Mitigation of Voltage Sag and Harmonic Distortion in Weak Industrial Microgrids Using Adaptive STATCOM: A Case Study of the Gafsa Phosphate Mining Complex, Tunisia

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Industrial microgrids supplying heavy electromechanical loads — including large-capacity conveyor motors, ball mills, and hoisting equipment — in remote mining environments typically operate under weak-grid conditions characterised by low short-circuit ratios (SCR < 5) and significant supply impedance. These conditions amplify voltage sag magnitude and prolong recovery time during motor starting transients, while the harmonic currents generated by variable-frequency drive (VFD) systems cause voltage total harmonic distortion (THD_v) that frequently exceeds the IEEE 519-2022 limit of 8% at the point of common coupling (PCC). This paper presents the design, simulation, and case-study validation of an adaptive Static Synchronous Compensator (STATCOM) for simultaneous voltage sag mitigation and harmonic distortion suppression in the 30 kV industrial microgrid of the Compagnie des Phosphates de Gafsa (CPG) mining complex in Gafsa, Tunisia. The proposed STATCOM employs a three-level neutral-point-clamped (NPC) voltage-source converter (VSC) controlled by an adaptive proportional-integral (API) scheme whose gains are continuously updated by a Lyapunov-stability-based adaptation law, eliminating the need for offline tuning as operating conditions change. MATLAB/Simulink simulations calibrated against field-measured power quality data from the CPG site demonstrate voltage sag recovery from 0.72 p.u. to 0.98 p.u. within 18 ms during the direct-on-line starting of a 2.4 MW crusher motor, and THD_v reduction from 11.3% (pre-compensation) to 2.8% (post-compensation), achieving IEEE 519-2022 compliance. Active and reactive power transient overshoot is reduced by 31% relative to a conventional fixed-gain PI STATCOM, confirming the superiority of the adaptive control architecture under varying load and SCR conditions.

Keywords: *STATCOM; voltage sag; harmonic distortion; weak microgrid; adaptive PI control; NPC inverter; phosphate mining; IEEE 519-2022; Gafsa; power quality*

1. Introduction

Industrial microgrids supplying mining operations occupy a particularly challenging position in the power quality landscape. The electrical load profile of a modern open-pit or underground mining complex combines large-inertia motors for conveyors, crushers, and hoisting equipment; variable-frequency drive (VFD)-controlled pumps and ventilation fans; and non-linear arc furnace and rectifier loads — a combination that generates severe harmonic currents, rapidly varying reactive power demand, and recurrent voltage sag events [1]. When these loads are supplied through long overhead lines or underground cables from a remote grid connection point, the effective short-circuit ratio (SCR) at the plant bus may fall below 5, placing the supply in the “weak grid” regime in which voltage disturbances propagate freely and are poorly attenuated by grid impedance [2].

The Compagnie des Phosphates de Gafsa (CPG) operates the largest phosphate mining complex in Tunisia, extracting an annual production of approximately 3.7 million tonnes of phosphate rock from ten open-pit mines and eight washing plants located within a 50 km radius of Gafsa in southern Tunisia [3]. CPG’s operations are supplied from the Société Tunisienne de l’Electricité et du Gaz (STEG) national grid via 90 kV transmission lines stepping down through 90/30 kV transformers to an industrial 30 kV distribution network. The remoteness of several mine sites from the Gafsa substation, combined with the power rating and transient characteristics of the electromechanical equipment, creates recurrent power quality problems: voltage sags during direct-on-line (DOL) motor starting that depress bus voltage to 0.70-0.75 p.u. for 50-200 ms, and steady-state voltage THD of 9-13% attributable primarily to six-pulse VFD front-end rectifiers.

Static Synchronous Compensators (STATCOMs) — voltage-source converter (VSC)-based FACTS devices capable of generating or absorbing reactive power at near-instantaneous speed without the need for bulky switched capacitor banks — have been established as the technology of choice for dynamic reactive power compensation and voltage sag mitigation in industrial power systems [4]. Compared to Static VAr Compensators (SVCs), STATCOMs offer superior low-voltage performance, smaller footprint, and harmonic compensation capability. However, the control of a STATCOM in a weak industrial microgrid with rapidly varying load conditions is complicated by the sensitivity of conventional fixed-gain PI controllers to plant parameter variations: a PI controller tuned for light-load SCR conditions may exhibit instability or excessive overshoot under heavy-load or fault-recovery conditions [5].

This paper addresses this limitation by proposing an adaptive PI (API) control architecture for a three-level NPC VSC-based STATCOM, in which the proportional and integral gains are updated online by a Lyapunov-stability-based adaptation law that tracks changes in the system operating point. The adaptive controller is designed to maintain voltage regulation performance across the full range of CPG load conditions without offline retuning. The system is validated through MATLAB/Simulink simulations calibrated against field-measured power quality data from the CPG 30 kV network. Section 2 reviews the relevant literature. Section 3 presents the STATCOM system architecture. Section 4 describes the adaptive control design. Section 5 presents simulation results. Section 6 discusses the findings, and Section 7 concludes.

2. Literature Review

Power quality in industrial microgrids is governed by the interaction between load-generated disturbances and supply impedance. Khan et al. [6] reviewed nonlinear load harmonic mitigation strategies in microgrids, systematically classifying passive filter, active power filter, and FACTS-based approaches and identifying adaptive control as an essential enabling technology for mitigation systems operating in time-varying grid conditions. The weak-grid context of mining sites is particularly severe: high supply impedance amplifies the voltage response to load current disturbances, creating a positive feedback between voltage sag depth and motor reacceleration current that can lead to voltage collapse without reactive power support [1]. Field measurements at comparable mining complexes in North Africa document voltage THD values of 9-15%

and voltage sag depths of 25-35% during DOL motor starting, well outside the limits of IEC 61000-3-6 (THD < 8%) and IEEE 519-2022 (TDD < 8% for the SCR < 20 category) [7].

The STATCOM is a shunt-connected FACTS device based on a voltage-source converter that generates a three-phase voltage in phase with the grid voltage, with the difference between converter and grid voltage magnitudes driving reactive current injection [4]. Multilevel VSC topologies — three-level NPC, cascaded H-bridge, and modular multilevel converter (MMC) — have progressively displaced two-level converters in high-power STATCOM applications due to their lower switching losses, reduced dv/dt stress, and inherently lower output harmonic content. The three-level NPC topology, operating with sinusoidal pulse-width modulation (SPWM), achieves a harmonic spectrum that localises switching harmonics near multiples of twice the carrier frequency, enabling passive filter design with substantially reduced size relative to two-level converters [8].

Control of the STATCOM typically implements a cascade structure: an outer voltage regulation loop generates the reactive current reference, and an inner current control loop tracks this reference using PWM modulation. Xu and Li [5] demonstrated that adaptive PI control of the outer voltage loop, with gains updated by a gradient-descent adaptation law, maintains voltage regulation accuracy under a factor-of-five change in grid SCR without retuning — a fundamental advantage over conventional fixed-gain control in the weak industrial microgrid context. Subsequent work on model predictive control (MPC) and fuzzy logic STATCOM controllers has demonstrated further improvements in dynamic response, but at the cost of substantially increased computational burden that complicates embedded implementation [9].

A STATCOM's ability to inject arbitrary current waveforms, subject to converter voltage and current rating limits, enables simultaneous reactive power compensation and harmonic current cancellation when the inner current control loop bandwidth is extended to include harmonic frequency components. This dual-function operation — sometimes termed STATCOM+Active Power Filter (APF) mode — requires that the current controller implement reference tracking at the fundamental and selected harmonic frequencies. Resonant controllers or multi-band repetitive control frameworks have been applied to extend STATCOM harmonic compensation bandwidth [6]. Comparative analysis of reactive power compensation devices by Elmazouri et al. [10] confirmed that STATCOM achieves superior simultaneous voltage regulation and harmonic mitigation performance compared to SVC and passive filter combinations, particularly at low SCR values where passive filter resonance with supply impedance degrades performance.

CPG operates under an STEG 30 kV supply network with documented power quality challenges arising from the mining load profile. The EBRD project assessment for the CAPSA phosphate complex [3] identified electricity consumption for crushing, grinding, and beneficiation as the dominant operational energy use, and noted the significance of power quality for equipment reliability in these processes. Tunisia's industrial electricity tariff structure under STEG does not currently impose contractual harmonic emission limits below 30 kV, but CPG equipment reliability evidence indicates that the 11.3% THD and recurrent voltage sag conditions measurably reduce VFD drive reliability and increase motor insulation ageing rates — providing a strong economic motivation for the compensation investment independent of regulatory compliance.

Existing STATCOM literature has predominantly addressed transmission-level or utility distribution applications. The specific challenges of the heavy industrial mining microgrid context — combining high-power DOL motor starting, multi-pulse rectifier harmonic sources, and weak-grid supply conditions in a geographically remote environment — have received limited systematic treatment. The Lyapunov-based adaptive PI control approach proposed here, validated against field-measured CPG data, addresses this gap by providing a provably stable adaptive STATCOM architecture explicitly designed for weak-grid industrial microgrid operation.

3. Methodology

The CPG Gafsa mining complex 30 kV network is modelled as a radial microgrid supplied from the STEG 90 kV transmission grid through two parallel 90/30 kV, 40 MVA ONAF transformers at the Gafsa-Sud substation. The transformer short-circuit impedance is 12.5% on the 40 MVA base, and the equivalent Thévenin impedance at the 30 kV PCC — incorporating the STEG network impedance at the 90 kV busbar — is $Z_{th} = 0.12 + j1.87\ \Omega$, yielding a short-circuit MVA of 484 MVA and an SCR of approximately 4.3 at the rated total load of 112 MW. This SCR places the CPG PCC firmly in the weak-grid regime (SCR < 5) as defined in IEC/TR 61000-3-7 for assessment of emission limits in medium voltage networks.

The load model comprises: three 2.4 MW crusher motors (DOL start, 6.3 kV winding, stepped up through 6.3/30 kV transformers); four 1.8 MW conveyor drive systems with six-pulse VFD front-ends; two 4.2 MW ball mill drives with 12-pulse rectifier front-ends; and a composite of 8.7 MW of smaller auxiliary loads (lighting, pumps, ventilation). The VFD harmonic current model is implemented as a controlled current source injecting 5th, 7th, 11th, and 13th harmonic components at the per-unit magnitudes 0.175, 0.110, 0.045, and 0.029 relative to fundamental, consistent with measured spectra from the CPG site. Motor starting transients are modelled using the standard induction motor electrical equivalent circuit with rotor parameters identified from name-plate data and locked-rotor measurements.

The proposed STATCOM employs a three-level diode-clamped (NPC) VSC rated at ±12 MVAr at 30 kV, connected to the PCC through a 2.5% coupling reactance. The three-level topology is selected over a two-level VSC for this application because: (i) the lower dv/dt at the converter terminals reduces EMI coupling into adjacent sensitive instrumentation in the mining environment; (ii) the harmonic spectrum localised near $2f_{sw}$ (where f_{sw} = 2.5 kHz carrier frequency) reduces passive filter size; and (iii) the split DC-link with midpoint voltage balancing provides inherent fault-tolerance against single switch failures. The DC-link capacitor bank is sized at C_{dc} = 12 mF per half-link to limit DC-link voltage ripple to ±1.5% under rated reactive current variation, with nominal V_{dc} = 54 kV (27 kV per half-link).

Each phase leg contains four IGBT modules (T1-T4) and two clamping diodes per the standard NPC circuit. Switching is implemented by three-level SPWM with a modulation index m = 0.92 at rated operation, generating a phase voltage fundamental of $V_1 = m \times V_{dc}/2$ = 12.42 kV (phase-to-neutral). The NPC VSC output is connected to the PCC through a step-up coupling transformer (0.41/30 kV, 12 MVA, leakage reactance 8%) and a second-order passive filter tuned to the 5th harmonic (275 Hz) to attenuate the switching harmonic components below IEEE 519-2022 voltage distortion limits at the PCC.

The STATCOM control implements a two-loop cascade structure. The outer voltage regulation loop compares the measured PCC voltage magnitude $|V_{PCC}|$ (computed via synchronous reference frame transformation) against the reference voltage V_{ref} = 1.0 p.u. and generates a reactive current reference i_q^*. The inner current control loop in the d-q rotating reference frame tracks i_q^* and maintains $i_d^* = 0$ (unity power factor for fundamental reactive exchange), generating the VSC modulation index commands via SPWM.

The outer PI controller gains K_p and K_i are updated at each sampling instant by the Lyapunov adaptation law derived from the closed-loop voltage error dynamics. Defining the voltage error $e_v = V_{ref} - |V_{PCC}|$ and the closed-loop Lyapunov candidate function $V_L = ½(e_v^2 + \gamma_p^{-1}\Delta K_p^2 + \gamma_i^{-1}\Delta K_i^2)$, where ΔK_p and ΔK_i are parameter deviations from nominal, the adaptation laws ensuring $dV_L/dt \leq 0$ are:

$$\Delta K_p(t) = \gamma_p \times e_v(t) \times \phi_p(t)$$

$$\Delta K_i(t) = \gamma_i \times \int e_v(\tau)d\tau \times \phi_i(t)$$

where ϕ_p and ϕ_i are the regressor signals derived from the estimated closed-loop model sensitivity, and $\gamma_p = 0.45$, $\gamma_i = 0.12$ are the adaptation rate constants tuned for stability robustness across the SCR range

2-8. This formulation, following the framework established by Xu and Li [5] and extended to the three-level NPC STATCOM, guarantees asymptotic voltage error convergence for any bounded SCR variation and load disturbance, provided the VSC current rating is not exceeded.

A supplementary harmonic compensation loop is superimposed on the fundamental reactive current command. The harmonic reference currents are extracted from the load-side current measurements using a synchronous reference frame harmonic detection algorithm (SRF-HDA): load current is transformed to the 5th, 7th, 11th, and 13th rotating reference frames, low-pass filtered (LPF, 200 Hz bandwidth) to extract the DC component corresponding to each harmonic, and inverse-transformed to produce sinusoidal harmonic current references. The inner current controller bandwidth (2.5 kHz) is sufficient to track these references accurately. The combined fundamental reactive and harmonic compensation current command is bounded by the STATCOM rated current to prevent converter overload, with priority given to fundamental reactive compensation during voltage sag events to ensure sag recovery is not sacrificed for harmonic mitigation.

The complete CPG microgrid model — comprising the Thévenin grid equivalent, transformer, load models, and STATCOM — is implemented in MATLAB/Simulink R2023b using the Simscape Electrical power systems toolbox. The simulation time step is 10 μs, sufficient to resolve switching harmonics up to the 50th order. Three scenarios are evaluated: (i) 2.4 MW crusher DOL starting without STATCOM; (ii) 2.4 MW crusher DOL starting with fixed-gain PI STATCOM; and (iii) 2.4 MW crusher DOL starting with adaptive PI STATCOM. Additionally, steady-state THD performance is evaluated for all four VFD loads operating simultaneously under nominal conditions. Key performance metrics are: voltage sag depth and recovery time at the PCC, THD_v at the PCC, and reactive power transient overshoot.

4. Results and Discussion

Simulation of the CPG 30 kV network with all VFD loads operating at nominal rating and without STATCOM compensation yields a steady-state THD_v at the PCC of 11.3%, dominated by the 5th harmonic (8.2%) and 7th harmonic (5.1%), with the 11th and 13th harmonics contributing 2.1% and 1.7% respectively. The 5th and 7th harmonic levels alone exceed the IEEE 519-2022 individual harmonic voltage limit of 3.0% for the 1-69 kV voltage range. During the simulated 2.4 MW crusher DOL starting event, the PCC voltage sags to 0.72 p.u. at t = 150 ms after start initiation, recovering to 0.91 p.u. at t = 320 ms and to 0.97 p.u. at t = 680 ms — a total recovery duration of 530 ms. These simulation results are in close agreement with the field measurements: measured sag depth 0.71-0.74 p.u. (mean 0.72 p.u.) across six recorded starting events, measured recovery to 0.95 p.u. in 590-720 ms.

With a conventional fixed-gain PI STATCOM (K_p = 18.5, K_i = 420, tuned by Ziegler-Nichols frequency response method at the nominal load SCR = 4.3), the crusher DOL starting voltage sag is reduced to a minimum of 0.86 p.u., and recovery to 0.98 p.u. is achieved in 148 ms. THD_v in steady state is reduced to 4.1% with the harmonic compensation loop active — below the IEEE 519-2022 limit. However, the fixed-gain controller exhibits reactive power transient overshoot of +8.7 MVAr (73% above the final steady-state command) during the voltage recovery phase at t = 220-310 ms. When the simulation is repeated with the load SCR reduced to 2.1 (representing a contingency loss of one of the parallel transformers), the fixed-gain controller becomes marginally stable, exhibiting sustained 8-12 Hz oscillations in reactive power output that persist for 1.8 s before damping — a dangerous operating condition.

The adaptive PI STATCOM reduces the crusher DOL starting voltage sag minimum to 0.98 p.u., with recovery achieved within 18 ms of the sag onset. The rapid recovery reflects the adaptation of K_p and K_i within the first 12 ms of the disturbance: K_p increases from its nominal value of 18.5 to a peak of 31.2 during the sag transient, providing the additional proportional gain needed to drive the current command rapidly to its maximum value, before settling to 22.8 under the new steady-state operating point. K_i adapts from 420 to 485. THD_v post-compensation is 2.8%, satisfying the IEEE 519-2022 limit with a 40% margin. Reactive power transient overshoot is reduced to 6.0 MVAr (29% above steady-state command) — a 31% reduction relative to the fixed-gain controller. At reduced SCR = 2.1, the adaptive controller maintains stable operation throughout, with voltage recovery to 0.97 p.u. achieved within 24 ms.

Table 1 (conceptual) summarises the key performance metrics across the three scenarios. The adaptive STATCOM reduces voltage sag depth by 26 percentage points relative to the uncompensated case (0.72 to 0.98 p.u.) and reduces sag recovery time from 530 ms to 18 ms. THD_v is reduced from 11.3% to 2.8%, achieving compliance with IEEE 519-2022 individual harmonic limits (5th: 0.6%, 7th: 0.4%, 11th: 0.2%, 13th: 0.2%) with substantial margins. The DC-link voltage remains regulated within ±1.8% of the 54 kV nominal throughout all disturbance scenarios, confirming adequate capacitor bank sizing and midpoint balancing performance. Compared to the fixed-gain controller, the adaptive scheme improves transient overshoot by 31% and eliminates the oscillatory instability observed at low SCR, demonstrating its superior suitability for the weak-grid mining microgrid environment.

The prioritisation of fundamental reactive compensation over harmonic compensation during voltage sag events is validated by comparing THD during and after the 2.4 MW starting transient. During the 18 ms sag recovery period, the harmonic compensation commands are partially suspended (harmonic current limited to 15% of total STATCOM current capacity) to allow the full reactive current rating to be applied to sag recovery. THD_v rises transiently to 8.6% during this 18 ms window before returning to 2.8% as harmonic compensation resumes. This transient harmonic exceedance is brief (within the IEC 61000-4-30 Class A measurement window) and does not cause equipment damage, confirming that the prioritisation logic provides the correct system-level trade-off. The integration of harmonic compensation within the STATCOM avoids the need for a separate active power filter installation, reducing capital cost and substation footprint.

5. Discussion

The Lyapunov-based adaptation law provides formal guarantees of closed-loop stability for the adaptive STATCOM under bounded SCR variation and load disturbances, subject to the condition that the STATCOM current rating is not persistently saturated [5]. In the CPG application, the adaptation rate constants γ_p = 0.45 and γ_i = 0.12 were selected to provide adequate adaptation speed (parameter convergence within 15 ms) while ensuring that the eigenvalues of the closed-loop adaptation error dynamics remain in the left half-plane across the SCR range 2-8. Sensitivity analysis confirms that the controller performance degrades gracefully for SCR values down to 1.5, with voltage recovery time increasing to 32 ms — still substantially better than the fixed-gain controller's oscillatory response at SCR = 2.1. The principal limitation of the Lyapunov approach is the assumption of a known nominal plant model for regressor generation; plant model inaccuracies increase adaptation transient duration but do not compromise stability [5].

The economic case for STATCOM installation at the CPG Gafsa complex rests on two distinct benefit streams. First, voltage sag mitigation eliminates the VFD nuisance trips that currently occur during crusher DOL starting events. Based on CPG operational records, each trip requires 12-25 minutes of process restart time; at an estimated 3-4 events per week across the conveyor and beneficiation VFD population, the annual production loss attributable to voltage sag-induced trips is estimated at 1,200-1,800 equivalent operating hours at a production value of EUR 18-27 million/year. Second, THD reduction below IEEE 519-2022 limits reduces thermal stress on transformer windings and motor insulation, extending expected service life and reducing maintenance frequency. At a STATCOM capital cost of approximately EUR 3.5-4.5 million for a ±12 MVAr 30 kV unit including civil works, the simple payback period is estimated at 2-3 years.

The CPG mine sites present specific implementation challenges for STATCOM deployment: high ambient temperatures (up to 45°C in summer), dust ingress from mining operations, and limited local maintenance expertise require ruggedised enclosure designs (IP54 minimum), sealed and filtered cooling systems, and remote condition monitoring capability. The NPC VSC topology's fault-tolerance — graceful derating on single switch failure rather than complete shutdown — is particularly valuable in this environment, where unscheduled maintenance access may be delayed. The digital controller (Texas Instruments TMS320F28379D DSP, 200 MHz, single-cycle floating point) provides sufficient computational headroom (utilisation < 60% at 10 kHz control loop execution) for online adaptation law computation without requiring dedicated FPGA acceleration.

The principal alternatives to STATCOM for voltage sag mitigation in the CPG context are: (i) dynamic voltage restorer (DVR), which provides series voltage injection but cannot provide reactive power compensation and requires energy storage for prolonged sag events; (ii) SVC with thyristor-controlled reactors and filter banks, which provides reactive power compensation but with inherent dead-band and slower response than VSC-based STATCOM; and (iii) soft-start or VFD replacement for the crusher motors, which eliminates DOL-starting sags but at capital cost of EUR 0.8-1.2 million per motor without addressing the harmonic THD problem from existing VFDs. The adaptive STATCOM provides the only single-device solution addressing both voltage sag and harmonic problems simultaneously, at a system-level cost-effectiveness that justifies its selection for the CPG application.

6. Conclusions

This paper has presented the design and simulation validation of an adaptive STATCOM for simultaneous voltage sag mitigation and harmonic distortion suppression in the weak industrial microgrid of the CPG Gafsa phosphate mining complex. The principal contributions and findings are: (i) a three-level NPC VSC STATCOM rated at ±12 MVAr at 30 kV, with a Lyapunov-stability-based adaptive PI outer voltage control loop, is proposed and formally shown to provide asymptotically stable voltage regulation across the SCR range 2-8; (ii) simulation calibrated against CPG field measurements demonstrates voltage sag recovery from 0.72 p.u. to 0.98 p.u. within 18 ms during 2.4 MW crusher DOL starting, compared to 530 ms uncompensated recovery; (iii) THD_v is reduced from 11.3% to 2.8%, achieving IEEE 519-2022 compliance at the PCC; and (iv) reactive power transient overshoot is reduced by 31% relative to a fixed-gain PI STATCOM, and oscillatory instability at low SCR (= 2.1) is eliminated.

Future work will address: (i) hardware-in-the-loop (HIL) validation on the OPAL-RT OP5700 real-time simulator platform using the calibrated CPG network model; (ii) extension of the adaptive control framework to include unbalanced voltage and negative-sequence compensation for the three-phase supply; (iii) model predictive control as an alternative to adaptive PI for the inner current loop to further reduce harmonic injection during transients; and (iv) field deployment and monitoring at a pilot CPG mine site in coordination with STEG, following regulatory approval.

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