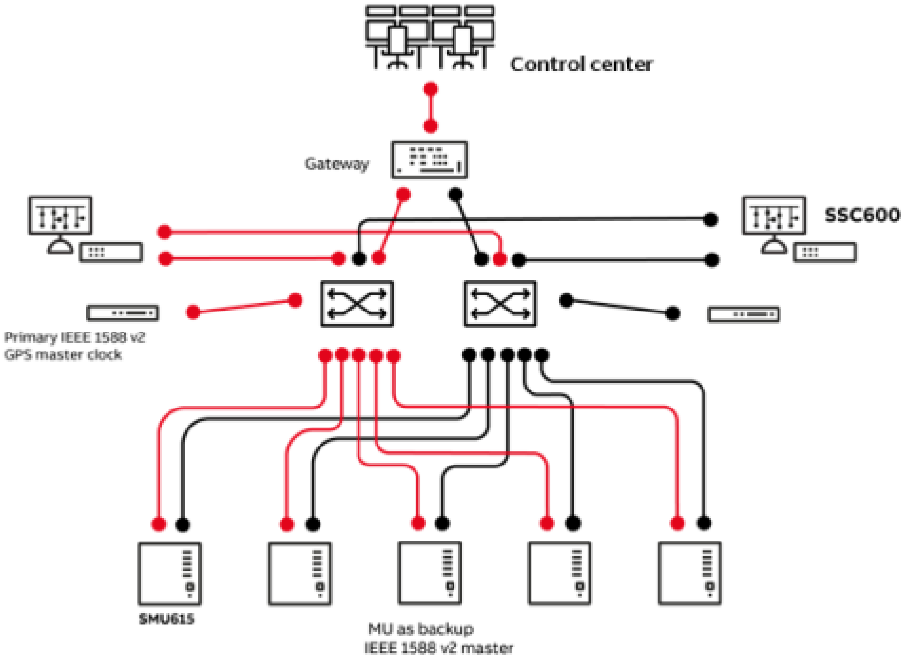


Figure 28- SSC600 full redundant architecture

This integrated centralized approach introduced by SSC600 not only improves the overall reliability and stability of the power network but also leads to cost savings by reducing the need for additional hardware, wiring, and maintenance activities.

7.2 Example Business case

7.2.1 Implementation of SSC600 in a Renewable Energy Integrated Power Grid

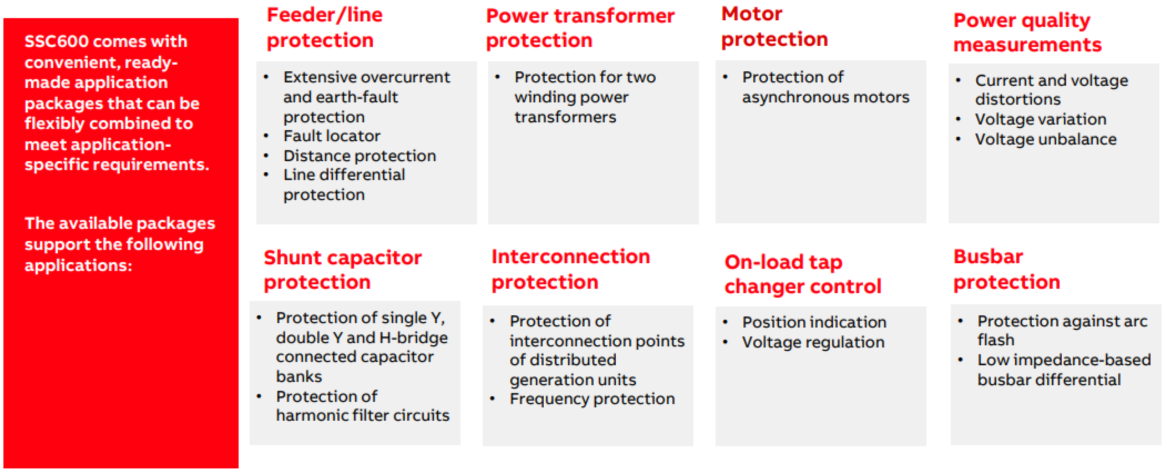
The integration of renewable energy sources such as wind and solar power into the power grid is becoming more important as the power grids are shifting towards sustainable solutions. However, integrating renewable energy sources often brings one major challenge due to their intermittent nature leading to fluctuations in supply. In this business case, the ABB SSC600 protection system is proposed for integration into a high renewable energy integrated power grid. The SSC600 could combine several protection functions, such as Busbar Differential Protection and Frequency Based Load Shedding and Restoration techniques as a solution to mitigate grid instability caused by renewable energy generation variability.

7.2.1.1 Overview

In this renewable energy integrated power grid, the main challenge is maintaining grid stability in the face of fluctuating renewable energy inputs and to ensure that faults are isolated in time to avoid cascade disruption.

SSC600 is developed making it possible to select suitable protection functions as per the preset application packages. The SSC600 Application pages are shown below.

7.2.1.2 How to Combine Busbar Differential Protection and Load Shedding



SSC600 comes with convenient, ready-made application packages that can be flexibly combined to meet application-specific requirements.

The available packages support the following applications:

Feeder/line protection
- Extensive overcurrent and earth-fault protection
- Fault locator
- Distance protection
- Line differential protection

Power transformer protection
- Protection for two winding power transformers

Motor protection
- Protection of asynchronous motors

Power quality measurements
- Current and voltage distortions
- Voltage variation
- Voltage unbalance

Shunt capacitor protection
- Protection of single Y, double Y and H-bridge connected capacitor banks
- Protection of harmonic filter circuits

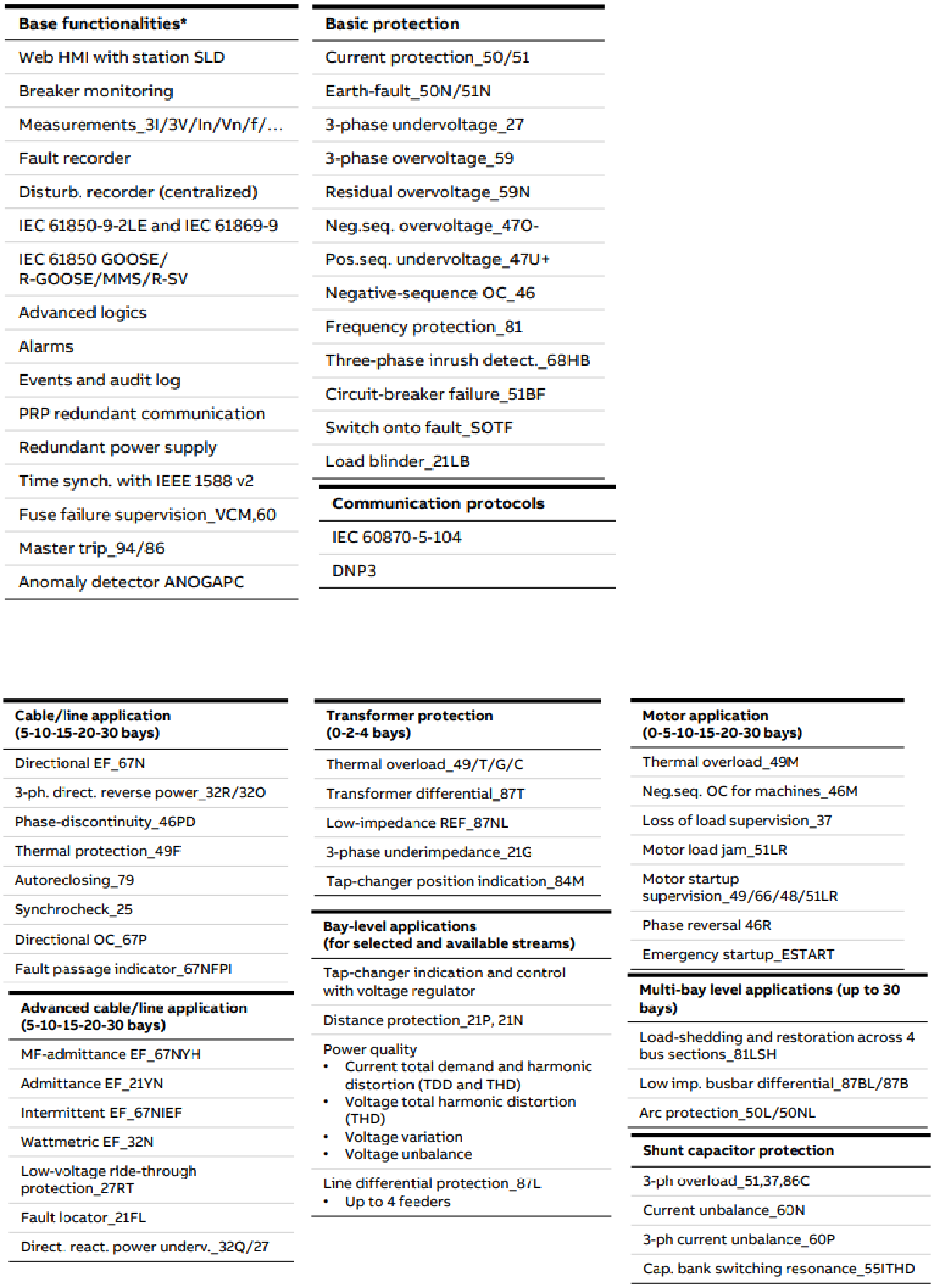
Interconnection protection
- Protection of interconnection points of distributed generation units
- Frequency protection

On-load tap changer control
- Position indication
- Voltage regulation

Busbar protection
- Protection against arc flash
- Low impedance-based busbar differential

Figure 29- SSC600 application packages

SSC600 provides the flexibility to combine several packages as per the required protection requirements in the grid. The diagram below illustrates what the available protection function under each application package.



Base functionalities*
Web HMI with station SLD
Breaker monitoring
Measurements_3I/3V/In/Vn/f/...
Fault recorder
Disturb. recorder (centralized)
IEC 61850-9-2LE and IEC 61869-9
IEC 61850 GOOSE/ R-GOOSE/MMS/R-SV
Advanced logics
Alarms
Events and audit log
PRP redundant communication
Redundant power supply
Time synch. with IEEE 1588 v2
Fuse failure supervision_VCM,60
Master trip_94/86
Anomaly detector ANOGAPC

Basic protection
Current protection_50/51
Earth-fault_50N/51N
3-phase undervoltage_27
3-phase overvoltage_59
Residual overvoltage_59N
Neg.seq. overvoltage_47O-
Pos.seq. undervoltage_47U+
Negative-sequence OC_46
Frequency protection_81
Three-phase inrush detect._68HB
Circuit-breaker failure_51BF
Switch onto fault_SOTF
Load blinder_21LB

Communication protocols
IEC 60870-5-104
DNP3

Cable/line application (5-10-15-20-30 bays)
Directional EF_67N
3-ph. direct. reverse power_32R/32O
Phase-discontinuity_46PD
Thermal protection_49F
Autoreclosing_79
Synchrocheck_25
Directional OC_67P
Fault passage indicator_67NFPI

Advanced cable/line application (5-10-15-20-30 bays)
MF-admittance EF_67NYH
Admittance EF_21YN
Intermittent EF_67NIEF
Wattmetric EF_32N
Low-voltage ride-through protection_27RT
Fault locator_21FL
Direct. react. power underv._32Q/27

Transformer protection (0-2-4 bays)
Thermal overload_49/T/G/C
Transformer differential_87T
Low-impedance REF_87NL
3-phase underimpedance_21G
Tap-changer position indication_84M

Bay-level applications (for selected and available streams)
Tap-changer indication and control with voltage regulator
Distance protection_21P, 21N
Power quality • Current total demand and harmonic distortion (TDD and THD) • Voltage total harmonic distortion (THD) • Voltage variation • Voltage unbalance
Line differential protection_87L • Up to 4 feeders

Motor application (0-5-10-15-20-30 bays)
Thermal overload_49M
Neg.seq. OC for machines_46M
Loss of load supervision_37
Motor load jam_51LR
Motor startup supervision_49/66/48/51LR
Phase reversal 46R
Emergency startup_ESTART

Multi-bay level applications (up to 30 bays)
Load-shedding and restoration across 4 bus sections_81LSH
Low imp. busbar differential_87BL/87B
Arc protection_50L/50NL

Shunt capacitor protection
3-ph overload_51,37,86C
Current unbalance_60N
3-ph current unbalance_60P
Cap. bank switching resonance_55ITHD

Figure 30- Protection functions in SSC600 application packages

Busbar Differential Protection (87BB)

The busbar differential protection function in the SSC600 will monitor all connected feeders up to 30. Based on low impedance principles it detects any differences between the incoming and outgoing currents and isolates faults within milliseconds, thereby minimizing the risk of further system damage. This protection is particularly useful in a grid with high renewable energy penetration, as RES generation can lead to voltage and current fluctuations that may cause faults on the busbar. SSC600 has the capability to create 4 protection zones across connected feeders and one check zone to identify any faults in the single bus or bus section.

Frequency-Based Load Shedding

Renewable energy integration often leads to imbalances between supply and demand. As a solution to maintain the balance the frequency based load shedding function in SSC600 continuously monitors the grid frequency. When the frequency drops below a pre-defined value due to generation changes or increase in demand, SSC600 automatically initiates load shedding to maintain the system balance. The noncritical and lowest priority loads can be shed in a controlled manner to allow the system frequency to stabilize.

Load Restoration

After a fault condition and system stabilizes, the frequency will return to normal levels, SSC600 has the capability to automatically restore the previously shed loads. And has the possibility to operate in manual mode and blocked mode for restoration, providing the possibility to operators to reconnect loads as required. The automatic restoration is done stepwise, ensuring that the load is gradually reintroduced to avoid any overloading of the system again.

7.2.3 Benefits of SSC600 in Renewable Energy Integrated Grids

1. Enhanced Stability with Renewable Energy Integration

The combination of low impedance busbar differential protection and frequency based load shedding ensures that the power grid remains stable even when renewable energy inputs fluctuate. SSC600 can quickly respond to both faults and frequency imbalances to maintain the system stability.

2. Reduced Operational Downtime

SSC600 integrated with frequency based load shedding and automatic restoration strategies minimizes the downtime of the energy supply caused by disturbances. This ensures that critical grid functions resume quickly, improving overall reliability.

3. Cost Savings

With the possibility of combining multiple protection functions into a single device, SSC600 reduces the need for separate protection relays in each feeder which reduces capital costs. SSC600 ability to monitor and protect up to 30 feeders from one unit further minimizes infrastructure, installation and maintenance costs

4. Simplified Management

SSC600 can be primarily modified via PCM600 software and upload improved protection functions remotely. This helps in configuration, monitoring, and diagnostics of protection schemes, allowing operators to manage all protection functions from a single interface and remotely. This approach reduces operational complexity and simplified process for resource management.

7.2.4 Return of Investment with SSC600

The integration of SSC600 in a renewable energy grid can be achieved in phases, starting with the installation of frequency based load shedding and busbar differential protection on key grid sections. It can then be combined with full integration of all protection functions to a single SSC600 device.

SSC600 integration into power grids with high renewable energy penetration provides considerable ROI. Mainly driven by the ability to enhance grid stability, reduce capital expenditures (CAPEX) and improve electricity availability. The key components contributing to the ROI are as follows,

1. Reduced Capital Expenditures (CAPEX)

The SSC600 system consolidates multiple protection functions into a single unit. The combined system CAPEX cost is significantly lower than integrating relay in every single feeder. This provides initial capital investments in hardware, installation, and infrastructure.

2. Lower Operational Costs (OPEX)

The integrated nature of SSC600 reduces maintenance and operational costs by minimizing the number of physical devices in the power system. And reduce the cost of maintenance and keeping spares. Additionally, the fleet management from ABB provide network operators to seamlessly monitor the performance and health of each device remotely. Which will reduce the downtime or maintenance and replacement of faulty devices. The SSC600 has the possibility to expand and improve protection functions as the power grid grows. Since the power grids are evolving rapidly, it reduces the risk of changing the entire systems in a few years as the demand and system structure changes. With SSC600 it is simply possible to add more feeders and additional protection functions as required in future.

3. Reduced Downtime and Enhanced Grid Stability

As the result of SSC600 rapid fault isolation and LS&R functions the grid recovery times during grid disturbances are lowered. Leading to fewer interruptions in power supply and low interruption periods. This improved system reliability reduces revenue losses caused by outages and triggered load shedding enhances overall grid performance and contributes to a higher ROI over time.

8 Conclusion

This thesis investigated the implementation and enhancement of a centralized load shedding and restoration strategy using the ABB SSC600 in the context of future smart power systems. With increasing integration of renewable energy sources, modern grids are experiencing greater variability and lower system inertia conditions that challenge the effectiveness of traditional, decentralized protection schemes. In response, this work explored how centralized architectures, adaptive logic, and high speed communication protocols can contribute to improved grid stability and operational reliability.

The ABB SSC600, a centralized intelligent electronic device compliant with IEC 61850 standards, was configured using PCM600 engineering software to simulate load shedding and restoration in a medium-voltage substation. The modeled substation architecture included two incomer feeders, one from a conventional power source and another from a renewable energy source along with multiple outgoing feeders representing distributed load points. This hybrid configuration allowed the SSC600 to monitor real-time system parameters across the entire substation, enabling coordinated control actions. Through this setup, the device demonstrated its ability to selectively disconnect non-critical feeders during underfrequency or ROCOF events and to restore them in a staged manner as system conditions recovered.

The system's performance was evaluated through two representative simulation scenarios designed to reflect realistic grid disturbances. The first scenario involved a gradual decline in system frequency due to a sudden reduction in renewable energy output, while the second tested the device's response to a rapid frequency deviation coupled with a steep rate of change conditions typical of low inertia power systems. During both cases, the SSC600 responded promptly and initiated appropriate load disconnection sequences within less than one second. After the situation once the system frequency stabilized, the restoration process commenced in a controlled, stepwise manner, successfully bringing loads back online without inducing instability.

Beyond performance validation, the thesis introduced adaptive enhancements aimed at future proofing SSC600 based protection strategies. These included real-time ROCOF threshold adjustments based on estimated system inertia, voltage stability monitoring through sensitivity indices, and integration with smart, controllable loads. These improvements suggest how the functional logic blocks in PCM600 can be implimented including a simplified implementation of the swing equation and inertia adaptive control structures. The recomendation support the feasibility of using SSC600 not only as a protection relay but as an intelligent grid stability manager.

A business case developed in collaboration with ABB confirmed the economic and operational advantages of centralized protection. Compared to traditional distributed relays, SSC600 significantly reduces hardware costs, simplifies system architecture, enables remote configuration, and scales easily with network expansion. Its compatibility with GOOSE messaging and real-time data visualization through WHMI further reinforces its suitability for modern substation automation.

In summary, this thesis demonstrates that the SSC600 provides a robust, flexible, and scalable foundation for implementing advanced load shedding and restoration strategies. Its centralized architecture, fast decision-making capabilities, and adaptability to evolving grid conditions make it an ideal solution for ensuring power system stability in high RES, low inertia environments. The findings support the wider deployment of intelligent centralized protection systems as a cornerstone of smart and sustainable energy infrastructure.

9 Future work

This thesis has explored the load shedding techniques in ABB SSC600, with a focus on addressing the limitations of traditional fixed-threshold schemes in low inertia, renewable energy dominated power systems.

The findings from the thesis derive the need for further development and implementation of advanced protection strategies that incorporate real time dynamics mainly the power system inertia. A key area for future work involves integrating real time inertia estimation directly into the SSC600 control logic. As identified within the thesis techniques such as swing equation based calculations and Kalman filter estimation offer promising methods for evaluating system inertia. However, these to be integrated within the SSC600 environment requires deeper investigation and to develop logic and functional blocks that can operate within the device's computational constraints.

Future work can also investigate how SSC600 can be integrated with external monitoring and management systems. By incorporating data from PMUs, and smart loads via IEC61850 communication. This approach could evolve SSC600 into a more proactive grid P&C device. Such integration would enable the load shedding function by anticipation of inertia drops, generation changes and load changes rather than responding only after disturbances occur.

Another significant direction for future research lies in the possibility of combining AI and machine learning algorithms for predicting frequency fluctuation and generation shifts in RES.

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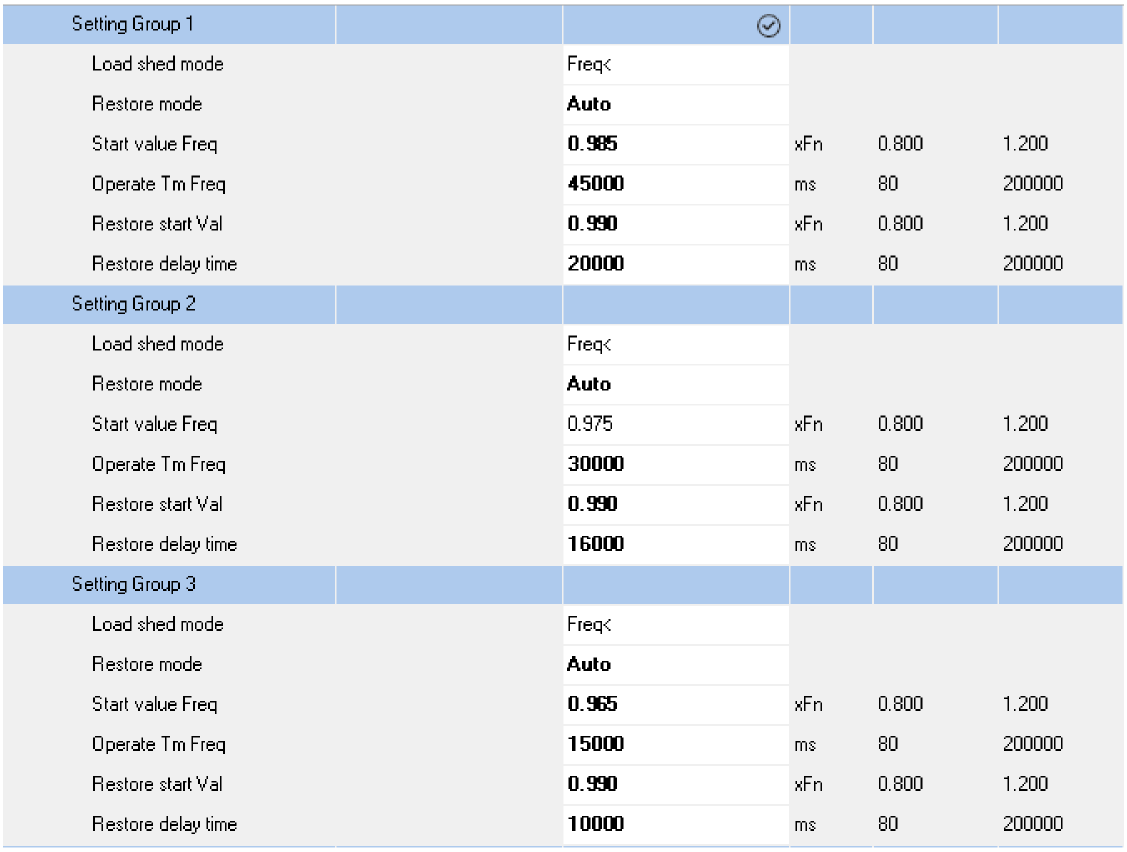
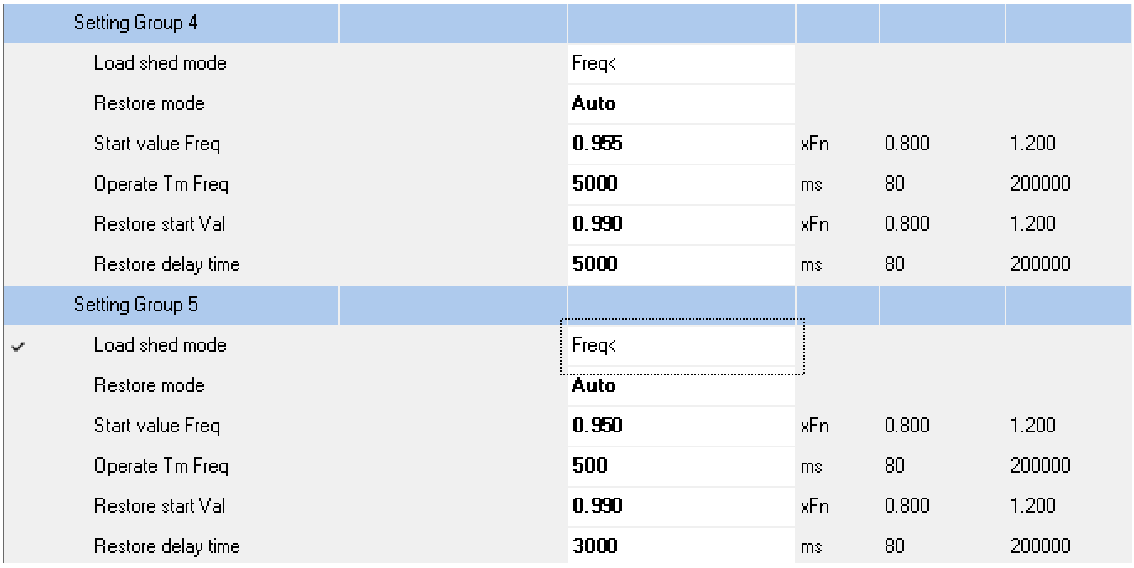
11 Appendices

11.1 Appendix 1 Test Scenario 1 functional settings

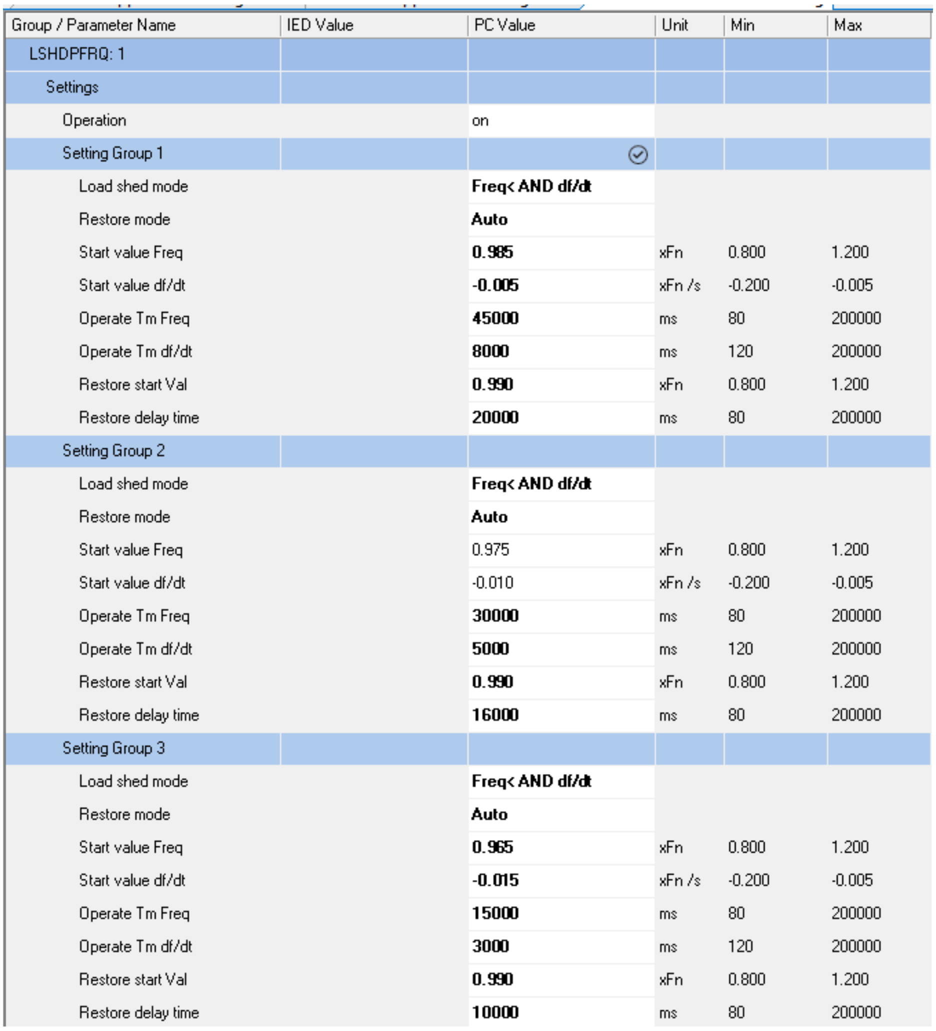


Setting Group 1	✓			
Load shed mode	Freq<			
Restore mode	**Auto**			
Start value Freq	**0.985**	xFn	0.800	1.200
Operate Tm Freq	**45000**	ms	80	200000
Restore start Val	**0.990**	xFn	0.800	1.200
Restore delay time	**20000**	ms	80	200000
Setting Group 2				
Load shed mode	Freq<			
Restore mode	**Auto**			
Start value Freq	0.975	xFn	0.800	1.200
Operate Tm Freq	**30000**	ms	80	200000
Restore start Val	**0.990**	xFn	0.800	1.200
Restore delay time	**16000**	ms	80	200000
Setting Group 3				
Load shed mode	Freq<			
Restore mode	**Auto**			
Start value Freq	**0.965**	xFn	0.800	1.200
Operate Tm Freq	**15000**	ms	80	200000
Restore start Val	**0.990**	xFn	0.800	1.200
Restore delay time	**10000**	ms	80	200000



	Setting Group 4				
	Load shed mode	Freq<			
	Restore mode	**Auto**			
	Start value Freq	**0.955**	xFn	0.800	1.200
	Operate Tm Freq	**5000**	ms	80	200000
	Restore start Val	**0.990**	xFn	0.800	1.200
	Restore delay time	**5000**	ms	80	200000
	Setting Group 5				
✓	Load shed mode	Freq<			
	Restore mode	**Auto**			
	Start value Freq	**0.950**	xFn	0.800	1.200
	Operate Tm Freq	**500**	ms	80	200000
	Restore start Val	**0.990**	xFn	0.800	1.200
	Restore delay time	**3000**	ms	80	200000

11.2 Appendix 2 Test Scenario 1 functional settings



Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
LSHDPFRQ: 1					
Settings					
Operation		on			
Setting Group 1		✓			
Load shed mode		**Freq< AND df/dt**			
Restore mode		**Auto**			
Start value Freq		**0.985**	xFn	0.800	1.200
Start value df/dt		**-0.005**	xFn /s	-0.200	-0.005
Operate Tm Freq		**45000**	ms	80	200000
Operate Tm df/dt		**8000**	ms	120	200000
Restore start Val		**0.990**	xFn	0.800	1.200
Restore delay time		**20000**	ms	80	200000
Setting Group 2					
Load shed mode		**Freq< AND df/dt**			
Restore mode		**Auto**			
Start value Freq		0.975	xFn	0.800	1.200
Start value df/dt		-0.010	xFn /s	-0.200	-0.005
Operate Tm Freq		**30000**	ms	80	200000
Operate Tm df/dt		**5000**	ms	120	200000
Restore start Val		**0.990**	xFn	0.800	1.200
Restore delay time		**16000**	ms	80	200000
Setting Group 3					
Load shed mode		**Freq< AND df/dt**			
Restore mode		**Auto**			
Start value Freq		**0.965**	xFn	0.800	1.200
Start value df/dt		**-0.015**	xFn /s	-0.200	-0.005
Operate Tm Freq		**15000**	ms	80	200000
Operate Tm df/dt		**3000**	ms	120	200000
Restore start Val		**0.990**	xFn	0.800	1.200
Restore delay time		**10000**	ms	80	200000
Setting Group 4					
Load shed mode		**Freq< AND df/dt**			
Restore mode		**Auto**			
Start value Freq		**0.955**	xFn	0.800	1.200
Start value df/dt		**-0.020**	xFn /s	-0.200	-0.005
Operate Tm Freq		**5000**	ms	80	200000
Operate Tm df/dt		**1000**	ms	120	200000
Restore start Val		**0.990**	xFn	0.800	1.200
Restore delay time		**5000**	ms	80	200000
Setting Group 5					
Load shed mode		**Freq< AND df/dt**			
Restore mode		**Auto**			
Start value Freq		**0.950**	xFn	0.800	1.200
Start value df/dt		**-0.025**	xFn /s	-0.200	-0.005
Operate Tm Freq		**500**	ms	80	200000
Operate Tm df/dt		**250**	ms	120	200000
Restore start Val		**0.990**	xFn	0.800	1.200
Restore delay time		**3000**	ms	80	200000