

DESIGN AND MODELING OF A DISTRIBUTION STATCOM USING PWM SWITCHING AND HYSTERESIS CURRENT TECHNIQUES FOR IMPROVED GRID POWER QUALITY

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Abstract

The increasing integration of nonlinear loads and renewable energy sources in modern electrical distribution systems has significantly deteriorated power quality, manifesting as voltage fluctuations, harmonic distortions, and reactive power imbalances. This research investigates the design and modeling of a Distribution Static Synchronous Compensator (DSTATCOM) employing Pulse Width Modulation (PWM) switching and Hysteresis Current Control (HCC) techniques to enhance grid power quality. The study hypothesizes that the combined implementation of PWM and HCC will effectively mitigate voltage sags, reduce Total Harmonic Distortion (THD), and improve power factor to meet IEEE 519 standards. A comprehensive simulation model was developed using MATLAB/Simulink for a three-phase distribution system with various load conditions. The methodology encompasses system design, controller implementation, and comparative performance analysis. Results demonstrate that the proposed DSTATCOM achieves voltage regulation within $\pm 2\%$, reduces THD from 28.4% to 3.2%, and improves power factor from 0.72 to 0.98 under varying load scenarios. The hysteresis current controller exhibits superior transient response with settling time below 40ms compared to conventional PI controllers. This research validates the efficacy of advanced control strategies in DSTATCOM applications for sustainable power distribution networks.

Keywords: *Distribution STATCOM¹, Power Quality², PWM Switching³, Hysteresis Current Control⁴, Harmonic Mitigation⁶*

1. Introduction

Power quality has emerged as a critical concern in contemporary electrical distribution networks due to the proliferation of sensitive electronic equipment, nonlinear loads, and distributed generation systems. The widespread adoption of power electronic devices, adjustable speed drives, and renewable energy sources has introduced significant challenges including voltage disturbances, harmonic pollution, reactive power deficiencies, and unbalanced load conditions. These power quality issues result in equipment malfunction, reduced operational efficiency, increased energy losses, and economic penalties for both utilities and consumers. The Indian power sector, experiencing rapid industrialization and urbanization, faces particularly acute power

quality challenges with estimated annual losses exceeding ₹75,000 crores due to poor power quality. Traditional power quality mitigation devices such as capacitor banks, passive filters, and synchronous condensers have inherent limitations including slow response times, fixed compensation capabilities, and resonance vulnerabilities. The Distribution Static Synchronous Compensator (DSTATCOM) represents an advanced Flexible AC Transmission System (FACTS) device specifically designed for distribution-level applications. Operating on the principle of voltage source converter technology, DSTATCOM provides dynamic reactive power compensation, harmonic filtering, load balancing, and voltage regulation through rapid current injection capabilities. The effectiveness of DSTATCOM implementation critically depends upon the control strategy employed. Pulse Width Modulation (PWM) switching techniques offer advantages including reduced switching losses, improved harmonic spectrum, and enhanced controllability. Hysteresis Current Control, characterized by inherent current limiting, fast dynamic response, and implementation simplicity, has demonstrated superior performance in current-controlled voltage source converters. The synergistic integration of PWM switching with hysteresis current control techniques presents significant potential for optimizing DSTATCOM performance in addressing multifaceted power quality challenges prevalent in Indian distribution systems. This research addresses the critical need for robust, responsive, and cost-effective power quality enhancement solutions suitable for medium-voltage distribution networks. By investigating the design, modeling, and performance characteristics of DSTATCOM systems incorporating advanced control methodologies, this study contributes to the development of indigenous power quality improvement technologies aligned with national grid modernization initiatives and renewable energy integration targets.

2. Literature Review

The evolution of FACTS devices for power quality improvement has been extensively documented in power systems literature. Singh and Solanki (2009) established foundational principles for DSTATCOM operation in distribution systems, demonstrating significant improvements in voltage profile and harmonic mitigation capabilities. Their experimental validation confirmed theoretical predictions regarding reactive power compensation and load balancing in three-phase four-wire systems. Subsequent research by Khadkikar (2012) presented comprehensive analyses of various DSTATCOM topologies and control strategies, emphasizing the superiority of voltage source converter configurations for distribution-level applications. The comparative study revealed that cascaded H-bridge and neutral point clamped inverters offered distinct advantages depending upon voltage levels and power ratings. Control strategy development has constituted a major research focus within DSTATCOM literature. Mishra and Karthikeyan (2008) introduced instantaneous reactive power theory-based control for DSTATCOM, achieving improved dynamic response under rapidly varying load conditions. The p-q theory implementation demonstrated effective harmonic isolation and reactive power calculation capabilities. Bhattacharya et al. (2011) advanced synchronous reference frame theory applications, enabling independent control of active and reactive current components with enhanced accuracy. Their experimental results validated superior performance compared to conventional d-q transformation methods.

PWM technique optimization has received considerable scholarly attention. Patel and Hoft (1973) pioneered sinusoidal PWM investigations, establishing fundamental relationships between modulation index, switching frequency, and harmonic content. Modern implementations have evolved significantly; Tekwani et al. (2005) compared multiple PWM strategies including space vector modulation, demonstrating trade-offs between switching losses and harmonic performance. Recent research by Gupta et al. (2015) explored selective harmonic elimination PWM techniques specifically tailored for DSTATCOM applications, achieving THD reduction below 5% while maintaining switching frequency constraints. Hysteresis current control methodology has been extensively investigated for voltage source converter applications. Brod and Novotny (1985) established theoretical foundations for hysteresis band PWM current control, analyzing stability conditions and steady-state performance characteristics. Kazmierkowski and Malesani (1998) provided comprehensive reviews of current

control techniques, highlighting hysteresis controllers' advantages including unconditional stability, excellent dynamic response, and inherent peak current limitation. Subsequent research by Mikkili and Panda (2014) demonstrated hysteresis current control superiority in DSTATCOM applications through comparative analyses with PI and fuzzy logic controllers.

Grid integration standards and power quality assessment methodologies have been codified through IEEE and IEC frameworks. IEEE Standard 519-2014 specifies harmonic distortion limits for electrical distribution systems, providing quantitative metrics for power quality evaluation. Recent research by Jayalakshmi et al. (2015) investigated DSTATCOM compliance with IEEE standards under various grid conditions, confirming feasibility of meeting stringent requirements through appropriate controller design. Artificial intelligence techniques have emerged in recent literature; Devassy and Singh (2016) implemented adaptive neuro-fuzzy inference systems for DSTATCOM control, demonstrating improved performance under uncertain and nonlinear operating conditions. Despite extensive research, gaps remain regarding integrated implementation of PWM and hysteresis control techniques for Indian distribution system conditions. Most existing studies focus on isolated control strategies without comprehensive performance comparison under realistic load scenarios. Furthermore, limited research addresses computational efficiency and practical implementation challenges for medium-voltage applications prevalent in Indian power distribution networks.

3. Objectives

- 1 To develop a simulation model of a three-phase 11 kV DSTATCOM using a Voltage Source Converter with PWM switching and hysteresis current control.
- 2 To assess the effectiveness of the proposed DSTATCOM in improving power quality under balanced, unbalanced, nonlinear, and dynamic load conditions, focusing on voltage regulation, harmonic reduction, and reactive power compensation.
- 3 To evaluate the dynamic and transient performance of the hysteresis current controller in terms of settling time, overshoot, steady-state error, and current tracking accuracy during load changes and fault conditions.
- 4 To verify the compliance of the DSTATCOM system with IEEE 519-2014 standards through analysis of harmonic distortion, voltage unbalance, and power factor improvement.

4. Methodology

The research methodology adopted a comprehensive simulation-based framework using MATLAB R2021a integrated with Simulink and SimPower Systems toolboxes to model, analyze, and evaluate the performance of a DSTATCOM system. A three-phase 11 kV, 50 Hz distribution network supplying mixed linear, unbalanced, and nonlinear loads was modeled to reflect realistic operating conditions. The source impedance and distribution transformer parameters were selected to emulate practical grid behavior, while dynamic load variations were introduced through programmed switching to assess transient performance. The DSTATCOM was implemented using a three-phase two-level Voltage Source Converter with IGBT switches, supported by a suitably designed DC-link capacitor, interfacing inductor, and coupling transformer for voltage matching and isolation. The control architecture comprised grid synchronization using a Phase-Locked Loop, reference current generation based on Instantaneous Reactive Power (p-q) theory, hysteresis current control, and PWM signal generation. An adaptive hysteresis band technique was employed to regulate switching frequency and enhance current tracking accuracy, while dead-time compensation ensured safe inverter operation. DC-link voltage regulation was achieved through a cascaded PI-based control structure with anti-windup protection for stable operation under transient conditions. Simulations were executed using a fixed-step solver with a 1 μ s time step to accurately

capture switching dynamics and harmonic content. Performance evaluation was carried out using metrics such as voltage and current THD, voltage regulation, power factor, voltage unbalance, and dynamic response indices, in accordance with IEEE standards, with comparative analysis against uncompensated cases to validate effectiveness.

5. Results

The simulation results comprehensively demonstrate the DSTATCOM system's effectiveness in improving power quality parameters across diverse operating conditions. Performance evaluation focused on voltage regulation, harmonic mitigation, reactive power compensation, and dynamic response characteristics under balanced loads, unbalanced loads, nonlinear loads, and transient conditions.

Table 1: Voltage Regulation Performance Under Various Load Conditions

Load Condition	Without DSTATCOM (kV)	With DSTATCOM (kV)	Voltage Deviation (%)	Regulation Improvement (%)
No Load	11.00	11.00	0.00	-
Balanced Linear (60%)	10.56	10.89	0.91	75.0
Balanced Linear (100%)	10.23	10.84	1.45	82.4
Unbalanced Load	10.38	10.87	1.18	79.0
Nonlinear Load	10.12	10.82	1.64	85.4
Dynamic Load Switching	9.87	10.79	1.91	88.7

Table 1 presents voltage regulation performance comparison across six operational scenarios. Without DSTATCOM compensation, voltage magnitude decreased significantly under loading conditions, reaching minimum 9.87kV during dynamic load switching events representing 10.3% voltage sag. The DSTATCOM intervention maintained voltage levels within narrow band 10.79-10.89kV corresponding to maximum deviation 1.91% from nominal value. The most substantial improvement occurred during dynamic load switching where DSTATCOM reduced voltage deviation from 10.3% to 1.91%, representing 88.7% regulation improvement. Under nonlinear loading conditions, voltage restoration from 10.12kV to 10.82kV demonstrated effective compensation of reactive power demands and harmonic distortions. The consistent voltage maintenance across all load scenarios validates the DSTATCOM's capability to meet IEEE Standard 1159 voltage variation limits of $\pm 5\%$ for distribution systems.

Table 2: Total Harmonic Distortion Analysis for Voltage and Current

Parameter	Baseline THD (%)	With DSTATCOM THD (%)	THD Reduction (%)	IEEE 519 Limit (%)	Compliance Status
Voltage (No Load)	1.2	0.8	33.3	5.0	Compliant
Voltage (Linear Load)	3.4	1.1	67.6	5.0	Compliant
Voltage (Nonlinear Load)	8.7	2.1	75.9	5.0	Compliant
Current (Linear Load)	4.2	1.8	57.1	8.0	Compliant
Current (Nonlinear Load)	28.4	3.2	88.7	8.0	Compliant

Table 2 quantifies harmonic distortion levels before and after DSTATCOM implementation across voltage and current parameters. The baseline condition exhibited voltage THD of 8.7% under nonlinear loading, exceeding IEEE 519-2014 permissible limit of 5% for distribution voltage levels. DSTATCOM intervention reduced voltage THD to 2.1%, representing 75.9% improvement and establishing compliance with regulatory standards. Current THD showed dramatic improvement from 28.4% to 3.2% under nonlinear loads, constituting 88.7% reduction. This substantial improvement resulted from the DSTATCOM's harmonic filtering capability through injection of compensating currents containing harmonic components equal in magnitude but opposite in phase to load harmonics. The voltage THD reduction under linear loads from 3.4% to 1.1% indicates mitigation of background harmonic distortion present in the supply system. All measured THD values with DSTATCOM operation remained well below IEEE 519 limits, confirming system compliance across operational spectrum.

Table 3: Reactive Power Compensation and Power Factor Improvement

Load Scenario	Load Reactive Power (kVAR)	DSTATCOM Injection (kVAR)	Grid Reactive Power (kVAR)	PF Without DSTATCOM	PF With DSTATCOM	PF Improvement (%)
25% Loading	1250	1180	70	0.85	0.99	16.5
50% Loading	2480	2390	90	0.78	0.98	25.6
75% Loading	3720	3580	140	0.74	0.97	31.1
100% Loading	4950	4730	220	0.72	0.98	36.1
Unbalanced Load	3150	3040	110	0.76	0.98	28.9

Table 3 demonstrates reactive power compensation effectiveness and consequent power factor improvement across loading levels. At full load condition, the system demanded 4950kVAR reactive power, reducing power factor to 0.72 lagging. DSTATCOM injected 4730kVAR reactive power, supplying 95.6% of reactive power requirement and reducing grid reactive power burden to 220kVAR. The power factor improved from 0.72 to 0.98, representing 36.1% enhancement and significant reduction in apparent power drawn from grid. Under 25% loading conditions, DSTATCOM supplied 1180kVAR of 1250kVAR total requirement, achieving power factor 0.99. The marginally lower compensation ratio at light loads reflects control algorithm prioritization of voltage regulation objectives. Unbalanced load scenarios exhibited reactive power compensation 3040kVAR with power factor improvement from 0.76 to 0.98. The consistent power factor maintenance above 0.97 across all loading conditions demonstrates DSTATCOM capability to eliminate reactive power penalties and reduce transmission losses.

Table 4: Individual Harmonic Component Analysis (Nonlinear Load Condition)

Harmonic Order	Voltage Without DSTATCOM (%)	Voltage With DSTATCOM (%)	Current Without DSTATCOM (%)	Current With DSTATCOM (%)	IEEE Limit Voltage (%)	IEEE Limit Current (%)
3rd	2.8	0.6	8.4	1.2	3.0	4.0
5th	5.2	1.2	18.6	2.1	3.0	7.0
7th	3.4	0.8	12.4	1.6	3.0	7.0
11th	2.1	0.4	6.8	0.9	3.0	3.5
13th	1.8	0.3	5.2	0.7	3.0	3.5

Table 4 provides detailed analysis of dominant individual harmonic components under nonlinear loading representing six-pulse rectifier characteristics. The 5th harmonic exhibited highest magnitude at 5.2% voltage distortion and 18.6% current distortion without compensation, exceeding IEEE 519 limits of 3% and 7% respectively. DSTATCOM intervention reduced 5th harmonic voltage to 1.2% and current to 2.1%, achieving compliance with substantial margins. The 3rd harmonic, typically associated with unbalanced and single-phase nonlinear loads, decreased from 2.8% to 0.6% in voltage and 8.4% to 1.2% in current. The 7th harmonic showed reduction from 3.4% to 0.8% voltage and 12.4% to 1.6% current. Higher order harmonics 11th and 13th exhibited lower baseline magnitudes but achieved similar reduction ratios. The comprehensive harmonic mitigation across multiple orders confirms the DSTATCOM's broadband filtering effectiveness through precise harmonic current injection based on instantaneous reactive power theory.

Table 5: Dynamic Response Performance During Load Switching

Performance Parameter	Load Increase Step	Load Decrease Step	IEEE Recommendation	Performance Status
Settling Time (ms)	38	35	<100	Excellent
Voltage Overshoot (%)	2.4	1.8	<5	Compliant
Voltage Undershoot (%)	2.1	-	<5	Compliant
Current Overshoot (%)	4.2	3.6	<10	Excellent
Steady State Error (%)	0.3	0.2	<1	Excellent
Recovery Time to 95% (ms)	28	26	<50	Excellent

Table 5 quantifies dynamic response characteristics during step load changes simulating realistic switching transients in distribution systems. Load increase from 50% to 100% rated capacity triggered transient voltage undershoot 2.1% with settling time 38ms, demonstrating rapid DSTATCOM response. The settling time significantly below IEEE recommended 100ms threshold confirms controller effectiveness. Current overshoot during load increase reached 4.2%, remaining well within acceptable 10% limit and indicating controlled power electronic switching without excessive stress. Load decrease step from 100% to 50% exhibited voltage overshoot 1.8% with settling time 35ms, slightly faster than increase step due to asymmetric power flow dynamics. The recovery time to 95% of steady-state value occurred within 28ms for load increase and 26ms for load decrease, validating hysteresis current controller's rapid tracking capability. Steady-state error below 0.3% confirms accurate reference tracking and effective integral action in control loops.

Table 6: Comparative Performance Analysis of Control Strategies

Control Strategy	Average THD (%)	Settling Time (ms)	Switching Frequency (kHz)	Power Factor	Implementation Complexity
PI Controller	4.8	65	10	0.94	Medium
Fuzzy Logic Controller	3.9	52	12	0.96	High
Hysteresis Current Control	3.2	38	10.5	0.98	Low
Sliding Mode Control	3.5	42	15	0.97	High
Proposed PWM+HCC	3.2	38	10.2	0.98	Medium

Table 6 presents comparative evaluation of the proposed PWM switching combined with Hysteresis Current Control against alternative control strategies under identical operating conditions. The proposed approach achieved lowest average THD of 3.2%, matched only by standalone hysteresis control but with improved switching frequency stability through PWM integration. Settling time of 38ms outperformed PI controller by

41.5% and fuzzy logic controller by 26.9%, demonstrating superior dynamic response. The switching frequency maintained stable average 10.2kHz with reduced variation compared to conventional hysteresis control, addressing the variable switching frequency limitation. Power factor achievement of 0.98 matched hysteresis control and exceeded PI controller performance. Implementation complexity rated medium, offering favorable trade-off between performance and practical feasibility compared to computationally intensive fuzzy logic and sliding mode approaches. The proposed strategy thus combines optimal dynamic performance with implementation practicality suitable for industrial deployment in Indian distribution systems.

6. Discussion

The simulation results comprehensively validate the research hypothesis that integrated PWM switching with Hysteresis Current Control significantly enhances DSTATCOM performance for power quality improvement in distribution systems. The voltage regulation capability demonstrated across all loading conditions confirms DSTATCOM effectiveness in maintaining stable voltage profiles despite varying reactive power demands and harmonic distortions. The maximum voltage deviation of 1.91% during severe dynamic load switching represents substantial improvement over the 10.3% baseline deviation, indicating robust control system design capable of rapid compensation response. The dramatic THD reduction from 28.4% to 3.2% for current under nonlinear loads constitutes a major contribution of this research. This improvement directly addresses the proliferation of power electronic loads in modern distribution systems, particularly prevalent in Indian industrial sectors including manufacturing, information technology, and commercial establishments. The achievement of IEEE 519 compliance across all operational scenarios eliminates concerns regarding harmonic pollution penalties and ensures compatibility with sensitive equipment requirements. The individual harmonic analysis reveals particularly effective mitigation of characteristic harmonics associated with six-pulse rectifiers, common in variable frequency drives and uninterruptible power supplies.

The reactive power compensation performance validates DSTATCOM capability to function as dynamic VAR support, supplying up to 95.6% of load reactive power requirements. This capability offers significant economic benefits through elimination of power factor penalties imposed by utilities, reduction of transmission losses, and release of generation and transmission capacity for active power delivery. For a typical 10MW industrial load operating at 0.72 power factor, the improvement to 0.98 power factor reduces apparent power demand from 13.89MVA to 10.20MVA, representing 26.6% capacity release. Extrapolated across India's industrial sector, such improvements could defer substantial infrastructure investments in generation and transmission expansion. The dynamic response characteristics with settling times below 40ms significantly outperform traditional reactive power compensation devices. Capacitor banks typically exhibit switching delays exceeding 100ms and suffer from discrete compensation steps. Synchronous condensers offer continuous compensation but respond sluggishly to rapid load changes due to mechanical inertia. The DSTATCOM's solid-state switching enables response speeds limited only by control algorithm execution and power electronics switching frequencies, providing protection against voltage sags and swells during motor starting, fault clearing, and load switching events.

The comparative analysis against alternative control strategies reveals important insights regarding optimal controller selection. While fuzzy logic and sliding mode controllers offer sophisticated adaptive capabilities, their computational complexity and parameter tuning requirements present implementation challenges for distribution-level applications where cost constraints dominate. The proposed PWM-HCC hybrid approach achieves comparable or superior performance with significantly reduced computational overhead, enabling implementation on standard industrial microcontrollers and digital signal processors. The inherent current limiting of hysteresis control provides valuable protection against overcurrent faults, reducing semiconductor

device stress and improving system reliability. Several practical considerations emerge from this research relevant to field deployment. The DC-link capacitor sizing significantly influences transient performance and energy storage capability during rapid load changes. The selected 10,000 μ F capacitance represents optimization between performance requirements and component cost and volume constraints. The coupling inductor design balances filtering effectiveness against voltage drop and switching ripple attenuation. The 5mH inductance provides adequate harmonic filtering while maintaining acceptable steady-state voltage regulation. The switching frequency selection of 10kHz optimizes the trade-off between switching losses and harmonic performance; higher frequencies improve filtering but increase semiconductor switching losses and electromagnetic interference.

The research identifies several areas requiring consideration for practical implementation. Thermal management systems must adequately dissipate switching losses and conduction losses in IGBTs, diodes, and passive components. The Indian ambient temperature conditions, frequently exceeding 45°C in summer months, necessitate robust cooling systems potentially including forced air or liquid cooling. Protection coordination requires careful consideration of DSTATCOM fault current contribution, particularly during grid faults where rapid disconnection prevents DSTATCOM damage. The control system must incorporate comprehensive protection features including DC overvoltage protection, AC overcurrent protection, semiconductor overtemperature protection, and grid abnormality detection. Grid integration standards compliance extends beyond harmonic limits to encompass voltage ride-through requirements, frequency variation tolerance, and grid support functions. The DSTATCOM design should incorporate low voltage ride-through capability enabling continued operation during voltage sags to 15% of nominal voltage for durations up to 625ms, consistent with Indian grid code requirements for distributed energy resources. The voltage regulation function provides inherent contribution to grid stability, particularly in weak distribution systems with high source impedance.

The economic viability of DSTATCOM deployment depends upon comprehensive cost-benefit analysis considering equipment costs, installation costs, operating costs, and quantifiable benefits including power factor penalty elimination, loss reduction, and improved equipment reliability. Preliminary estimates for a 1.5MVA DSTATCOM system including power electronics, passive components, control systems, and enclosures range ₹60-80 lakhs. For industrial consumers facing power factor penalties averaging ₹8-12 lakhs annually plus equipment downtime costs, payback periods of 5-7 years appear achievable, improving with electricity tariff escalation and equipment cost reduction through indigenous manufacturing. The research demonstrates applicability to renewable energy integration scenarios increasingly relevant to India's energy transition targets. Solar photovoltaic systems introduce voltage regulation challenges due to variable generation and limited reactive power support from inverters. DSTATCOM deployment at solar integration points can provide voltage support, harmonic filtering, and unbalance compensation, enabling higher photovoltaic penetration levels without distribution system upgrades. Similarly, the device supports electric vehicle charging infrastructure by mitigating voltage disturbances and harmonic pollution from fast chargers. Limitations of this research include reliance on simulation rather than hardware validation, simplified grid representations excluding multi-bus configurations and distributed generation, and idealized component models neglecting parasitic effects and non-idealities. Future research should address experimental validation using laboratory prototypes, investigation of coordinated control strategies for multiple distributed DSTATCOM units, integration of energy storage systems for extended voltage support capability, and development of machine learning-based adaptive controllers for uncertain and varying system conditions.

7. Conclusion

This research successfully demonstrates the design, modeling, and performance validation of a Distribution STATCOM employing integrated PWM switching and Hysteresis Current Control techniques for

comprehensive power quality enhancement in electrical distribution systems. The simulation results conclusively establish DSTATCOM effectiveness in achieving voltage regulation within $\pm 2\%$, reducing Total Harmonic Distortion from 28.4% to 3.2%, and improving power factor from 0.72 to 0.98 under diverse loading conditions including balanced, unbalanced, and nonlinear scenarios. The proposed control strategy achieves dynamic response with settling times below 40ms, substantially outperforming conventional approaches while maintaining implementation simplicity suitable for practical deployment. All power quality parameters achieve compliance with IEEE 519-2014 standards, validating the system's regulatory conformance. The research contributes valuable insights for power quality improvement in Indian distribution networks facing increasing challenges from nonlinear loads and renewable energy integration. The demonstrated performance characteristics, combined with favorable cost-benefit projections, support DSTATCOM technology adoption for sustainable grid modernization initiatives. Future work should focus on experimental validation, multi-unit coordination strategies, and adaptive control enhancements to address evolving power system requirements.

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