Operational Strategies for a Multi-Source 66 kV Network: Design & Implementation

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Abstract - This paper explores the operational and control strategies of a 66 kV electrical network linking the Ugandan national grid to two remote Central Processing Facilities (located 50 km and 100 km away), each equipped with independent generation units.

It presents the design principles of the electrical control system, emphasizing the implementation of frequency and voltage regulation mechanisms to maintain grid stability in a multi-source environment. The study also investigates synchronization challenges arising from the integration of heterogeneous generation sources and introduces a Fast Load Shedding scheme designed to enhance system reliability under contingency conditions.

Operational feedback from the end user is analyzed to evaluate the effectiveness and resilience of the deployed solutions in real-world applications.

Index Terms — Multi-source power network, industrial power systems, frequency and voltage control, synchronization, Fast Load Shedding (FLS), Under-Frequency Load Shedding (UFLS), islanded operation, GTG, long-distance 66 kV cable networks.

I. INTRODUCTION

The deployment of large industrial facilities in remote areas imposes stringent requirements on electrical power systems in terms of reliability, stability, and operational flexibility. Such systems must accommodate multiple sources of generation while ensuring secure operation during both grid-connected and islanded conditions, as well as during transitions between these modes.

The integration of different generation sources within a high-voltage network presents significant technical challenges. These include the coordination of frequency and active power control, voltage and reactive power regulation, and the synchronization of independent power sources operating under diverse control philosophies. These challenges are further amplified by long 66 kV connections (>50km) with pronounced capacitive effects, which increase system sensitivity to disturbances.

Ensuring continuity of service under such conditions requires a robust and clearly structured control approach, capable of managing steady-state operation as well as transient events such as generation loss, network faults, or disconnection from the utility grid. Special consideration must be given to contingency management, where timely corrective actions are required to avoid cascading disturbances or a complete system collapse.

To address these requirements, a distributed control architecture has been implemented, based on a centralized Electrical Control System (ECS) coordinated with local Power Management Systems (PMS). Dedicated operational philosophies are defined for normal and degraded operating modes, complemented by a Fast Load Shedding scheme and underfrequency protection functions designed to enhance system resilience.

This paper presents the design principles, control strategies, and operational feedback associated with this approach, illustrating its effectiveness in maintaining stability and reliability in a multi-source industrial power network.

The first part presents the EACOP Project and outlines the main electrical architecture of the 66 kV hub, including the Electrical Control System (ECS) and its coordination with the local Power Management Systems (PMS). It is followed by a comprehensive overview of the global control philosophy, covering voltage and frequency regulation, the load shedding scheme, and synchronization mechanisms.

II. SYSTEM DESCRIPTION

A. EACOP Project

The East African Crude Oil Pipeline Project (EACOP) is a 1,443km pipeline that will transport oil produced from Uganda to the port of Tanga in Tanzania where the oil will be loaded onto tankers. It will have a peak capacity of 246,000 barrels/day.

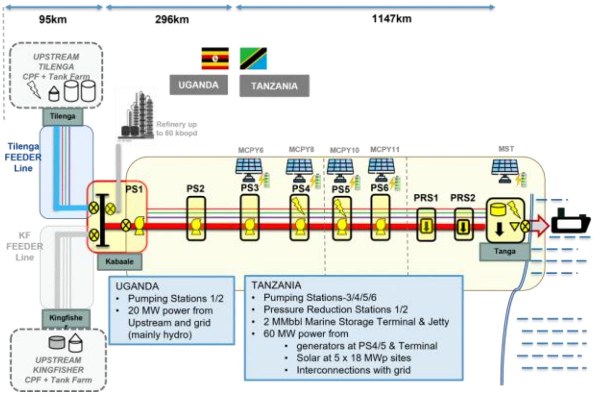

Figure 1: EACOP electrical architecture.

To transport oil over long distances, various subsystems are necessary. Regular "Long Line Heat Tracing" systems (LLHT) are installed to heat the pipeline and prevent the oil to solidity, with LLHT substations placed every 60 km. Additionally, pumping stations (PS) are essential for moving the oil through the pipeline, and pressure reduction stations (PRS) are required primarily due to the area's topography. Finally, a generation system, including grid connections, photovoltaic (PV) plants and gas turbine generators (GTG) is in place to power all these subsystems and utilities.

B. *Electrical network topology*

From electrical prospectives, the pipeline is split into four different and independent sections called section 1, 2, 3 and 4, of roughly 400km each.

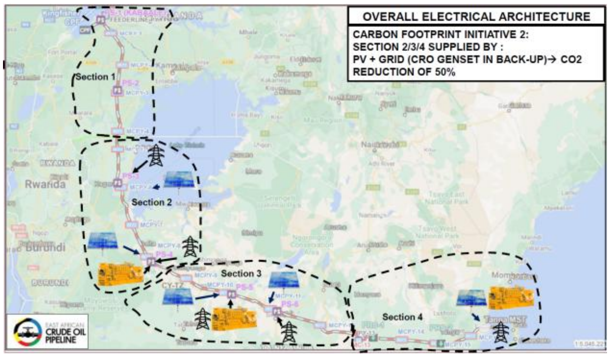

Figure 2: Overall electrical architecture of the 4 sections.

This article focuses exclusively on the 66 kV hub of Section 1, located in Uganda, where crude oil production is carried out at two Central Processing Facilities (CPFs), namely Tilenga and Kingfisher. From an electrical perspective, a 66 kV hub substation has been implemented to interconnect the Tilenga CPF, located approximately 100 km from the substation, with the Kingfisher CPF, situated about 50 km away. The 66 kV hub is interfaced with the national 132 kV transmission grid. In addition, a dedicated 66 kV feeder from the hub supplies the pipeline infrastructure and associated utilities for Section 1.

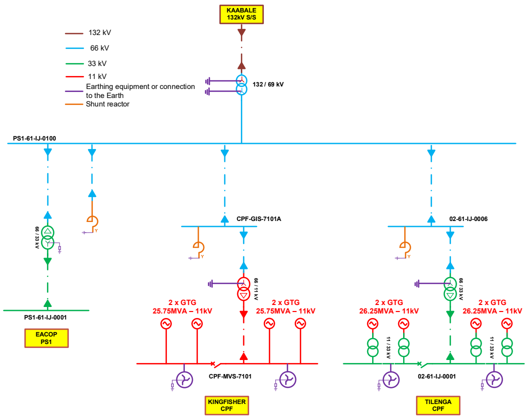

Figure 3: 66kV power system

Both CPFs are each equipped with four 26 MVA gas turbine generators. These units are dedicated to supplying the facilities' internal process loads and are also capable of providing electrical power to the PS1 66 kV hub, which is interconnected with the Ugandan national grid.

The power supply philosophy for Section 1 is designed to provide high operational flexibility while maintaining a centralized supply to EACOP through the PS1 66 kV hub. Depending on source availability, the hub may operate with all three interconnected sources (UETCL grid, Kingfisher GTGs and Tilenga GTGs), or under degraded conditions with only two or a single source connected.

C. *ECS–PMS Control Architecture*

The master Electrical Control System (ECS) is located at the PS1 66 kV hub and coordinates the operation of the network by exchanging control setpoints and feedback signals with the local Power Management Systems (PMS) at the Tilenga and Kingfisher CPFs. The local PMS translate ECS commands into generator-level controls (AVR and speed governor) applied to the gas turbine generators (GTGs).

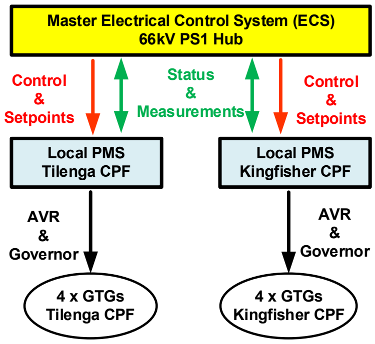

Figure 4: Hierarchical control architecture of the 66 kV network.

Any corrective command issued by the ECS is transmitted to the local PMS, which subsequently translates these commands into appropriate control actions applied to the gas turbine generators (GTG), including automatic voltage regulation (AVR) and speed governor control (GOV). This control architecture and the information flow between the different systems are illustrated in the following Figure 5.

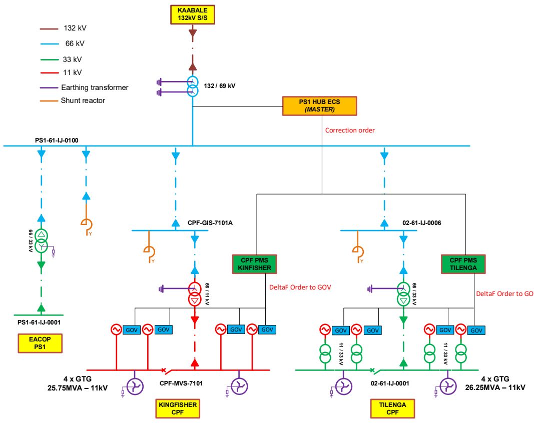

Figure 5: Main overview of the 66kV HUB Controls

Two categories of data are exchanged between the ECS and the local PMS, including equipment status and electrical measurements. Depending on their criticality, data exchange is either performed via fiber-optic communication based on standard protocols (IEC 61850), without stringent response time requirements, or through hardwired signaling (hardwire–fiber optic–hardwire) when fast reaction times are required, typically below 200 ms.

III. P/F AND V/Q CONTROLS

A. Generalities

This section describes the normal operation of the active power–frequency (P/F) and voltage–reactive power (V/Q) control functions implemented on the PS1 hub power system.

The scope is limited to the 66 kV network of Section 1, including the two CPFs. Voltage and reactive power regulation are achieved through the action of gas turbine generators, shunt reactors installed at the PS1 hub and at each CPF, and power transformers equipped with On-Load Tap Changers (OLTC). Frequency and active power control are primarily managed by the GTGs located at Tilenga and Kingfisher CPFs.

B. Required Control Functions for the PS1 Hub

Depending on the operating configuration (grid-connected or islanded), the active power–frequency (P/F) and voltage–reactive power (V/Q) control strategies are applied differently:

- **Frequency control** is implemented to maintain the electrical network at 50 Hz during islanded operation, when the national grid (UETCL) is disconnected.

- **Active power exchange control** is used to manage power flows between EACOP and the UETCL grid when connected.

- **66 kV voltage regulation** is performed to maintain the PS1 hub bus voltage within acceptable limits.

- **Reactive power exchange control with the grid** is applied to avoid undesired reactive power export and to keep the power factor within the specified range.

- **Reactive power compensation of the Tilenga–PS1 66 kV cable** is managed by the Tilenga CPF PMS in conjunction with the local shunt reactor.

- **Reactive power compensation of the Kingfisher–PS1 66 kV cable** is handled either by the Kingfisher CPF PMS using the local shunt reactor or by the PS1 hub ECS through the PS1 HUB shunt reactor.

- **Reactive power management of the Tilenga and Kingfisher transformers** is performed locally by the respective CPF PMS.

- **Continuous exchange of 66 kV status and measurement data** is ensured between the PS1 hub, the Tilenga and Kingfisher CPFs, and the UETCL grid to support coordinated system operation.

Pre-requisite: All GTGs at the Kingfisher and Tilenga CPFs operate in droop mode, and the local PMS are configured for load sharing. In addition, all shunt reactors, transformer AVR, and OLTC are operational.

C. P/F Control Philosophy – Grid connected mode

When the PS1 hub is connected to the UETCL grid, the system frequency is imposed and maintained by the upstream grid.

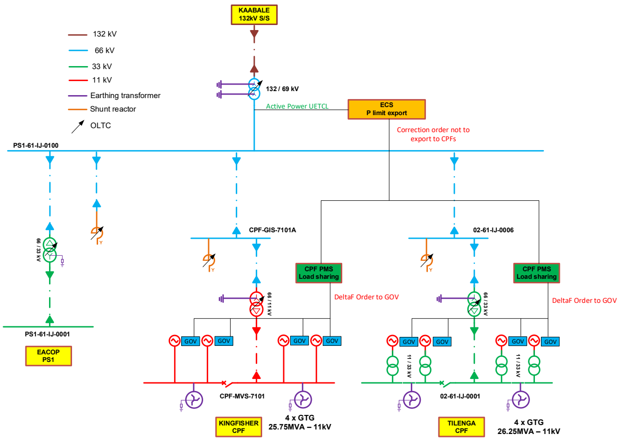

Figure 6: Overview of the 66kV Controls – Grid connected mode

In this configuration, the ECS at the PS1 hub may manage the active power exchange with the grid when required. An export limit can be defined either locally by the operator via the EACOP ECS or through a setpoint received from the national grid by software communication.

The local PMS are responsible for implementing the ECS commands in accordance with local operational constraints.

Tilenga and **Kingfisher CPF PMS** adjusts their active power setpoints (ΔP) applied to their GTGs governors considering their process-related and internal plant constraints linked to the gas available of their respective CPF's.

D. P/F Control Philosophy – Islanded mode

When the PS1 hub operates in islanded mode following disconnection from the national grid, system frequency is no longer imposed by the grid and is instead regulated by the GTGs at the CPFs.

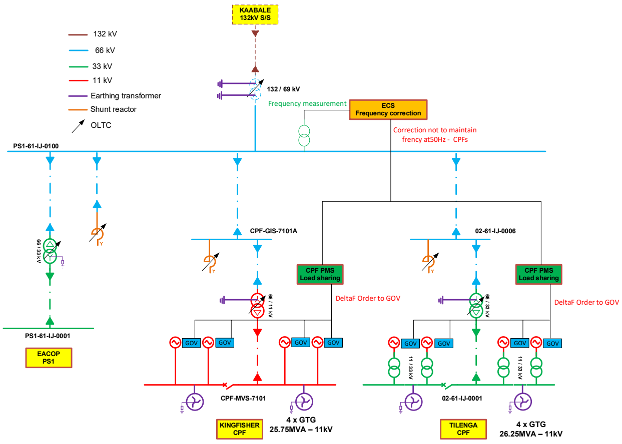

Figure 7: Overview of the 66kV Controls – Islanded mode

In this configuration, both CPFs participate in frequency control by contributing to the correction of frequency deviations.

The PS1 66 kV hub ECS is responsible for calculating the required frequency correction commands and transmitting them to the local PMS at each CPF. The **Tilenga CPF PMS** and **Kingfisher CPF PMS** then implement these commands by adjusting the frequency setpoints (ΔF) applied to the gas turbine governors to maintain the network frequency at 50 Hz.

This frequency control function is automatically enabled as soon as the national grid is disconnected from the PS1 hub, regardless of whether one or both CPFs are connected. If only one CPF remains connected to the PS1 hub, frequency regulation is performed exclusively by the available CPF.

E. V/Q Control Philosophy – Control loops

The objective of the control loops implemented within the system is to ensure coordinated voltage regulation and reactive power management across the different voltage levels of the network. These control functions include regulation of the 33 kV voltage at the Tilenga CPF, regulation of the 11 kV voltage at the Kingfisher CPF, and control of the reactive power exchange with the national grid. In addition, dedicated control loops manage the reactive power exchanges between each CPF and the 66 kV network, as well as the 66 kV voltage regulation at the PS1 hub.

Reactive power compensation is implemented on the 66 kV interconnections between the PS1 hub and the Tilenga and Kingfisher CPFs, with approximately 50 % of the cable reactive power compensated at each end. This arrangement limits reactive current circulation and prevents current and thermal overloading of the cable at a single termination point. The detailed control principles associated with these functions are described in the following sections.

All control loops operate independently, without any interaction or coordination between them.

F. V/Q Control Philosophy – Grid connected mode

When the PS1 hub is connected to the national grid, a dedicated voltage and reactive power control philosophy is applied. This control scheme remains active regardless of whether the CPFs are connected to the PS1 hub.

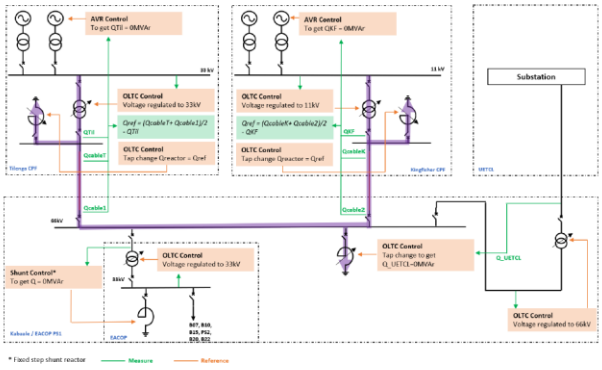

Figure 8: Overview of 66kV V/Q Controls – Grid connected mode

At the CPF level, the local Power Management Systems are responsible for voltage regulation and local reactive power management to avoid any overloading.

Tilenga CPF PMS controls the reactive power exchange between Tilenga and the PS1 hub, maintaining zero reactive power flow at the 66 kV side of the transformer through gas turbine generator AVRs. It also regulates the 33 kV bus voltage using the AVR and OLTC of the 66/33 kV transformer and compensates approximately 50 % of the reactive power generated by the 66 kV cable using the shunt reactor and its AVR.

Kingfisher CPF PMS performs equivalent functions, managing the reactive power exchange with the PS1 hub, regulating the 11 kV voltage through the AVR and OLTC of the 66/11 kV transformer, and compensating approximately 50 % of the 66 kV cable reactive power via the local shunt reactor and its AVR.

At the system level, the **PS1 66 kV hub ECS** manages the reactive power exchange between the PS1 hub and the national grid, maintaining zero reactive power flow using the variable shunt reactor equipped with AVR and tap changer. In addition, it regulates the 66 kV bus voltage via the AVR and OLTC of the 132/66 kV transformer.

G. V/Q Control Philosophy – Islanded mode

In islanded operation, voltage and reactive power control functions are enabled whenever at least one CPF remains connected to the PS1 hub. This includes operating configurations in which both the Kingfisher and Tilenga CPFs are connected, as well as configurations with only Kingfisher CPF or only Tilenga CPF connected. In the latter situation, voltage and reactive power control are manually activated following grid loss and automatically disabled when the connection to the utility grid is restored.

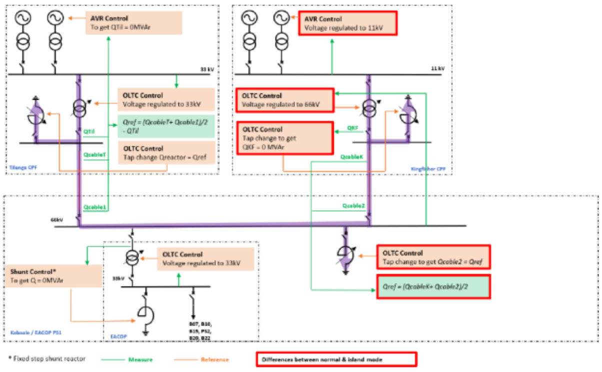

Figure 9: Overview of 66kV V/Q Controls – Islanded mode

Note: New control functions introduced compared to grid-connected operation are highlighted in red.

Under islanded conditions, control responsibilities differ significantly from grid-connected operation, as voltage and reactive power support are no longer provided by the utility grid and the grid transformer. Consequently, local Power Management Systems assume a primary role in voltage regulation and reactive power management by acting through gas turbine generator AVRs, transformer OLTCs, and shunt reactors. The PS1 66 kV hub Electrical Control System complements these local controls by providing additional reactive power compensation to support the 66 kV bus voltage and ensure overall system stability.

IV. LOAD SHEDDING SYSTEMS

A. *Generalities*

In typical islanded industrial power systems, load shedding strategies are generally based on the available spinning reserve and the loss of a single gas turbine, allowing the amount of load to be shed to be calculated accordingly. However, this conventional approach cannot be applied directly to the network considered in this paper.

The presence of multiple, geographically remote generation sources introduces additional electrical constraints, particularly related to voltage regulation and reactive power flows over long interconnections. Consequently, the load shedding system has been designed as a comprehensive scheme combining event-based load shedding, frequency-based load shedding, and additional coordinated actions such as intertripping to ensure overall system stability.

B. *Fast Load Shedding Philosophy*

Fast Load Shedding (FLS) is implemented in a distributed manner across the two CPFs and the PS1 66 kV hub to ensure rapid mitigation of severe contingencies. At each CPF, the local PMS manages internal events, such as GTG trips, with the load to be shed determined based on spinning reserve, operating load level, and contingency type. External contingencies are detected through hardwired signals to minimize response time, allowing immediate initiation of predefined load shedding actions.

The PS1 66 kV hub Electrical Control System acts as the central coordination level for fast load shedding affecting the interconnected network. It performs load shedding calculations for major events such as grid disconnection or significant generation loss and executes load shedding on the EACOP 33 kV system when required. Prior to implementation, dedicated power system studies were carried out to assess the impact of contingencies and to define the appropriate corrective actions ensuring that the electrical system remains stable within acceptable voltage and frequency limits. When multiple entities are involved, the PS1 hub ECS allocates the total load to be shed between EACOP and the CPFs in accordance with the predefined contingency logic, ensuring a coherent and stable system response.

In addition to shedding a predefined amount of active power, the FLS strategy also incorporates dedicated operational actions aimed at mitigating adverse transient phenomena. Severe contingencies may lead to rapid voltage rises, especially due to the presence of long 66 kV interconnecting cables (higher than 50km). To address these effects, the FLS scheme may trigger complementary actions such as the disconnection of long transmission cables, switching of shunt reactors or, in extreme cases, the intentional electrical islanding of one or both CPFs.

These coordinated actions contribute to limiting transient over-voltages and ensuring that the system remains within acceptable voltage and frequency limits following major disturbances.

An illustrative result from the power system studies is presented below, showing the voltage and frequency responses following the unwanted trip of one GTG at the Tilenga CPF. The simulation considers an islanded operating configuration in which both CPFs (Tilenga + Kingfisher) and the PS1 hub remain electrically coupled, with the national grid unavailable.

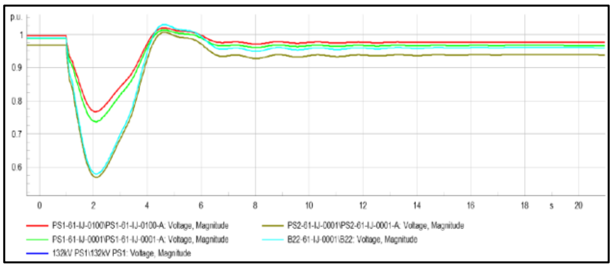

Figure 10: Voltage profile at PS1 without FLS – Loss of one GTG at Tilenga CPF

The loss of one GTG at the Tilenga CPF causes a significant voltage dip across the network. As shown in Figure 10, this contingency leads to severe transient undervoltage at the PS1 hub, despite sufficient spinning reserve being available from the remaining generators, demonstrating that active power reserve alone is insufficient to maintain voltage stability without Fast Load Shedding (FLS).

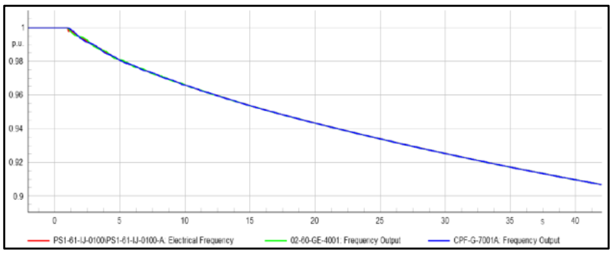

Figure 11: Frequency profile at PS1 & CPFs without FLS – Loss of one GTG at Tilenga CPF

In the absence of Fast Load Shedding (FLS), the loss of one GTG at the Tilenga CPF results in an uncontrolled frequency decline across the PS1 hub and both CPFs. As illustrated in Figure 11, the frequency continuously decreases without stabilization, reflecting a sustained generation load imbalance. This behavior indicates a loss of dynamic stability, ultimately driving the system toward frequency collapse.

Following the unintentional trip of one GTG at the Tilenga CPF, a 15 MW load shedding action corresponding to the lost generation is applied at Tilenga. With Fast Load Shedding (FLS) enabled, both voltage and frequency are maintained within acceptable operational limits, as illustrated in Figure 12 & Figure 13, allowing the system to successfully stabilize and sustain islanded operation.

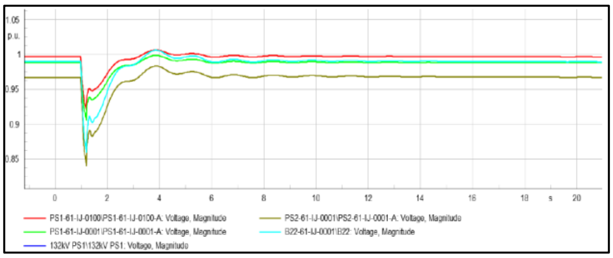

Figure 12: Voltage profile at PS1 with FLS – Loss of one GTG at Tilenga CPF

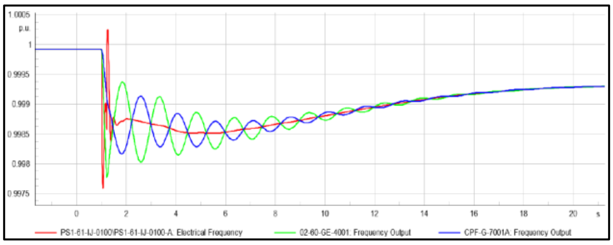

Figure 13: Frequency profile at PS1 & CPFs with FLS – Loss of one GTG at Tilenga CPF

These results confirm that the load shedding strategy effectively rebalances active power and alleviates reactive power stress caused by long 66 kV cables, enabling a stable transition to islanded operation.

Overall, the simulation results clearly demonstrate that load shedding plays a critical role in maintaining voltage and frequency stability following the loss of a gas turbine generator (GTG), thereby validating the control and protection design choices implemented for the PS1 multi-source 66 kV network.

C. *Under-Frequency Load Shedding Philosophy*

An under-frequency load shedding (UFLS) scheme is implemented at the PS1 hub and the two CPFs. The primary objective of this system is to prevent a total system collapse following a frequency decline during off-grid (islanded) operation. A drop in system frequency indicates an imbalance between the power generated by the GTGs at the CPFs and the total electrical load connected to the network. Without corrective action, such an imbalance would lead to progressive frequency decay and potential system blackout.

The UFLS scheme is based on a set of predefined frequency thresholds associated with specified load shedding steps. These thresholds are designed to trigger progressive and coordinated load reduction across the different entities, providing a last layer of defense complementing the Fast Load Shedding strategy and ensuring that the electrical system remains within acceptable frequency and stability limits under extreme operating conditions.

An example of the results obtained from the power system studies are presented in the Figure 14 , illustrating the frequency responses following loss of one GTG in Kingfisher CPF (Blue curve) or one GTG in Tilenga CPF (Red curve) with UFLS (dotted line) & without UFLS (line).

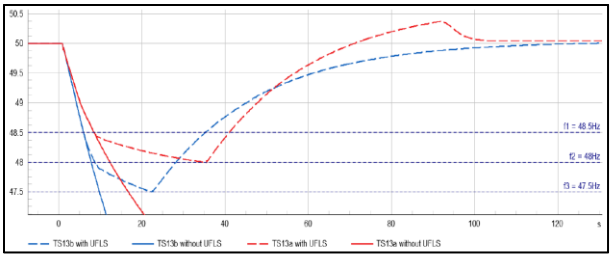

Figure 14: Frequency with & without UFLS – Loss of 1 GTG

These results confirm that UFLS effectively stabilizes system frequency following the loss of a GTG, whereas the absence of UFLS leads to unacceptable frequency deviations.

V. SYNCHRONISATION

Synchronization between the PS1 66 kV hub and the two CPF substations is a critical operation that enables safe electrical interconnection between independent power systems. Owing to the presence of multiple generation sources and varying operating configurations, synchronization must be performed under controlled conditions to ensure compatibility in voltage magnitude, frequency, and phase angle. The synchronization process is therefore tightly coordinated between the PS1 hub and the CPF control systems to avoid transient disturbances, excessive circulating currents, or stability issues during coupling operations.

In this network, synchronization procedures are designed to accommodate both grid-connected and islanded operating modes, considering the specific roles of the ECS at the PS1 hub and the local PMS at each CPF. The complexity of the synchronization process is further increased by the geographical separation of the three power sources, interconnected through long 66 kV cables of approximately 50 km and 100 km. The synchronizing coupler actively issues corrective commands to the master CPF (Tilenga or Kingfisher) to align voltage amplitude, phase angle, and frequency on both sides of the circuit breaker to be closed. As a result, communication transmission delays and the dynamic response time of the generation and control systems must be carefully considered to ensure successful and stable synchronization.

A. *Synchronization requirement*

To enable the PS1 hub synchronization panel, specific control functions must be temporarily inhibited on both sides of the interconnection, namely at the PS1 hub and at the CPF substations. These inhibitions are required to ensure safe and controlled synchronization conditions and to avoid conflicting control actions during the synchronization process.

The functions to be inhibited include high-voltage and medium-voltage voltage control loops, reactive power flow control at both the CPF level and the PS1 hub level, as well as frequency control functions.

B. *Interconnection and Synchronization Scenarios*

Several interconnection and synchronization scenarios have been identified at the PS1 66 kV hub, depending on the initial availability of the EACOP feeder, the national grid connection, and the generation sources at the two CPFs. These scenarios cover events such as the return of the utility grid, the reconnection of a CPF, or the coupling of previously isolated generation sources.

Depending on the initial configuration and the triggering event, synchronization may be performed at different locations within the system, namely at the PS1 hub, at the Tilenga CPF substation, or at the Kingfisher CPF substation. When a single CPF is reconnected following a grid restoration, synchronization is preferably carried out locally at the corresponding CPF substation or at the PS1 hub. In configurations where both CPFs are energized but not yet coupled, synchronization operations may be performed to couple the two CPFs without direct involvement of the utility grid.

In more complex configurations where both CPFs are already coupled, synchronization with the national grid generally requires the temporary disconnection of one CPF. The remaining CPF is first synchronized with the grid at the PS1 hub, after which the second CPF is resynchronized locally at its respective substation. Certain configurations, such as the direct connection of EACOP when all sources are already synchronized, do not require any synchronization operation.

Overall, these scenarios illustrate the flexibility of the 66kV PS1 hub synchronization scheme, which allows synchronization to be performed either centrally or locally according to network topology, source availability, and operational constraints. Preferred synchronization locations are defined to minimize operational risk while maintaining secure and controlled interconnection of the electrical network.

VI. CONCLUSIONS

This paper has presented the design, implementation, and operational experience of a 66 kV multi-source electrical network supplying a large-scale industrial infrastructure in a remote environment. The studied system, characterized by geographically dispersed generation sources interconnected through long 66 kV links and operating under both grid-connected and islanded conditions, requires a robust and carefully coordinated control strategy to ensure stability and continuity of supply.

The proposed control architecture, based on a centralized ECS coordinated with local PMS, has demonstrated its effectiveness in managing frequency, voltage, and power flows across multiple operating configurations. Emphasis was placed on the coordination of active and reactive power control, synchronization procedures between heterogeneous and distant sources, and the deployment of complementary protection mechanisms such as Fast Load Shedding and Under-Frequency Load Shedding. Power system studies played a key role in defining these strategies and validating the corrective actions required to maintain the system within acceptable voltage and frequency limits during severe contingencies.

By adopting a pragmatic engineering approach and maintaining close technical coordination with the end user, the proposed solutions were optimized through iterative design, detailed power system studies, and operational validation, ensuring their suitability with respect to both system performance and real-world operating constraints.

One aspect that has not been addressed in this paper and is currently under investigation concerns the poor quality of the power supplied by the national grid, including issues such as voltage sags, prolonged disturbances, and severe grid faults. In the context of interfacing with weak utility networks, further enhancements to the robustness of the proposed control strategy could be achieved through the integration of grid-stabilization technologies such as STATCOMs, Battery Energy Storage Systems (BESS), or medium-voltage DC (MVDC) solutions.

II. REFERENCES

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III. VITA

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