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Analysis of Electromechanical Transient Propagation and Cascading Failure in Auxiliary Systems: A Deterministic Resilience Framework for Voltage-Dip Mitigation at Hwange Thermal Power Station

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Abstract

Under-voltage transients represent a critical power quality disturbance that compromises the operational reliability of thermal generation assets, particularly those with aging auxiliary electrical infrastructures. Moreso, the recurrent voltage dip-induces forced outages resulting in reduced constant power production at Hwange Power Station Zimbabwe's principal coal-fired baseload plant. This research establishes a deterministic resilience framework for the station's auxiliary systems through an integrated engineering methodology, combining historical disturbance analytics from SCADA and operational records with high-fidelity dynamic electromechanical simulation in DIgSILENT PowerFactory, standards-based benchmarking per IEEE guidelines, and a structured risk assessment via Failure Mode and Effects Analysis. Focusing on critical auxiliary subsystems including automatic changeover schemes and protection, control circuits, the study identifies vulnerable equipment, elucidates root-cause failure mechanisms, and evaluates practical mitigation strategies. The resulting technical framework is designed to enhance baseload reliability at Hwange and provide a translatable reference for voltage-dip resilience in analogous regional thermal power stations.

Subject Areas

Electric Engineering

Keywords

Electromechanical Transient Propagation, Cascading Failure, Auxiliary Systems

1. Introduction

Voltage dips, defined per IEEE Std 1159 as transient under-voltage events with root mean square reductions between 10%-90% of nominal input value lasting from half cycles to one minute, represent a critical power quality disturbance in interconnected networks, predominantly originating from short-circuit faults, large motor starting transients, transformer energization inrush currents, and switching operations [1]. These brief but severe voltage depressions are particularly disruptive in thermal generation assets due to their reliance on electrically driven auxiliary systems including induced draft fans, boiler feed pumps, coal mills, and distributed control systems where electromechanical stress or control-power interruption during a dip can cascade into unit instability and forced outage [2]. Hwange Power Station, Zimbabwe's principal coal-fired baseload plant, exemplifies this vulnerability. Originally commissioned under historically robust grid conditions, its largely unmodified auxiliary infrastructure now operates within a transformed Southern African power system characterized by altered fault levels, topology, and protection schemes, resulting in increased dip frequency and severity. This has manifested in recurrent failures of critical 3.3 kV auxiliary circuit breakers and loss of DCS indication, culminating in boiler instability and turbine trips. While transmission-level grid stabilization initiatives aim to reduce dip incidence, they do not address the deterministic ride-through capability of generation-side auxiliary systems [3]. Consequently, this research establishes a mechanistic framework to quantitatively evaluate the voltage-dip resilience of Hwange's auxiliary electrical systems and develop tailored mitigation strategies to enhance plant-level dynamic stability and baseload reliability.

2. Literature Review

While voltage dips are recognized as the most prevalent power quality disturbance, primarily originating from network faults, motor starting transients, and switching operations, existing research predominantly characterizes grid-side phenomena using stochastic voltage sag profiles, leaving a critical gap in mechanistic models for auxiliary electrical networks within thermal power stations operating on weak grids which are basically from the coal feeder systems as shown in **Figure 1** [4].

This literature review establishes that auxiliary system vulnerability stems from deterministic electromechanical failure modes as shown in **Figure 2**, which are a result of diverse factors of different nature but mainly from electromechanical sense [5].

Variable speed drives experience DC-link collapse and inverter blocking when voltage dips exceed 35% - 40% depth, AC contactors exhibit nuisance dropout at

35% - 60% of nominal coil voltage due to loss of magnetic holding force, and degraded UPS and DC battery systems suffer reduced autonomy, compromising control-power integrity.

Figure 1. Coal Feeder system.

Figure 2. 33 kV Fault breaker fell off after fault.

Figure 3. Damaged 3.3Kv Breaker.

Furthermore, the dynamic interaction between medium-voltage breaker protection sequences, automatic changeover logic, and post-dip recovery of motor loads remains insufficiently quantified, particularly for aging infrastructure and it results in unforeseen damages such as in **Figure 3** [6]. These identified gaps specifically the absence of integrated, plant-level dynamic models accounting for AC and DC interdependencies, aging-aware component ride-through thresholds, and retransfer dynamics directly motivate the present study's simulation-based, risk-prioritized methodology to develop deterministic resilience strategies for auxiliary systems [7].

3. Background

A historical analysis of voltage dip events at Hwange (2023-2025) reveals that station-level generation loss is primarily an electromechanical cascade initiated by faults on the 33 kV auxiliary network or the 330/88 kV transmission corridor, manifesting as a severe voltage depression on the station auxiliary buses [8]. The deterministic factor for unit survivability is not the generator itself but the dynamic response and protection coordination of downstream auxiliary subsystems. Recurring failure mechanisms include the undervoltage tripping of critical 3.3 kV cooling water pumps, leading to condenser vacuum collapse, DC link voltage collapse in coal feeder variable-speed drives, causing furnace instability and the drop-out of control air compressor motors, which triggers pneumatic control failure and burner retraction [5]. Furthermore, systemic vulnerabilities are compounded by protection miscoordination such as improperly set REF542 Plus undervoltage relays and degradation in recovery-critical systems, including UPS and DC charger instability, faulty essential supply changeover logic, and the failure of AC coil contactors to re-energize post-fault. Events like the 29 June 2025 disturbance demonstrate that a moderate voltage sag, when coupled with DC system degradation and defective re-transfer relay logic, can escalate into a multi-unit trip, while high-impact incidents like the 14 November 2025 lightning strike illustrate how a single 33 kV network contingency can induce widespread auxiliary collapse, resulting in significant generation loss [9]. The chronology conclusively establishes that auxiliary system resilience, governed by the ride-through capability of its constituent loads and the reliability of its DC essential power systems, is the principal determinant of overall plant performance during network disturbances.

4. Methodology

To evaluate the impact of voltage-dip transients defined as a reduction in root mean square voltage to between 10% and 90% of nominal per IEEE Std 1159 on the electromechanical response and stability of auxiliary power networks at Hwange Power Station. The aim is to characterize historical disturbances via stochastic analysis of SCADA and fault records, develop high-fidelity dynamic models of critical auxiliary subsystems in DIgSILENT PowerFactory, and simulate dip scenarios to assess motor ride-through margins, Variable Speed Drive DC-link stability, and protection sequencing [10]. Through Failure Mode and Effects Analysis, the study identifies the most vulnerable components, quantifies trip risks, and formulates deterministic mitigation strategies such as optimized protection coordination, control-power reinforcement, and ride-through technology integration that are subsequently validated through comparative simulation to ensure compliance with IEC and IEEE standards and enhance overall generating unit reliability. The scope of this research is delimited to the auxiliary electrical power distribution networks within Hwange Power Station Units 1-6, encompassing the 33 kV, 3.3 kV, 380/400 V AC, and 24 V/110 V DC subsystems, with specific focus on critical components including uninterruptible power supply and DC battery systems, coal-feeder and mill variable speed drives, cooling-water and essential service motors, control-air compressors, auxiliary transformers, essential changeover and re-transfer logic, and 3.3 kV circuit breakers. The study is methodologically bounded by the absence of permanent high-resolution power quality monitoring on auxiliary buses, constraining waveform granularity and necessitating reliance on aggregated SCADA fault data supplemented by industry-standard worst-case sag profiles for stochastic modeling; furthermore, operational safety protocols preclude on-load testing of auxiliaries, and the analysis is explicitly delimited to voltage-dip transients, excluding total blackout scenarios, generator excitation dynamics, national transmission stability, and market or environmental impacts. A deterministic methodology for assessing voltage-dip resilience in the auxiliary electrical systems of Hwange Power Station, employing a structured validation chain of observe, model, test, validate and recommend that integrates historical disturbance analytics from SCADA and fault records, standards-based benchmarking against IEEE criteria, and high-fidelity dynamic simulation in DIgSILENT PowerFactory to reconstruct sag propagation, electromechanical deceleration of induction motors, and DC-link collapse in variable speed drives [11]. The framework is underpinned by a Failure Mode and Effects Analysis to quantify risk-prioritized failure modes such as Variable Speed Drive undervoltage trips, contactor dropout, UPS inverter collapse, and 3.3 kV breaker failure and is validated through operational data correlation, ensuring that the developed mitigation strategies are defensible and tailored to enhance auxiliary ride-through capability and unit stability. The voltage dip scenario at Hwange, characterized by a sharp transient followed by a damped recovery, exemplifies the electromechanical transients resulting from grid-side faults, where the instantaneous imbalance between generation and network voltage induces a rapid sag initiation, a defined minimum voltage point, and a restoration period aligned with profiles in IEC 61000-2-8 and IEC 61000-4-11 [12] [13].

5. Results and Discussions

The simulation results show a clear distinction between faults applied on the 33 kV station supply and those effectively isolated by the unit transformer supply path. When faults occur on the station supply, the 3.3 kV Unit Board 1 voltage collapses severely, with voltage drops ranging from 33% to 94%, which is sufficient to cause widespread motor and contactor dropout. In contrast, when the auxiliaries are supplied through the unit transformer, the 3.3 kV bus voltage remains above 2.7 kV in all cases, corresponding to voltage drops of only 6% - 18%. The simulation data confirm that the source impedance pathway critically governs voltage stability during motor starting transients, with unit-transformer-supplied auxiliaries demonstrating superior voltage regulation maintaining 92% of nominal voltage versus 88% for station-supplied systems due to the lower equivalent impedance and closer electromagnetic coupling that better confines the reactive inrush current, thereby reducing the voltage dip magnitude by one-third and directly corroborating the empirical ride-through superiority observed in historical events where units on self-supply configurations avoided cascading auxiliary collapse as demonstrated by the graph shown in **Figure 4**. The simulation results align with physical interpretations thus to say the lower source impedance and tighter electromagnetic coupling during unit supply localize reactive inrush current, reduce voltage dip magnitude, and materially improve ride-through capability during motor starting transients. Dynamic simulations of 33 kV busbar faults including three-phase, two-phase-to-ground, and single-phase-to-ground contingencies quantify the propagated voltage depression at the 3.3 kV unit board, revealing severe attenuation to as low as 6.1% of nominal during a three-phase fault under station transformer supply, versus an 81.8% retention under unit transformer supply, thereby delineating the supply path's critical role in sag magnitude. Compounding this, the failure mode of ABB NF22E-12 essential supply changeover contactors specifically their inability to auto-re-energize post-dip despite coil voltage restoration introduces a deterministic recovery flaw, where contactor dropout persists until manual reset, creating a systemic hysteresis that disrupts the automatic restoration sequence of critical auxiliaries. This triad of real-event waveform analysis, simulated fault propagation, and component-level behavioral pathology underscores that plant resilience is governed not only by the depth and duration of the voltage sag but by the synergistic vulnerability of protection coordination, supply architecture topology, and the post-disturbance re-engagement characteristics of low-voltage control devices.

The dynamic braking effect of induction motor loads during voltage dips exacerbates network undervoltage conditions through a positive feedback mechanism, wherein the depressed terminal voltage induces stator flux decay, causing motors to draw elevated reactive current to restore magnetic coupling, thereby imposing an additional burden on the already fault-weakened source impedance and significantly retarding the post-fault voltage recovery trajectory; this phenomenon, analogous to the simultaneous starting of a large motor cohort, is quantitatively demonstrated through simulation where concurrent acceleration of multiple 3.3 kV auxiliary motors results in a prolonged 42-second acceleration interval, confirming that sustained high-slip operation under sag conditions prolongs high current demand, which can precipitate secondary voltage collapse, contactor

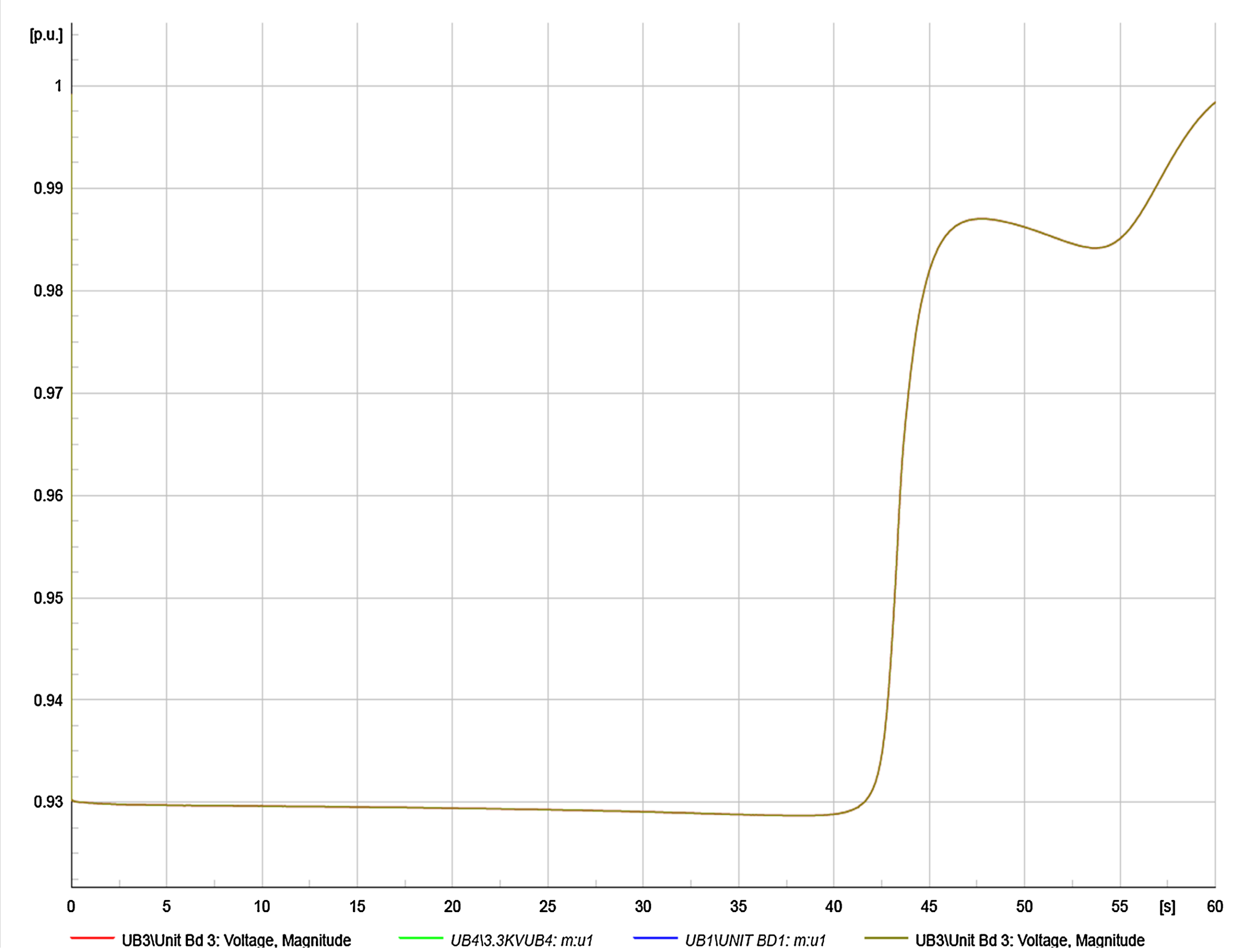

Figure 4. Simulated voltage dips due to auxiliary motor starting (Unit Supplies).

dropout, and protection mis operation by extending the period of depressed bus voltage beyond the ride-through capability of sensitive control equipment. The corresponding speed time and voltage recovery characteristics are illustrated in **Figure 5**, which shows the prolonged acceleration and slow voltage restoration associated with concurrent motor starting.

In **Figure 6**, a Failure Mode and Effects Analysis of auxiliary subsystems, structured to rank risk based on severity, occurrence, and detectability which is tamed Risk Priority Number (RPN). Basically, it is a multiple of severity, occurrence and detection. Meaning to say that the greater the calculated numerical value of the RPN the greater the concern and the need for immediate attention. In principle the value ranges from 1 - 1000 so any value greater than 100 usually attracts a recommendation action. In our case the identified coal feeder is RPN 441, UPS and DC systems, and pumps such as CW, ACW and BCW the highest-risk cohorts due to their severe impact on generation, frequent manifestation in the 2023-2025 event record, and limited early detectability, with dominant failure modes being DC link undervoltage, battery degradation-induced control blackout, and motor undervoltage leading to vacuum collapse, respectively. The DC supply is mainly

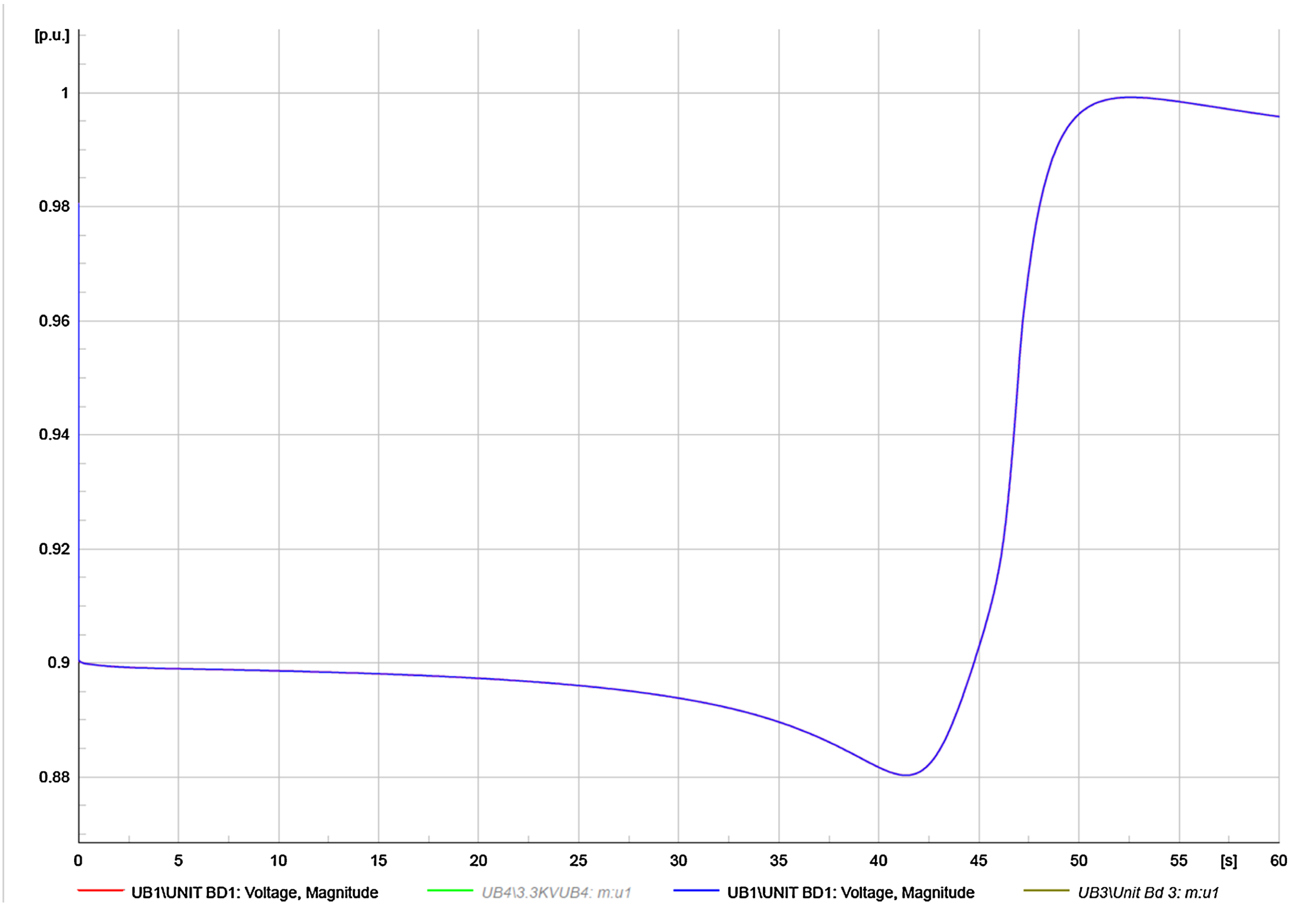

Figure 5. Simulated voltage dips due to motor starting (Station Supplies).

the battery or supercapacitor which usually degrades on the control part. Control air compressors the likes of RPN 280 and DG changeover or re-transfer logic of RPN 288 occupy a medium-high risk band, reflecting critical but less frequent failures, while AC coil contactors of RPN 210 type present a medium risk due to their role in essential board non-recovery, collectively confirming that voltage dip-induced generation losses are governed by a concentrated set of electromechanical and control vulnerabilities within the auxiliary infrastructure. The coal feeder (Figure 1) ride-through optimization initiative, centred on implementing kinetic buffering and configuring automatic undervoltage restart logic within ABB ACS550 variable-speed drives, directly targets the critical of about 13 - 15 second post-trip combustion stability window defined by the residual quantity of 200 kg of mill coal inventory. It means there is need of inertia, however the mechanical inertia will be in retard because of the tripped drivers. In that case the energy storage will be ideal for this specification. Based from the Figure 7 simulated parameters, this engineering intervention mechanistically addresses the previously insufficient manual recovery timeline by enabling drive auto-reset within parameters such as a 2-second fault-to-restart delay, as empirically validated during the Unit 4 event where only the optimally configured Feeder 4D successfully re-engaged within 2 seconds following a dip to 307 V, thereby preventing furnace destabilization and

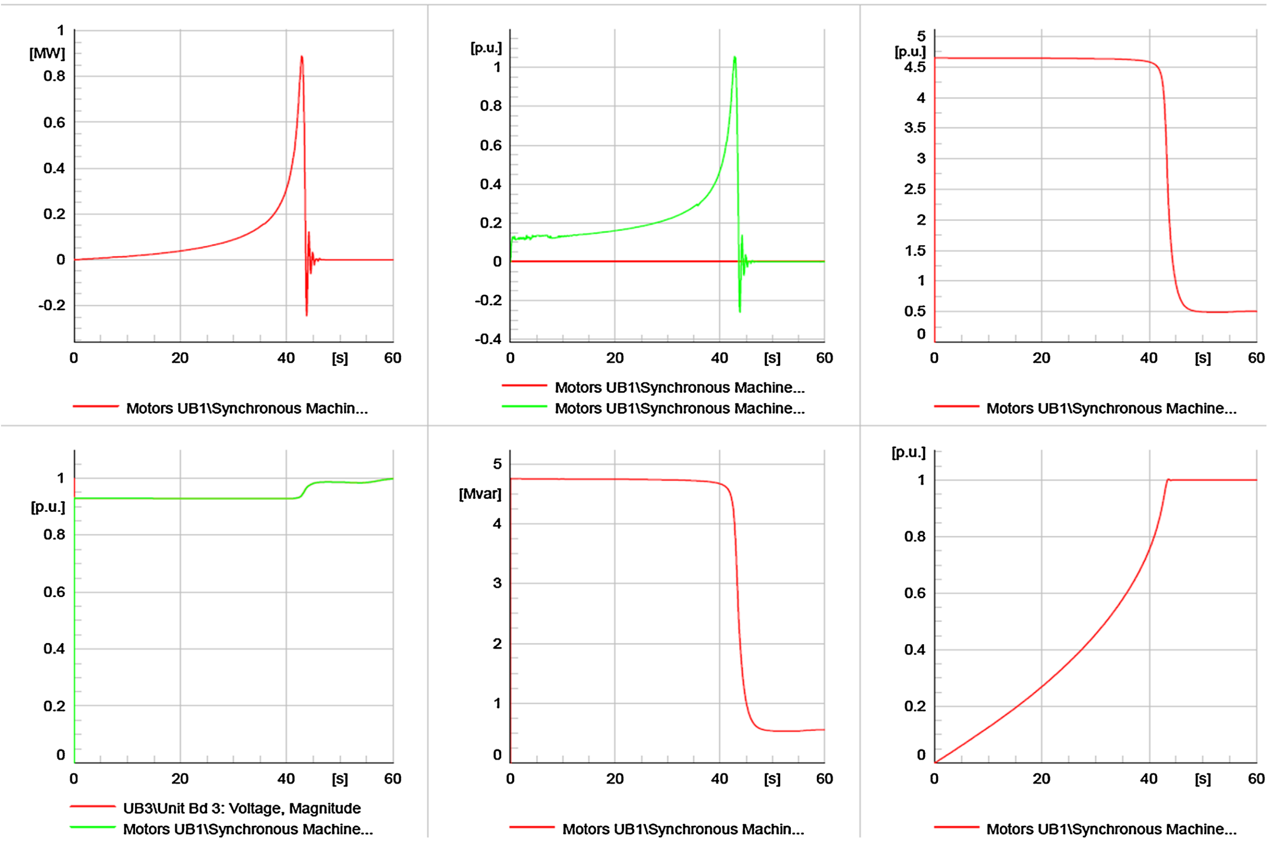

Figure 6. speed time and voltage recovery characteristics.

	A	B	C	D	SETTINGS
PARAMETER					
1610 DISPLAY ALARMS		X	X	X	0 = NO, All alarms are suppressed
					1 = YES, All of the above the alarms are enabled.
2005 OVERVOLTAGE CTRL		X			0= DISABLES CONTROLLER
			X	X	1= ENABLES CONTROLLER
2006 UNDERVOLTAGE CTRL					0 = DISABLES CONTROLLER
		X			1= ENABLE (TIME) enables CONTROLLER WITH 500ms time limit for operation
			X	X	2 = ENABLES allows CONTROLLER TO OPERATE WITHOUT LIMIT FOR OPERATION
3101 NUMBER OF TRIALS		0	3	3	Number of automatic resets allowed in trial time
3102 TRIAL TIME		30	30	30	Sets the trial time for limiting the number of resets
3103 (DELAY TIME/s)		0	4	2	Delay time from fault detection to fault resetting Automatic Resets the fault after fault detection and the drive is and the drives resumes normal operation
3105 (AR OVERVOLTAGE)		X	X		0= DISABLES AUTOMATIC RESET
				X	1 = ENABLES AUTOMATIC RESET
					Automatic Resets the fault (DC OVERVOLT) AFTER THE DELAY SET BY 3103 and the drives resumes normal operation
3106 (AR UNDERVOLTAGE)		X			0= DISABLES AUTOMATIC RESET
			X	X	1 = ENABLES AUTOMATIC RESET

Figure 7. Actual Field ACS550 Parameters.

demonstrating that automated control-sequence modification is essential to align electrical recovery dynamics with the boiler's transient thermodynamic fuel-inventory constraints.

In addition, Figure 8 showing the Hwange Power Station showing the stages of reticulation. Moreso, Figure 9 and Figure 10 is showing the critical pillar of short circuit analysis on the Hwange unit supplies from the different sources of generation. The emerging mitigation framework, encompassing DC and UPS reinforcement through systematic battery replacement and revised changeover logic alongside compressor ride-through optimization via either auto-restart sequencing or migration to 110 V DC control supply, targets the root-cause electromechanical cascade identified in the synthesis shown in Figure 11, where auxiliary collapse primarily through CW pump undervoltage trips, coal feeder

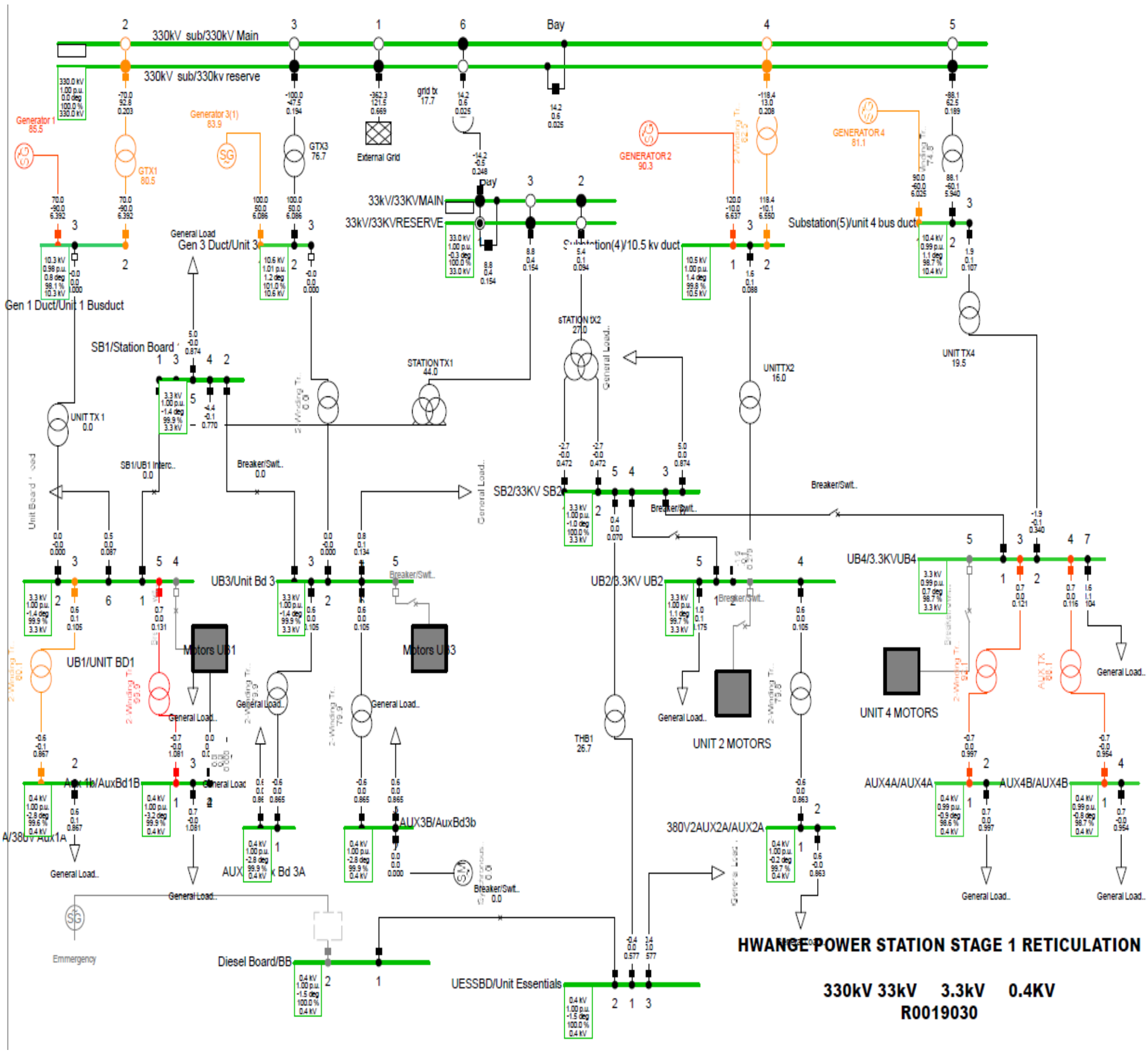

Figure 8. Hwange power station Stage1 reticulation load flow.

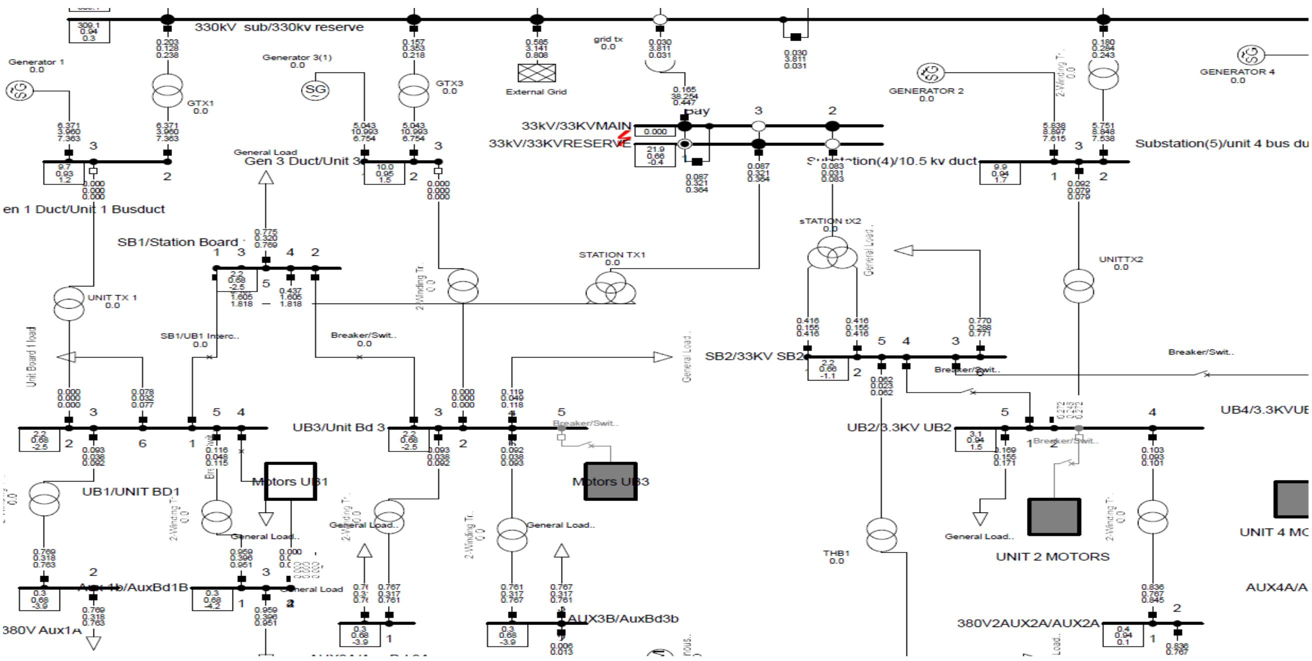

Figure 9. Short circuit analysis on unit supplies.

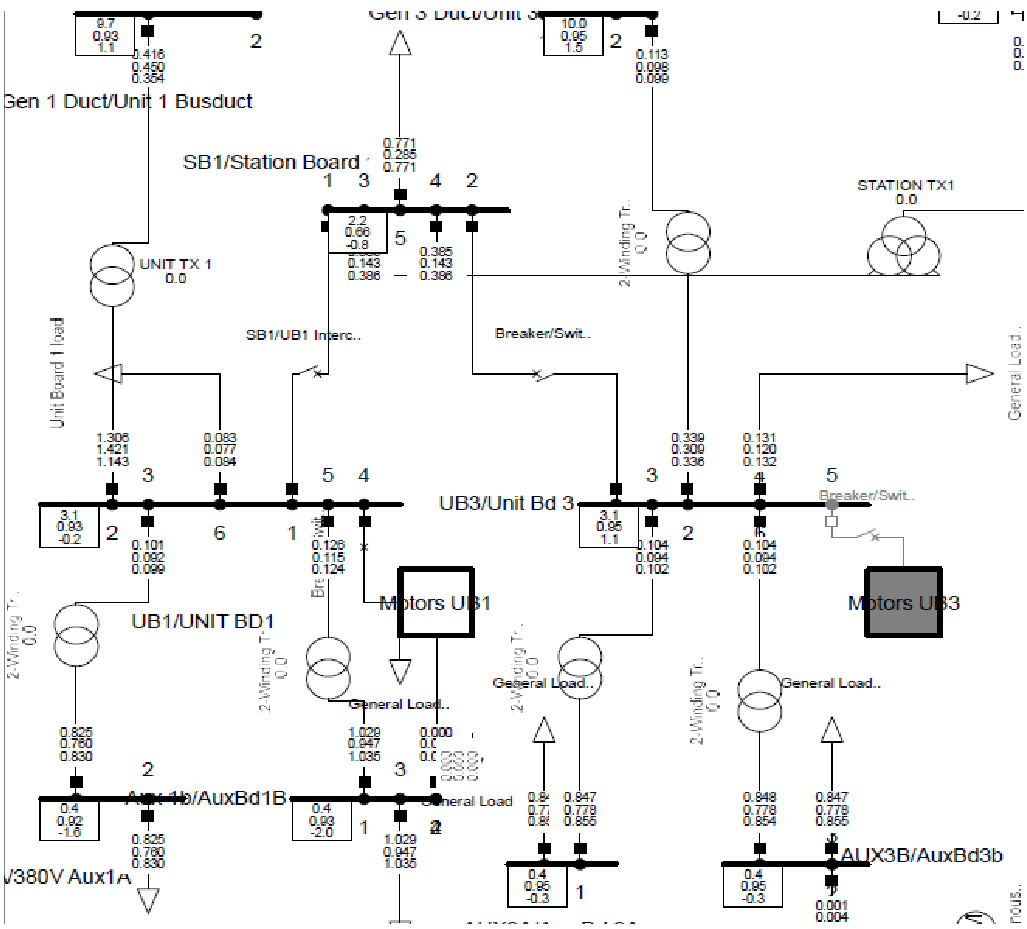

Figure 10. Short circuit analysis on station supplies.

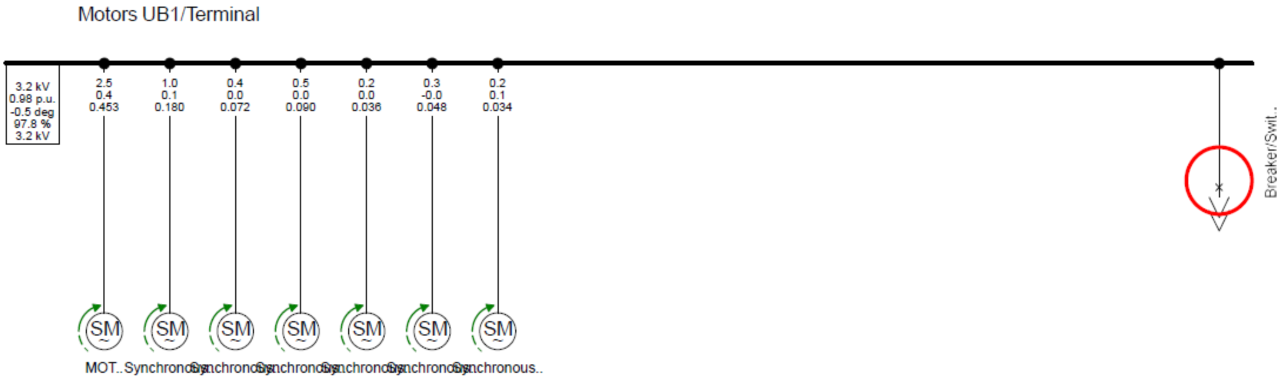

Figure 11. Motor circuits simulation on Unit Board 1.

Variable Speed Drive DC-link failure, and UPS and DC degradation is the dominant generator trip mechanism, as confirmed by FMEA ranking these subsystems highest in risk due to severe impact and frequent occurrence; while coal feeder optimization trials empirically validate that kinetic buffering and automatic reset logic can align electrical recovery with the boiler's transient thermodynamic stability window, the collective findings, notwithstanding limitations in waveform resolution and observational timeframe, conclusively establish that plant-level voltage dip resilience is governed by auxiliary system robustness and control-power integrity rather than prime mover stability alone.

6. Conclusion

Synthesizing historical event chronology, dynamic simulation data, and FMEA-derived risk prioritization, this integrated analysis conclusively identifies the auxiliary system collapse spearheaded by the vulnerability set of cooling water pumps, coal feeder Variable Speed Drives, control air compressors, UPS and DC systems, AC coil contactors, and diesel changeover schemes as the dominant failure mode converting grid disturbances into generation losses, a mechanism validated by the coal feeder optimization case where kinetic buffering and automatic undervoltage restart logic demonstrably improved ride-through. Consequently, the paramount engineering recommendations are prioritized as follows first, implementing automatic restart and standardized DC-link undervoltage thresholds on all coal feeder Variable Speed Drives, second, executing a rigorous DC battery health management program and migrating critical control circuits to DC supply to fortify UPS integrity; third, re-coordinating undervoltage protection and instituting staged restart sequences for CW and ACW and BCW pump motors; and fourth, deploying automatic restart logic and converting control circuits to 110 V DC for critical air compressors a targeted mitigation portfolio focused on the electromechanical and control-power interfaces that govern the plant's transient stability during voltage depressions.

Conflicts of Interest

The authors declare no conflicts of interest.

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